Developmental dynamics binding processing efficiency, working memory, and reasoning:

A longitudinal study

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June 2008

ISBN 978-9963-9509-0-4

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INTRODUCTION TO THE STUDY

Background

Cognitive processes, such as speed of processing, inhibitory control, and working memory, are used to describe the dynamic interaction of the cognitive system with the physical, the cognitive, the social, and the emotional environment. These processes define the way the cognitive system differentiates, selects, and concentrates at certain aspects of the world to form internal representations that can be mentally operated upon, transformed semantically, stored in memory, and retrieved from storage when decisions are to be made and actions are to be taken. These are hypothetical processes (Jensen, 1998) that most probably depend on the structural properties of the brain, and they are highly correlated with general intelligence as it was first introduced by Spearman (1904). Moreover, these cognitive processes are consistently found to be highly correlated with IQ, suggesting that they play an important role in dealing with novel tasks which require problem solving.

Logical reasoning tasks are a highly interesting group of novel tasks. These tasks activate the construction of new mental rules or the retrieval of existing ones from memory for the sake of processing of the information conveyed by the propositions. They also activate the construction of mental models under the constraints imposed from the reasoning type itself. Specifically, the inferential process is differentiated according to the nature of the logical argument processed. Inductive and deductive reasoning are differentiated in terms of the validity of their arguments, the effect additional information can have on the extracted conclusion and the degree to which they add the individual's semantic knowledge. The relation of reasoning performance with the parameters of processing efficiency, i.e. with speed and control of processing, and with memory resources, is of great importance to the understanding of the dynamic interplay of the mental processes. Moreover, the developmental course of these processes and the pattern of changes that can be observed during the primary school years are vital in the understanding of intelligence.

Conceptual Underpinnings for the Study

Cognitive psychologists have extensively studied the functioning of the mental processes humans use to adapt to their environment and successfully face the problems it presents. Individual differences in each of these processes have also been studied. The combination of the knowledge derived from both the cognitive and the psychometric approaches sets the stage for the analysis of cognitive task complexity and therefore for providing researchers (and educators) with a scientifically robust pool of tests. Furthermore, the study of the developmental course of each process, from early childhood to early adulthood, has revealed the range and the constraints, in physical terms, of speed and control of processing and of working memory capacity. Finally, the role of each of these mental processes in intelligence, as it is measured with the IQ tests, was studied mainly through cross-sectional designs where different groups at different ages were tested.

Research on reasoning has mainly focused in the study of deductive reasoning, especially conditional reasoning. The various theories advanced explain individual differences in reasoning in reference to (i) the content and context of tasks, (ii) the mental rules supposedly used in reasoning and (iii) the mental models constructed while reasoning (Rips, 1983; Cheng & Holyoak, 1985; Johnson-Laird, 1983). Although research on reasoning has been in the forefront of psychological research for decades, it was not until recently that reasoning was investigated in relation to various information processing efficiency cognitive processes (Markovits & Barrouillet, 2002; 2004). This research is briefly reviewed below.

Speed of Processing

The relation between speed of processing and intelligence is studied systematically. IQ measures and complex reasoning tests are regularly used in this research. IQ measures and performance on complex reasoning tests are strongly correlated with the general intelligence factor. Jensen (1998) reports that IQ scores, obtained from a battery of standard IQ tests, such as the Wechsler Intelligence Scale for Children (WISC) and for Adults (WAIS), are highly correlated (more than .95) with the general intelligence factor obtained from the whole battery of tests. Based on this extremely high correlation of IQ measures with the general intelligence factor, the relation between speed of processing and intelligence was primarily revealed by correlating measures of speed of processing obtained from various elementary cognitive tasks, and various psychometric tests such as IQ tests. A strong correlation between mental speed and intelligence, averaging -.52 (Vernon, 1983), was reported. Additional evidence on the strong relation between the general intelligence factor and mental speed is provided by the correlation of the performance on non-speeded reasoning tests with speed of processing (Wilhelm &

Schulze, 2002). Finally, Kyllonen and Christal, (1990) reported a strong relation of speed of processing with intelligence. Their findings were based on measurements of complex speed tasks, which tap individual differences in inhibitory control and working memory capacity and are strongly related to reasoning and intelligence. Jensen (1998) considers that the strong relation of speed of processing with the functions attributed to working memory and with reasoning is evidence supporting the view that mental speed is fundamental to human intelligence.

The developmental course of mental speed was widely studied, mainly by cross-sectional research. A meta-analysis of studies on speeded performance, conducted by Kail (1991), revealed that in early and middle childhood processing speed increases substantially and then, during early and middle adolescence, it changes more gradually. Adult levels of speeded performance are not achieved until the middle of adolescence. Furthermore, the role of speed of processing as a developmental factor in age-related differences of performance on various tests was examined by Salthouse (1992). He showed that age-related differences in various cognitive domains diminish significantly after variance associated with processing speed is removed. This suggests that processing speed is important in age-related differences in many domains. Age-related changes in processing speed seem to affect cognitive performance on various domains by influencing the speed of specific processes (Kail & Salthouse, 1994).

Developmental data strongly suggest that processing speed is highly related to intelligence in adolescents and adults, but only marginally in young children of 4 to 6 years of age (Miller & Vernon, 1992). An explanation for this pattern of correlations is the fact that very simple speed tasks are used in the tests addressed to young ages. However, the relationship between speed of processing and intelligence increases with increasing complexity of the speed tasks (Hunt, 1980; Stankov & Roberts, 1997). Thus the full size of the relation between speed of processing and intelligence is concealed. The weak correlation between speed of processing and intelligence in younger children can also be ascribed in reference to genetic factors (Vernon & Mori, 1992). That is, it is assumed that the influence of speed on intellectual capacity is not manifested until late childhood or early adulthood (Miller & Vernon, 1996).

Control of Processing

Information processing efficiency requires mechanisms that would enable one to have control of processing and stay focused on goal-relevant information while filtering out interfering and goal-irrelevant information (MacLeod, 1991; Navon, 1977). Relevant and non-relevant information usually co-exist and the control mechanisms are activated in order to inhibit premature responses which are usually activated by dominant but irrelevant information (Demetriou, Efklides, & Platsidou, 1993). Inhibitory control is considered as a part of a broader mental ability, namely executive control, which refers to inhibiting attention to irrelevant stimuli, to inhibiting prepotent or premature responses, to concentrating on goal-relevant information and to maintaining information and the appropriate rules in working memory so that a strategic plan of action can be made (Zelazo, 2004). Executive control skills are incorporated in the functions of working memory (Baddeley, 1986; 2000). Bracketing prepotent or stereotypical responses and controlling contradictory representations, which are functions attributed to inhibitory control, facilitate the access and operation on internal representations (Baddeley, Emslie, Kolodny, & Duncan, 1998), which are functions attributed to working memory.

The strong association of executive control with working memory is, according to Baddeley (2000), largely due to their common reliance on conscious awareness. Conscious awareness is present in information transformation and storage and it is highly activated when the inhibitory control mechanisms are triggered. Mental representations, which constitute the conscious contents of working memory and the result of the smooth synergy of the inhibitory control and the storage mechanisms, provide the basis for reasoning and problem solving. Valid argumentation and therefore reasoning processes draw upon the executive control functions. Performance on inductive and deductive reasoning tasks is based on the efficiency of executive control functions (Pennington & Ozonoff, 1996). Therefore, constraints in these functions are a major source of variance in reasoning and can be used to explain developmental changes in children's reasoning ability (Johnson-Laird & Byrne, 1991; Markovits, 2000). Miyake and Shah (1999) incorporate the inhibition of belief-based responses, often encountered in the reasoning process, into the function of executive control. Moreover, neuro-imaging research suggests that inhibitory processes may be involved on reasoning problems in which beliefs are incongruent with the logical response (Goel, Buchel, Frith & Dolan, 2000). Seen from a developmental perspective, this ability is involved in monitoring and managing the deployment of cognitive resources as children enter adolescence (Kuhn & Pease, 2006). Cognitive functioning and learning become more effective and executive functions significantly contribute to the development of metacognitive awareness. As a result, one can temporarily nullify the perspective shaped by personal beliefs or understanding, in order to extract meaning and reason based on decontextualized representations.

Generally speaking, inhibitory control improves during childhood and declines during late adulthood (Williams, Ponesse, Schachar, Logan & Tannock, 1999). A same age-related pattern of change occurs in belief-based biases in informal (Klaczynski, Gordon & Fauth, 1997) and formal (Moshman & Franks, 1986) reasoning. Young children tend to be misled by belief-biases more often than young adults do, while older adults tend to be less accurate than younger adults in reasoning problems in which logic and belief lead to different responses (Klaczynski & Robinson, 2000). These findings imply an ongoing interplay between inhibitory control, working memory and reasoning.

Working Memory

Working memory is conceptualized as a limited capacity system for information processing. It is widely accepted that it is not a unitary system that includes several subsystems. Baddeley proposed an influential multi-component model (Baddeley & Hitch, 1974; Baddeley, 1992; 2000) which encompasses a central executive system that coordinates and processes the information of the other components of the model, two unimodal storage systems, namely the phonological loop and the visuospatial sketchpad which manipulate and store acoustic information and visual images, respectively, and a multimodal limited capacity system capable of integrating information into unitary episodic representations, the episodic buffer. Repovš and Baddeley (2006) note that the model suggests the fractionation of working memory into independent stores and processes, sheds light on the nature of representations in individual stores, tracks the mechanisms of their maintenance and manipulation, assumes the way the components of working memory relate to each other, and reveals the role they play in other cognitive abilities.

In the theory of working memory proposed by Just and Carpenter (1992) individual differences in working memory result from differing levels of available activation. As children mature their level of activation increases, leading to improved performance in working memory tests. The correlation between working memory capacity and IQ increase with the complexity of working memory tasks, ranging from 0.46 to 0.59 (Cohen & Sandberg, 1980).

Evidence suggests that there is dissociation between visual and verbal working memory (Shah & Miyake, 1997), and that there maybe an additional domain for numerical information (Leather & Henry, 1994). Therefore, it is assumed that different domains of information processing (e.g., verbal, quantitative, spatial) may draw on different pools of activation and thus they may have different working memory capacities (Hale, Myerson, Rhee, Weiss, & Abrams, 1996).

In his meta-analysis, Dempster (1981) showed that most of the developmental improvement in memory span occurs during the early school years in a nonlinear fashion that parallels the nonlinear increase in processing speed over the same developmental period. Moreover, a study conducted by Siegel (1994) suggested that a similar nonlinear pattern describes the development of working memory when its executive functions are activated. Gathercole and Baddeley (1993) reviewed the literature on the development of working memory and they concluded that the increase in children's memory ability with age is based on increases in the efficiency of the working memory system. On the other hand, Cowan (1992) suggests that preschool children perform more poorly on memory span measures than older children because there are qualitative differences in the mnemonic strategies used at different ages.

Age related differences in working memory capacity are closely related to the quantity of processing resources available to execute cognitive processes. Case (1985) maintained that short-term storage space is a key component which refers to the amount of information that can be processed at a given time. Case claimed that age-related increases in the capacity of short-term storage space, which come from a corresponding increase in processing efficiency, are responsible for developmental changes across a broad spectrum of domains. Pascual-Leone (1970) proposed that a central computing space exists which increases systematically during development. Pascual Leone assumed that mental power increases from 1 unit of information at the age of 3 to 7 units of information at the age of 15, increasing by one unit every second year. Larger computing space leads to higher speed of processing, because increased processing space enables parallel processing of more information or more efficient exchange of information between the computing space and long-term memory.

The effect of age on the interrelationships between speed, working memory, and intelligence in children, was studied by Miller and Vernon (1996) and by Fry and Hale (1996). In both studies the results reveal a weak role of processing speed as far as intelligence is concerned. Miller and Vernon (1992) demonstrated that although working memory and speed of processing could both significantly predict general intelligence among adult participants, working memory was a better predictor. Furthermore, it was demonstrated that working memory not only is highly related to intelligence, but it is also important in the relationship between intelligence and speed of processing. Working memory tends to correlate more strongly and to account for considerably more variability in intelligence than speed of processing. On the other hand, Kail (1992) suggests that the age-related differences in memory span could largely be explained by age-related differences in processing speed. Case and his colleagues (Case, 1992; Case, Kurland, & Goldberg, 1982; Case & Okamoto, 1996), proposed that increases in processing speed with age reduces the space required for operations, and as a result more space is left available for short-term storage. Thus, according to Case, the crucial developmental factor is growing processing efficiency, rather than the increase of working memory capacity. Cowan (1997) and Demetriou, Christou, Spanoudis and Platsidou (2002) opposed to this thesis and they proposed that processing speed and processing capacity are independently increasing or their development is mediated by a third variable such as increasing knowledge.

Nevertheless, the correlation between performance on working memory tests and tests of fluid intelligence appears strong (Kyllonen & Christal, 1990; Fry & Hale, 1996). According to Kyllonen and Christal, working memory is highly correlated with reasoning ability (ranging from 0.82 to 0.88) whereas processing speed is moderately correlated to working memory (ranging from 0.35 to 0.48). These correlations imply that working memory capacity significantly contributes to individual differences in reasoning because it draws upon the retrieval processes during mental model construction. It is also suggested that the conscious contents of working memory provide the base for reasoning and problem solving.

Reasoning Ability

Researchers of inductive and deductive reasoning proposed models of how one formulates a line of reasoning based on valid argumentation. The most common aspect studied is how reasoning with conditional propositions takes place and what the cognitive and developmental parameters of conditional reasoning are. Some researchers emphasized the critical role of the content-specific representation of propositions and how it mediates performance. Cheng and Holyoak (1985) emphasized the role of semantic forms and semantic meanings such as permission, obligation and causality in representing the propositions. Specifically, they suggested that there exists a pool of mental schemes, formed by experiences and memories of experiences, from which the reasoner extracts and applies the appropriate ones in relation to the semantic form and meaning of the propositions. Klaczynski and Narasimham (1998) claim that none of these semantic concepts has its own concept-specific reasoning scheme because other parameters, such as the specific content and the specific knowledge incorporated in the propositions, affect reasoning by interfering in the process. Furthermore, it is claimed that the availability of mental representations of alternatives accounts for most of the variance in reasoning performance, because it directly affects the construction of mental models.

Seeking and retrieving alternatives from long term memory and keeping them activated in working memory is an important procedure in mental model construction, as proposed by Johnson-Laird (1983). Though this theory suggests that individual differences emanate from the ability to reach and retrieve the whole spectrum of alternatives and from the efficiency in activating inhibitory control in order to suppress premature responses and to restrain the intrusion of non-relevant alternatives, no theoretical connection between reasoning performance and working memory is proposed. An attempt to bridge the gap in the theory was made by Markovits and Barrouillet (2002) who developed a model based on Johnson-Laird's mental model theory. Their model attributes developmental improvements in deductive reasoning to increased capacity in manipulating multiple mental models, i.e., placing value on some cognitive parameters, and in the greater availability of knowledge stored in memory.

Although inductive and deductive reasoning involve distinct inferential processes in terms of the rules they use and the nature of the conclusion they generate, they may share common cognitive resources. They are both prone to errors due to belief biases (Kuhn, 1989) which interfere in the process and cause the premature termination of examining the alternatives (deductive reasoning) or the search for additional covariates (inductive reasoning). Moreover, school age children base their argumentation by testing a very small number of alternatives (usually one) when they reason in the context of deductive reasoning and by making inductive inferences based on the evidence of a single co-occurrence of two events. The ability to inhibit the premature responding that terminates processing and prevents the thinker to consider alternatives and additional covariates, when engaged in deductive and inductive reasoning, respectively, and the ability to temporarily inhibit one's beliefs in order to accurately represent the evidence embedded in the propositions, are reflected in the functions of executive control.

Statement of the Problem

Different theories have emphasized the role of different processes in the understanding of intelligence. Some theorists considered speed of processing central in the operation of the mind, assuming that it affects the functioning of working memory and reasoning and mediates their relation (Kail & Salthouse, 1994). Others (Miller & Vernon, 1996; Fry & Hale, 1996) have questioned its importance. Likewise, there is the lack of consensus about the functions of working memory itself, contributing to the vagueness and imprecision in the field.

The clash between theories calls for a different research approach. These discrepancies can be attributed to the isolated study of each mental process without taking into account its dynamical interrelations with the other processes. Research failed to view the multidimensionality of the web of cognitive processes and to uncover their interplay. The combination of the knowledge derived from both the cognitive and the psychometric approach to studying reasoning ability in order to facilitate the analysis of the cognitive complexity of reasoning tasks has not yet been achieved. Furthermore, a sound developmental profile of speed and control of processing and of working memory has not yet been provided. Finally, the role of each of these mental processes in intelligence was studied mainly through cross-sectional designs which confound age differences with individual differences (Fry & Hale, 1996). The fact that very few longitudinal studies have been reported in the study of speed (Kail, 2007), control of processing (Schneider, Lockl, & Fernadez, 2005; Zelazo, Müller, Frye, & Marcovitch, 2003), and working memory (Schneider, Lockl, & Fernadez, 2005) perpetuates the theoretical gap in developmental psychology.

Purpose of the Study

The purpose of this study is to highlight how the different mental processes which reflect processing efficiency and information storage, retrieval, and integration, are dynamically interrelated in web and how their dynamic interplay affects their development during the age span of 6 to 11years. The study will examine how these aspects of cognitive development unfold during a critical period of child development and will provide a theoretical perspective for understanding the role and functioning of each mental process during this developmental course. It will also propose a model for the conceptualization of the development of reasoning as it is affected by the interplay of the various processes. Developmental stages in reasoning development will be viewed within a comprehensive framework of all cognitive processes involved and implications for teaching and learning will be suggested. Moreover, a cognitive task analysis will be proposed which advances a complexity metric for specifying the complexity of reasoning tasks. This metric aims to reflect psychometric, cognitive, and developmental aspects of reasoning ability.

Research Questions

1. How are the various cognitive processes structurally interrelated and how are they related with the general intelligence factor? What is the causal relation between the cognitive changes which appear during childhood? Do changes appear in a unidirectional bottom-up or top-down fashion or do they appear in both directions in tandem?
2. What is the developmental course of each process during the age span 6-to-11 years? Is there a critical period in which drastic changes occur?
3. Do these relations between processes change with development?
4. How do changes in efficiency and memory affect the reasoning ability? How does the system capitalize on the various cognitive processes?
5. How is the content of reasoning tasks related to their complexity?
6. Are there different clusters of reasoners? If yes, what is the cognitive profile of each cluster?
7. Which task parameters affect or define the complexity level of the reasoning tasks? Is it possible to predict reasoning performance when the parameters that define task complexity, are known? Can the parameters of information processing and working memory capacity, in conjunction with task complexity parameters, serve as predictors of reasoning performance?

Hypotheses

1. The cognitive processes are hierarchically structured in such a way that a general factor residing at the apex of the hierarchy accounts for the individual differences encountered both in age-peered populations as well as developmentally. This general factor should reflect general intelligence and it should map strongly onto other factors residing lower in the hierarchy. The general intelligence factor should account for the common variance manifested in a group of other general, albeit less so, factors, such as processing efficiency, working memory and reasoning ability. Each of these less general factors stand in their own right, as complete autonomous process, while maintaining its own specificities. Further analysis of any factor at the second level should reveal an underlying hierarchy comprising more specific processes, such as sheer speed of processing, inhibitory control, short term working memory capacity, inductive reasoning.
2. Each of the specific cognitive processes is related with the other mental processes in such a way that the more fundamental processes are embedded in the more

complex ones. A dynamic interplay among the cognitive processes should emerge, suggesting a cascaded arrangement of the processes. This cascaded arrangement of the processes should imply that changes happen in a bottom-up fashion, that is, changes in the more simple processes should drive changes in the more complex processes, and, therefore, it is expected that some processes will be identified as individual differences factors, and others will be identified as developmental factors.

3. During the age span studied here, it is expected that drastic developmental changes will occur in all processes. The profile of the age-related differences, should suggest that a common mechanism underlies these changes. It is hypothesized that the processing efficiency parameters, namely the speed and control of processing, initiate and maintain changes in the representational processes, namely working memory and reasoning ability.
4. Seen from a longitudinal perspective, it is expected that individual differences in the processes residing lower in the hierarchy determine, to a significant degree, the condition of the more general processes in subsequent points in time.
5. Reasoning ability develops in distinct stages and it should, at each of these, exhibit quantifiable and measurable characteristics. These characteristics constitute an absolute reflection of the cognitive processes. It is expected that each reasoning stage will be quite accurately described based on the processing efficiency parameters and the working memory capacity. Advancing to a higher reasoning stage should require changes in the cognitive processes.
6. A proposed cognitive task analysis formula based on semantic, procedural, and mental constructs parameters should provide a reliable prediction of the individuals’ reasoning ability. This is effected as a result of the calibration of the reasoning tasks’ difficulty and the individuals’ ability on a common imaginary metric provided by Rasch analysis. High correlation of the task distribution, based on their complexity analysis, with the obtained distribution from the Rasch analysis, would render the proposed task analysis formula both a predictor and an assessor of reasoning ability.

Limitations, Assumptions, and Design Controls

This study was addressed to school-aged children, i.e. children from 6 to 11 years of age. Parental consent was obtained for all participants. All children attended the same school. Two testing waves were conducted, with a time interval of one year apart. All participants from the first testing wave were included in the second testing wave (except those who during the first testing wave attended Year 6 – the 11-years-olds). Restrictions about the time each individual participant would spend on the testing procedure as a whole, which were set by the school program and by the Ministry of Education and Culture, imposed limitations on the length of the test battery. Specifically, the test battery which was used at the first testing wave included three times more tasks than the test battery used in the second wave (of course the selection of the tasks was based on sound criteria which will be presented in the third chapter). On the other hand all of the school pupils participated in the second testing wave, thus tripling the number of the participants in relation to the first wave.

The testing took place at the school premises (in the computer lab) during the everyday lesson program. Since a large part of the tests was computerized, a basic assumption of the study was that all participants were familiar with using the keyboard (pressing the buttons specified at each test). Moreover, it was assumed that all participants had the minimum reading and instructions' comprehension ability so that no variance in the performance would be attributed to individual differences in these factors.

In the case of the unspeeded reasoning tests all participants were given the time they needed to complete the tests without any time constraints. Nevertheless, it was unavoidable to control the possibility that participants would not complete the whole test even if time was given to that purpose.

Finally, since the test was administered in three different sessions (one session for the reasoning test, one session for the processing efficiency tests, and one session for the working memory and information integration test) it was assumed that this did not affect the performance during any of the three sessions and that the same results would have been obtained in any case.

Summary

Cognitive and developmental findings suggest that human intelligence is related with various mental processes. Researchers have focused on different aspects of this multidimensional pattern of relations and have experimentally approached them in multiple ways. The general intelligence landscape still needs to be demystified. The role of each of these processes in the structure of intelligence and the way the maturational changes, which are manifested during the critical period of 6-to-11 years of age, alter the processes' interplay with general intelligence, comprise the main research questions of this study. To this end, structural and developmental evidence, based on a cohort sequential design, combining cross-sectional and longitudinal data, will be applied on theoretical models in order to provide sound answers to the research questions.

The basic theoretical and experimental data on the cognitive and developmental profile of the mental processes (speed and control of processing, working memory and reasoning) will be presented in the second chapter. Next, the research design and the methodology of our study will be presented in the third chapter where the research questions and the hypotheses of the study will be stated. The analysis of the data and the structural and developmental models which were applied on the data will be presented in the fourth chapter. Answers will be given to the research questions and hypotheses will be confirmed or rejected as a result of the data analysis. Moreover, a task complexity model will be introduced and theoretical and statistical argumentation will be offered to support it. Finally, in the fifth chapter the findings will be presented and conclusions will be drawn based on the research questions. Some implications for practice and some future research will be suggested.

CHAPTER 2

REVIEW OF THE LITERATURE

Introduction

The human mind and the functions ascribed to it have been the focus of scientific interest ever since the first philosophical questions about it were raised in ancient Greece. Plato identified the cognitive aspect of mind, which he called “*reason*”, with the soul. He maintained that the soul consists of *reason*, *emotion,* and *appetite*. Reason was considered as the dominant aspect of soul under which *emotion* and *appetite* are subjected. Thus, in Platonism, the reasoning mind is treated as a perfect attribute, common to all humans, and as such, it is incompatible with the notion of individual differences and idiosyncrasies. It was not until the mid-nineteenth century that Plato’s notion of mind was challenged and individual differences in mental ability were identified. Reasoning ability is definitely not a perfect human attribute and the mental processes that make it possible undergo extensive developmental changes and are confined by many cognitive constraints. As a result, the ability to reason springs from the dynamic interplay of these developmental and mental processes. General intelligence is closely related to reasoning because they share many common properties and processes.

The General Factor of Intelligence

The Psychometric Approach

Among the first to introduce the idea of individual differences in mental ability were Darwin, Spencer, and Galton. Darwin’s theory of natural selection was influential in how scientists viewed intelligence as an adaptive ability. His theory led students of intelligence to consider variation in mental ability as a product of human evolution. Furthermore, Spencer, who paid specific attention to individual differences in intelligence, viewed the mind as an organically evolved adaptive mechanism and the individual differences as the raw material on which natural selection operates. Galton believed that mental ability comprises both a general ability and special abilities such as linguistic, mathematical, musical, artistic and memorial. He conducted a series of experiments using simple speeded tasks which led him to conclude that mental ability was inherited, though he never actually succeeded in to measure individual differences in intelligence (Jensen, 1998).

Galton's belief that individuals differ in their mental ability capacity and efficiency opened the way for the psychometric approach to invent tests that would measure intelligence and reveal individual differences in a scientifically acceptable way. In fact, the basic assumption underlying psychometric models is that the structure of intelligence can be revealed by studying the intercorrelations of the various mental tests. The first valid test of intelligence was invented in 1905 by Binet who borrowed some of Galton's simple tests and devised some complex tests on reasoning, judgment, planning, verbal comprehension and acquisition of knowledge.

Spearman (1904) approached Galton's intuition on the existence of a general mental ability and a set of specialized abilities more systematically. He proposed a theory and a pioneering statistical method which set the stage for new methodological approaches and new analyses of the data. According to Spearman's two-factor theory every mental test measures only two factors, namely, a general, important, factor (*g*) and a less important factor specific to each test (*s*). Using factor analysis, Spearman concluded that the general mental ability factor, which he believed to correspond to a fixed amount of "mental energy" which an individual can assign to different mental tasks, is present in every mental activity, and that the specific factors act as specialized "engines" which use the mental energy for the execution of certain tasks. Individual differences in mental ability are attributed to variances in the amount of available mental energy and in the efficiency by which the specific factors utilize it. According to Spearman, general and specific factors are uncorrelated.

A different statistical approach was used by Thurstone (1938) who maintained that mental ability consists of distinct uncorrelated abilities and that there is no general ability factor. He originally proposed a multifactor model where a wide range of primary mental abilities are highly correlated with each other. These abilities are verbal comprehension (knowing and understanding the definitions of words), word fluency (fast production of words), number facility (mathematical computations and problem solving), space (mental rotation), perceptual speed (fast stimuli recognition), induction (finding rules and solving analogies), and memory (rote memory of words, pictures, or numbers). In his model there was no general factor, although the high correlations between the primary mental abilities factors indicated the existence of *g*. Eventually he himself recognized that the primary mental abilities do correlate and that in every test which was designed to measure a specific mental ability there was a measure of the general mental ability factor which may be uncovered by appropriate analysis as a second-order factor. According to this method of analysis, namely the hierarchical factor analysis, variables are correlated with *g* only via their correlation with the first-order factors.

Contemporary Psychometric Models

Contemporary psychometric models propose a hierarchical structure to intelligence as an attempt to bridge the gap between the measurements based on psychometric tests and the need for theoretical constructs which would account for the variance observed in the test measurements. Cattell's theory of fluid and crystallized intelligence (Cattell, 1971) and Carroll's three-stratum theory (Carroll, 1993) are among the most widely accepted hierarchical psychometric theories of intelligence.

Cattell (1966) suggested a hierarchical view of intelligence by proposing a theory on the existence of a general fluid intelligence (Gf) and a general crystallized intelligence (Gc) over Spearman's single overarching factor *g*. Cattell (1971) suggested that fluid intelligence, often called fluid reasoning, is the capacity to figure out novel problems by relation eduction and depends on minimum use of prior learned knowledge, or preexisting skills or strategies. Fluid intelligence is traceable in tests with no scholastic or cultural content, such as perceptual and figural tests (for example Raven's matrices), or in verbal tests that depend mainly on figuring out the implicit relationships between certain words whose meaning is familiar. Fluid intelligence "is an expression of the level of complexity of relationships which an individual can perceive and act upon when he does not have recourse to answers to such complex issues already stored in memory" (Cattell, 1971, p. 99). On the other hand, crystallized intelligence reflects consolidated knowledge as a result of scholastic and cultural knowledge acquisition and it is traceable in tests measuring numerical, mechanical, and lexical abilities. Crystallized intelligence "arises not only from better educational opportunity but also from a history of persistence and good motivation in applying fluid intelligence to approved areas of learning" (Cattell, 1971, p. 96). It is obvious that the contribution of fluid intelligence to the development of crystallized intelligence is critical. People with high fluid intelligence tend to acquire more crystallized intelligence from their learning opportunities than people with lower fluid intelligence. Based on this relation of fluid and crystallized intelligence, Horn and Cattell (1971) have proposed the Investment theory.

The Investment theory postulates that fluid intelligence allows for the development of crystallized intelligence because it is primarily related to genetic factors and neurological functioning and it is thus invested in all kinds of complex learning situations.

As a result, the acquired crystallized abilities are highly and positively correlated since they are all the outcome of the investment of fluid intelligence in all kinds of complex learning situations. Individual differences in fluid intelligence determine individual differences in crystallized intelligence among persons with similar educational and cultural opportunities since the rate of acquiring new knowledge and skills depends on the level of fluid intelligence. Thus, in homogenous groups of people crystallized intelligence closely parallels fluid intelligence so that they are highly correlated. As a result, they are often not clearly differentiated and merge into a single general factor, *g*.

Gustafson (1988), ran an analysis to investigate what happens when a very large battery of tests yielding Gf and Gc, along with other second-order factors, are subjected to a hierarchical factor analysis. He found that the third-order factor, *g*, is perfectly correlated with Gf, so that when all the second-order factors were residualized, Gf disappeared meaning that the factor that stands for fluid intelligence is subsumed into the general third-order factor *g*. This perfect correlation can be attributed to the fact that Gf strongly affects the acquisition of knowledge and, therefore, the individual differences which are observed in tests which are based on previously acquired knowledge and skills are fully explained by Gf. Accordingly, Gf acquires the role of the *g* factor vis-à-vis the other factors.

Carroll's three-stratum hierarchical factor model could be considered as a successful development and application of the hierarchical factor analysis. The structure of intelligence is considered as a pyramid. At the apex of the hierarchy (Stratum III) lies the single third-order factor which is the conceptual equivalent of Spearman's *g* and which dominates the variance in all factors lying lower in the hierarchy. Lower in the hierarchy lie eight second-order factors which are differently influenced by the third-order factor and which represent enduring characteristics of the individuals. Therefore, each of these broad factors affects the performance in a given domain and it is influenced by the general intelligence factor. The eight second-order factors are fluid intelligence, crystallized intelligence, general memory and learning, broad visual perception, broad auditory perception, broad retrieval ability, broad cognitive speediness, and processing speed. At the base of the hierarchical structure lie numerous specialized skills which reflect the acquisition of specific knowledge and strategies, some of which represent Thurstone's primary factors. Carroll's factor analysis gave a major thrust in the revival and further development of the psychometric approach to intelligence because he demonstrated that a century of research provided a reliable and consistent model of the dimensions and levels of individual differences in intelligence.

Variances in g Estimates

All factor analysis methods, except those that mathematically exclude the emergence of a higher order general factor, indicate the presence of a general mental ability factor. Jensen and Weng (1994) evaluated the various factor analytic methods for estimating *g* and concluded that all of these methods obtained estimates of *g* that deviated very little from the true values. It is suggested, therefore, that an extremely small portion of the variation among the different estimates of *g*, can be attributed to differences in the methods employed. Deviance in g estimates is attributed to the differences in the statistical characteristics of the groups tested and to the specificity of each instrument used. Specifically, when a representative sample of the general population is used, then the *g* estimate is more likely to be close to the real value of *g*. The *g* estimates obtained when testing individuals whose IQ belongs at the upper half of the normal distribution differ from the estimates obtained when testing individuals whose IQ belongs at the lower half of the distribution. This deviance in *g* estimates is explained by the Spearman's Law of Diminishing Returns. According to this law *g* accounts for less of the variance in a battery of tests for the upper half of the population distribution of IQ than for the lower half, even though the upper and lower halves do not differ in the range of test scores or in their variance. High-*g* persons have more differentiated abilities independent of *g*, and the variance in their abilities lies more in specified group factors than in the general factor. Jensen (1998) offers an explanation on that based on the automatization through practice. As he puts it "one might say that in the course of mental development *g* (or fluid ability, G*f*) becomes increasingly invested in specialized skills, in which proficiency becomes partly automatized through practice" (p. 585).

Detterman (1987) postulated that mental ability involves processes which can be divided into two categories, according to their role in the functioning of other processes. Some processes are central and some are non-central. Central processes strongly affect the functioning of a wide range of less central processes. Deficiencies in a central process, which is the case with low-*g* people, handicaps many mental functions and results in lower overall performance on almost every kind of mental test. Therefore, higher correlations between the tests are observed and, subsequently, greater *g*-variance. When deficiencies exist in less central process, which is the case with high-*g* people, this only affects the functioning of narrower processes. Therefore, lower correlations between the tests are observed and, subsequently, lower *g*-variance. It could be argued that what Detterman calls "non-central processes" are domain specific aspects of intelligence which can be clearly differentiated from one another (like Gardner's independent intelligences, to be discussed below) and that what he calls "central processes" are high level processes like reasoning and executive control which share some common operations.

Variances in g estimates can also be attributed to the tests' specificity which is a function of the nature and the variety of the tests in a battery. The specificity of a test increases as the variety of the tests in the battery increases. As variety decreases, the variance that would constitute specificity becomes common factor variance and thus contaminating the extracted *g* factor and its estimation. Various methods of factor analysis had established the types of items which are most *g* loaded, those being the ones that involve inductive or deductive reasoning, and problems that involve spatial visualization, quantitative reasoning, and verbal reasoning. Tests do not "contain" g; rather some tests are better indicators of g than others though they represent only a part of the whole continuum of g loadings. Jensen (1998) proposed that the items that call for relation eduction (that is, inductive and deductive reasoning) should be evenly balanced among verbal, spatial and numerical contents so as to allow most of the variance in the total score to represent a general intelligence factor which is relatively uncontaminated by group factors. According to Jensen, the extraction of *g* as a second-order factor in a hierarchical factor analysis requires a minimum of nine tests, which should be a representative sample of all types of mental tests, from which at least three primary factors can be obtained.

The substantial correlation of the various *g* estimates across different test batteries provides the basis for the ascription of a numerical value to *g*. This correlation implies that the different obtained values of *g* can all be interpreted as estimates of a true, but unknown, *g*. Nevertheless, "unknown *g*" is not contained in a test or in a test battery. It has been erroneously suggested that IQ-test scores can be used as a means of assigning *g* a numerical value (Jensen, 1998). General intelligence accounts for an important part of the variance in IQ scores, but it is certainly beyond the limitations of IQ scores. Therefore, IQ scores should not be considered as an arithmetic expression of *g*.

Towards a Cognitive Approach

Opposing theories to the existence of a general intelligence factor which dominates the variance of the various mental processes have been occasionally suggested. The strongest of these theories were directed from the specificity doctrine postulating that intelligence consists of a repertoire of specific knowledge and skills which are learned with practice and experience. It is further assumed that all complex mental abilities are entirely the result of such learning. The degree to which those skills have been acquired is a reflection of the person's intelligence. Moreover, it is assumed that environments differ in the opportunity they grant each individual to acquire these various skills. These theories are in fact the first steps towards the study of intelligence from a cognitive, rather than a psychometric, perspective. Nevertheless, the substantial correlations between highly dissimilar items or individual differences in a variety of tasks that are novel to all subjects could not be explained by the specificity doctrine. Transfer of prior learning is quite task-specific and practicing one kind of task does not affect any general domain ability, much less general intelligence.

Thorndike (1927), Thomson (1951), and Humphreys (1994) proposed theories of intelligence which view *g* as an overlap of complex, uncorrelated, mental tests. Thorndike's theory of connectionism held that learning consists of selecting and connecting stimuli and responses. The stimuli and response connections, called bonds, constitute a basic source of individual differences. Thorndike claimed that individuals differ in the total number of potential bonds they are able to acquire through learning and experience and in the number of nerve cells available for acquiring such bonds, which are innate. Mental test correlations were thought of as the common bonds that are activated when a person is tested on different mental abilities.

Thomson shared the same ideas with Thorndike regarding the interpretation of Spearman's *g*. He had formalized Thorndike's argument in mathematical terms in a formulation that became known as "sampling theory of intelligence". Thomson claimed that although Spearman's *g* can be extracted from the test intercorrelations by means of factor analysis, this does not justify Spearman's hypothesis that *g* reflects the general level of neural or mental energy available to the brain's activity. Positive correlations among mental tests are explained by the overlap of the multiple uncorrelated causal elements that enter into performance on all mental tests. Thomson's sampling theory assumes that "each mental ability is composed of some but not all bonds, and that abilities can differ very markedly in their 'richness', some needing very many 'bonds', some only few" (Thomson, 1951, p. 324).

In accord with Thomson's sampling theory is the pragmatic behavioristic sampling theory of intelligence, suggested by Humphreys (1994) who postulates that intelligence is the acquired repertoire of all cognitive skills and knowledge available to the person at a particular point in time. This repertoire of observable behavior is acquired during development, and it is stored and retrieved when needed. Thus, there are both a genetic and an environmental substrate for each trait. Individual differences in intelligence are related to the size of this repertoire.

The Cognitive Approach

The conceptualization of intelligence as a multivariate, complex system with different conceptual underpinnings and instantiations in different cultural contexts, and the identification of its constituent parts, those being the mental processes, their intercorrelations, and their dynamic interactions, have set the stage for the cognitive approach to intelligence. Some of the most pioneering theories are those proposed by Gardner (1983), Sternberg (1985), and Ceci (1996) respectively.

Strongly opposed to Spearman's general intelligence factor is Gardner's (1983) theory of multiple intelligences. Gardner proposes the existence of eight intelligences (linguistic, logical-mathematical, spatial, musical, bodily-kinesthetic, intrapersonal, interpersonal, and naturalist) instead of a unitary intelligence, which are relatively independent from one another, though they can coexist within a domain. Intelligence is defined as the ability for problem solving and creating products that are valued within one or more cultural settings (Gardner, 1993). In addition to the fact that only the first three intelligences reflect abilities that a conventional intelligence test can measure, Gardner used observation and real-world settings as a means of testing these intelligences, since he believes that the best way to measure them is in the contexts they occur. Individual differences in intelligences are attributed to the differentiation in the genetic inheritance, the educational and other cultural differences, and training.

In support of his theory Gardner (1993) invokes recent neuropsychological research on the organization of the brain in content areas and the neural structures each area develops. These areas and their specialized neural structures are functionally related to the brain modules. Modules refer to localized, innate, brain processes which have developed in the course of human evolution and are connected with various kinds of abilities. Some processes are reflected in some of the specialized intelligences, such as the linguistic, the visuospatial, the numerical-mathematical, the musical and the kinesthetic, whilst some, virtually universal abilities, as the ability to acquire language, the recognition of faces, and three-dimensional perception, do not are not manifested as an attribute of a specific intelligence.

Sternberg's (1985) triarchic theory of intelligence postulates that intelligence is a synthesis of three integrating aspects which work together. Variance in the strength to which each aspect is developed in each individual causes intra-individual differences while the degree to which individuals capitalize on their strengths and work on their weaknesses is a reflection of their intelligence. Information processing skills that guide intelligent behavior, the ability to harmonically match the internal skills and the demands from the external environment, and the ability to capitalize on the skills to solve problems, are the three integrating aspects of intelligence. The triarchic theory suggests a hierarchical structure of the mental processing skills. Specifically, it is postulated that processing skills include metacomponents, performance components, and knowledge acquisition components. Metacomponents, which are higher order executive processes, are used to guide, monitor, and evaluate the problem solving procedure. Performance components are lower order mental processes which are used to implement the outcome of the metacomponents' employment. The knowledge acquisition components, which are lower order mental processes too, help the person understand how to acquire knowledge and capitalize on it. The second aspect of intelligence engages the exploitation of the mental processes to the real world situations. Finally, the third aspect of intelligence refers to the utilization of the accumulated experience to novel situations and to automatized procedures. Further, it refers to the ability of a person to adapt to a new environment. Individual differences in the metacomponents reflect the *g* factor.

The bioecological theory, proposed by Ceci (1996), suggests that intelligence is the result of the synergy of innate abilities, environmental resources, and the motivation to capitalize these innate potentials and utilize the environmental resources. Specifically, it is assumed that abilities are derived from various information-processing resource pools which are biologically determined and independent from one another. The development of each cognitive potential is determined by its ongoing interaction with the environmental resources. Changes foster more changes and this cascading effect shapes a person's intellectual development. According to the theory, environmental resources are of two types, namely the proximal processes and the distal resources. Proximal processes involve enduring, reciprocal interactions between the person and the immediate environment, such that complex mental behavior is developed. In Davidson and Downing's words (2000, p. 45), "proximal processes play the important role of transforming the genotype into phenotype". Distal resources consist of all aspects of the environment which influence the quality of the proximal resources, such as the parenting style and the stress level. In order for this interaction to have the best possible result, the person needs to be motivated to capitalize on the mental resources and take advantage of the environmental parameters.

The Developmental Approach

Piaget's Theory

Piaget viewed intelligence as a unitary component which develops through a sequence of stages from birth to early adulthood. His research led him to propose a number of developmental stages, well defined, in terms of processes and achievements, and in terms of the mechanisms that propel development. Specifically, Piaget's theory postulates that human intelligence is a biological adaptation of the individual to its environment with all its constraints and complex presuppositions. Intellectual development is realized through four stages, namely the sensorimotor stage (from birth to 2 years of age), the preoperational stage (from 2 to 7 years of age), the concrete-operational stage (from 7 to 12 years of age), and the formal-operational stage (from 12 years to adulthood). The child's interaction with the environment during the first stage gives rise to the process of internal symbolic representations in the second stage. Natural language and other symbolic means serve the ability of the child to represent thought and subsequently be receptive to learning opportunities and become a successful problem solver. During the preoperational stage reflecting on more than one aspects of a situation is not yet achieved. Children's thinking is egocentric, that is, it is dominated by the inability to distinguish between their and others' viewpoint. Moreover, their thinking is driven by the centration force, meaning that perceptual rather than conceptual features of things are dominating. These limitations are overcome as children enter the concrete-operational stage, though their thinking is still constrained to tangible situations. Conquer of logical reasoning as it is realized when hypothesis testing is made is the milestone of the formal operational stage which allows the reasoner to propose a theory, test it and reach for conclusions.

This progression from the sensorimotor to the formal operational stage is made possible by two basic mechanisms, namely adaptation which occurs through the processes of assimilation and accommodation, and organization. These mechanisms allow the intellectual organism to transform and rearrange representations according to the demands of the environment. Internal representation is transformed to fit the new information from the environment and vice versa. Piaget claimed that the driving force behind cognitive development and, therefore, behind the activation of the basic mechanisms of adaptation and organization, is the need to resolve mental inconsistencies and conflicts between an individual's understanding and reality. This driving force is what he called 'reflective abstraction'.

One of the most critical contributions of Piaget's theory is the research method it proposes for studying and understanding intelligence. The focus of attention is drawn in revealing the qualitative differences which exist in the way individuals process information (Piaget, 1978). Although the psychometric tests may offer a clear picture on the individual differences in intellectual behavior they are not informative in respect to the nature of the mental abilities and the qualitative parameters of information processing and mental representations. Piaget was a pioneer in recognizing the limitations imposed by the psychometric perspective in measuring intelligence and in applying a different methodology which would address the need for understanding the *how* and *why* of the intellectual behavior which go much beyond the mere *what*.

Piaget's theory initiated the occurrence of a number of other developmental theories, namely the neo-Piagetian theories, which aimed at accommodating some of the inconsistencies and lacks in Piaget's stages of development and shed light on the structure and organization of mental processes (Demetriou, 1998). Neo-Piagetians primarily draw resources from the information processing tradition which uses the computer hardware as an analogue to the way information is being processed. In a sense, the neo-Piagetians managed to bring together the cognitive, the developmental and the information processing perspectives of intelligence under the same umbrella.

The Neo-Piagetian Models of Cognitive Development

Pascual-Leone (1970) proposed the first neo-Piagetian model on cognitive development. His research in information processing capacity resulted in a big repertoire of techniques and experimental schemes which were used by other researchers in the field of cognitive development. Pascual-Leone proposed a two-level cognitive system which develops by following the Piagetian stages driven by a mental force, namely the *mental power* (Mp) which corresponds to the maximum number of mental schemes that can be coordinated by the individual. The first level of the cognitive system reflects the individual's potential in the amount and type of information that can be processed. Obviously, this level is strongly related to and draws upon the information processing tradition. The second level reflects mental operations the individual activates to process the information and it originates from Piaget's theory. Like Piaget, Pascual-Leone believes that the intellectual system is in a state of continuous change in order to adapt to the environment. So, he suggests that the transition from one developmental stage to the other is caused by the increase in the individual's Mp.

In order to accurately define and provide a numerical substrate to the construct of mental power, Pascual-Leone postulated that each mental scheme requires one unit of Mp. He designed a number of tasks, which he analyzed in terms of the number of mental schemas which can be simultaneously coordinated at each age and therefore he was able to specify their Mp demands. Therefore, he managed to suggest a correspondence between the ages from 3 to 15 years and Mp, and propose a model on intellectual development. His analyses led him to conclude that Mp increases every two years starting from the age of 3 with a value of e+1 reaching a value of e+7 at the age of 15, where e stands for a constant parameter representing the processing space which is required by the executive demands of the task situation, as for example are the given instructions which must be understood by the individual in order to deal with the situation successfully.

The construct of Mp as it was introduced by Pascual-Leone (1970) placed emphasis on the capacity of the system to represent and process an amount of information. This construct is often compared to the construct of working memory, though Mp is a much broader construct. Nevertheless, it was Case (1985) who proposed a theory which merged the constructs of working memory capacity and the efficiency of information processing into a common construct, namely the executive operating space. The executive operating space reflects both the capacity of the system to efficiently process an amount of information in a certain time and to store information in the short-term memory. Efficiency in information processing is primarily reflected in the speed of processing and it directly affects the amount of space needed to perform any operations. Operating space is the construct Case uses to accommodate the parameters of processing efficiency and short-term storage space is the construct he uses to accommodate the parameters of short-term memory. According to the theory, there is no development in the executive operating space. Rather, what change are the relative magnitudes of its two integral components. Specifically, when the efficiency of information processing increases, as indicated by increasing processing speed, the operating space decreases since less space is needed for the processing of the same amount of information. This decrease in the operating space is left free for the short-term storage space which increases. The manifested increase in short-term memory capacity is not the result of a developmental change in memory per se, but it is a byproduct of developmental changes in the processing efficiency.

Case considers intelligence as a multifaceted attribute which is a synthesis of information processing, structural, and conceptual features. The linear relation between the operating space and the short-term storage space with the executive operating space refers to the information processing aspect of intellectual development. This information processing aspect is directly related with the structural and conceptual aspects of intelligence which Case introduced with the construct of *executive control structures*. Executive control structures reflect the process of representing the problem situation in a relatively analytical way, and setting goals and forming strategies in a *first things first* fashion, in order to successfully solve the problem (Case, 1992). These control structures are developed as a function of the changes in the executive operating space (i.e., changes in the processing efficiency and, subsequently, changes in the short-term storage space) and they follow a four stages sequence (the sensorimotor, the interrelational, the dimensional, and the vectorial) which strongly resembles the sequence of the Piagetian stages.

Case, suggested that the development of the executive control structures reflects both brain changes as they are manifested in changes in processing efficiency, and practice of an operation which improves efficiency and, therefore, places less demands on short-term storage space. It should be noted that Case (1992; Case, Okamoto, Griffin, McKeough, Bleiker, Henderson, & Stephenson, 1996) applied his theory on various domains and concluded that executive control structures can explain individual differences and developmental patterns in some, but not all, domains. Furthermore, he proposed the existence of central conceptual structures which are defined as “networks of semantic notes and relations” (Case et al., 1996, p. 5). These are broad structures which set the context in which many executive control structures can be constructed. They involve core processes and principles which, in turn, allow for the organization of the information on a wide range of domains. New executive control structures are produced based on some change mechanisms which allow for the activation and combination of already present structures (schematic search), the activation and evaluation of alternative groups of schemes in order to choose the most goal relevant one (schematic evaluation), the identification of the new structure and its activation as an independent structure (schematic retagging), and the reworking and rehearsing of the new structure aiming at its mastery (schematic consolidation).

Though recent research has questioned Case’s claim about the stability over age of the executive operating space and the expansions of memory capacity as a function of the developmental changes in speed of processing (Halford, Maybery, O’Hare, & Grant, 1994) it remains a fact that Case’s most important contribution to the research on intelligence is his realization of the importance of processing efficiency in cognitive development (Halford, 2002). Furthermore, Pascual-Leone (1970) and Case (1985) had set the stage for the study of cognitive development using the knowledge which the information processing doctrine has constructed and combining it with some important parts of Piaget’s theory.

Bridging the Gap of Psychometric and Cognitive Theories: The Case of the Encapsulation Model

The psychometric approach to intelligence was strictly based on tasks and statistical indices (Cornoldi, 2006) and it was thus proved unable to explain the cognitive structure and the developmental evidence in regards to intelligence. On the other hand, the cognitive approach to intelligence has isolated powerful mental processes which constitute an important part of intelligence. Still, these two approaches seem to reside on the two apposite ends of the research in intelligence. The great distance between these two approaches has been recently minimized by the work of Gustafsson and Carlstedt (2006) who proposed a model of intelligence which could be regarded as the most serious effort in bridging the gap between the psychometric and the cognitive approaches to intelligence.

Gustafsson and Carlstedt (2006) have proposed the Encapsulation Model which combines aspects from both the psychometric and the cognitive approach. They use the psychometric constructs of fluid and crystallized intelligence under a cognitive perspective and therefore, they claim to have bridged the gap and propose a powerful model which can explain individual differences in mental processes and performance. Fluid intelligence is considered as the basic source of individual differences in the knowledge and skills acquisition at the young ages, while its role diminishes as a function of age. Furthermore, crystallized intelligence is considered a better predictor of achievement than fluid intelligence in adults (Beier & Ackerman, 2001; Ackerman & Beier, 2006). Learning and achievement, according to the Encapsulation theory are affected by both types of intelligence since “measures of Gc include Gf variance, which is predictive of learning and achievement…[and]…Gc reflects individual differences in knowledge and skills which are of importance for further learning and achievement” (Gustafsson & Carlstedt, 2006, p. 16).

The Encapsulation Model suggests that there is a dynamic relationship between the abilities lying on the fluid-crystallized ability continuum, as Lohman (2004) has proposed it, “with causality going from the fluid end to the crystallized end of the continuum” (Gustafsson & Carlstedt, 2006, p. 17). Each type exerts its influence in learning and achievement in a clearly differentiated way. Fluid intelligence influences crystallized intelligence (that is, the accumulation of knowledge and the development of skills) and crystallized intelligence influences achievement in high school. Eventually, high school achievement influences achievement in higher education. The theory suggests that fluid intelligence influences achievement in high school in an indirect way and that achievement in higher education is indirectly influenced by both fluid and crystallized intelligence. The essence of the Encapsulation theory is that the decomposition of the variance observed in the achievement in higher education can be attained with reference to all the rest factors. Specifically, the variance in crystallized intelligence contains all variance of fluid intelligence, and the variance in high school achievement contains all variance in crystallized intelligence. Finally, the variance in higher education achievement contains all variance in high school achievement. This can be conceptualized as a set of expanding circles in such a fashion that each circle is enclosed in the next one, with the outer circle being the one which represents the variance in the higher education achievement.

Gustafsson and Carlstedt (2006) report an empirical study conducted in order to test the validity of their model. Their findings support the Encapsulation Model. Specifically, the dynamic interrelation between the cognitive abilities and the direction of causality, are further established. Furthermore, it is reported that the variance in the educational quality affects the nature and the strength of the effect that crystallized intelligence has on learning while it seems to have no effect on fluid intelligence measures. The Encapsulation theory suggests that fluid intelligence measures can be regarded as capacity measures when they are obtained at young age, before any organized instruction starts. Further, it is suggested that any covariation of fluid and crystallized intelligence be put under the perspective of a longitudinal study which will reveal whether the contribution of fluid intelligence to the development of knowledge and skill acquisition is contaminated by their common influence from education.

Bridging the Gap of Psychometric, Cognitive and Developmental Theories: An Overarching Theory

Demetriou has developed an influential model on cognitive development that originates from the Piagetian tradition and assimilates notions from the processing information and psychometric theories. His model involves both general mechanisms and functions and specialized module-like systems that deal with different domains of knowledge and relations in the environment (Demetriou, Efklides, & Platsidou, 1993; Demetriou et al., 2002; Demetriou & Kazi, 2001; 2006). Specifically, according to Demetriou's model the developing mind is a three-level hierarchical.

The first level accommodates domain-specific systems of thought that deal with representing and processing the relations in different domains of the environment such as the spatial, verbal, numerical, categorical, causal, and social domains (Demetriou, 2004; Demetriou & Efklides, 1985, 1989; Demetriou, Efklides, & Platsidou, 1993; Demetriou, Efklides, Papadaki, Papantoniou, & Economou, 1993; Demetriou, Pachaury, Metallidou, & Kazi, 1996; Demetriou, Platsidou, Efklides, Metallidou, & Shayer, 1991; Demetriou & Kazi, 2001; Kargopoulos & Demetriou, 1998; Shayer, Demetriou, & Prevez, 1988). The second level of the mind's architecture accommodates a domain-general system that engages processes and functions that are responsible for self-awareness and self-regulation. Demetriou uses the term *hypercognitive system* to refer to the crucial role of these processes in monitoring, planning, mapping, regulating, evaluating and coordinating all kinds of mental processes and action involved in the others two levels of the system. Conscious awareness is an integral part of the hypercognitive system and it accounts for the individual's accumulated knowledge and experience on cognitive functioning (Demetriou, 2000; 2003; Demetriou, et al., 1993; Demetriou & Kazi, 2001; 2006). Finally, the third level poses constrains on the processes residing in the other two levels that define the representational and processing capacities of the mind. Speed of processing, inhibition and attentional capacity, and working memory capacity, are the parameters of this level that set constrains on the system and act as factors for individual differences as well as developmental factors (Demetriou, Christou, Spanoudis, & Platsidou, 2002; Demetriou, Efklides, & Platsidou, 1993). During life span various changes occur in all three levels of the system. The processing efficiency and working memory capacities increase from early childhood to early adulthood, they remain stable until middle age and they then start to decline. Thought in the various environment-oriented domains becomes increasingly more complex and abstract. Hypercognitive processes become more accurate, refined, and focused.

Demetriou's model accounts for the plasticity of mind by suggesting that mechanisms of cognitive change are manifested from early childhood (Demetriou & Raftopoulos, 1999; Demetriou, Raftopoulos, & Kargopoulos, 1999). These mechanisms are responsible for binding, differentiating, refining, and abandoning already existing concepts, skills, and processes in order to construct new ones that would be more functional and offer the system more efficiency and flexibility in meeting the needs of the environment.

The general intelligence factor reflects some part of the individual differences in both simple and complex mental abilities which depend on the operation of cognitive processes, if seen from the perspective of mind operations, and on neural processes, if seen from the perspective of brain operations. It is beyond the scope of this research work to study the biological substrate of general intelligence. So, in the next section a thorough presentation of the basic cognitive processes will be attempted under the prism of the three traditions of psychology, namely, the psychometric, the cognitive, and the developmental tradition. It should be noted, that researchers have not always worked solely based on the premises of just one of the three traditions. Therefore, there is no clear cut point which would serve as a criterion of what belongs to one tradition and what to another. Rather, it is often the case that research findings are blended in a way that allows the observer to see things in a more global way.

General Intelligence and Cognitive Processes

Mental Ability Tests and Cognitive Tasks

The general intelligence factor emerges as a higher order factor in a wide variety of mental ability tests. Though certain types of tests consistently show higher *g* loadings than other tests, the characterization of such tests as being either the 'essence' or the 'defining characteristic' of *g* is not justified (Jensen, 1998). The general intelligence factor should not be regarded as "a cognitive process or as an operating principle of the mind, or as a design feature of the brain's neural circuit. [Rather,] *g* may be thought of as a distillate of the common source of individual differences in all mental tests" (Jensen, 1998, p. 74). Mental ability tests are the means for estimating *g* and performance on such tests reveal the existing individual differences and reflect discrepancies in the underlying cognitive processes. Cognitive processes are hypothetical processes reflecting the structural and psychological properties of the brain (Jensen, 1998) and are used to trace individual differences (psychometric psychology), identify the structural and functional essence of the mind (cognitive psychology), and attribute meaning to intellectual development (developmental psychology).

The high correlations between mental ability tests is a good indication that they can be used as measures of cognitive processes, though performance on these tests is only an approximation of the true state of the cognitive processes. Cognitive processes refer to "particular cognitive transformation performed on a particular mental representation" (Lohman, 2000, p. 288). Therefore, measures of cognitive processes rely on mental ability tests which use information processing tasks of varying complexity, content, and context. As a result, various information processing models are being proposed, which, despite any conceptual, methodological, or other differences between them, share as a common feature, the *real time* at which processing takes place. Time is the natural scale of measurement of the efficiency of the information processes. The speed at which information is processed is a manifestation of the efficiency of this operation which, in turn, is the main source of the observed individual differences in the functioning of the cognitive processes. Whether information is processed in a sequential (serial) or in a simultaneous (parallel) mode is a subject that needs further investigation and most importantly, it is strongly depended on the inter-stimulus conditions and the capacity load they carry (Townsend & Fific, 2004). Nevertheless, it remains a fact that when speeded measures are used in mental ability tests, they offer a more precise picture in regards to the efficiency of the information processing. Elementary cognitive tasks (ECT) are simple tasks, freed of specific information content and with no knowledge demand so that all participants can perform them easily. They are designed in such a way in order to minimize the contribution of higher order cognitive functions that would be included in intelligence such as learning, motivation, strategy knowledge and strategy application, and other confounding factors, therefore giving rise to individual differences in performance due to variance in cognitive processes per se. ECTs are used to identify, measure and understand the causal nature of the variance of various cognitive processes such as speed of processing, perceptual and conceptual control of the incoming information and inhibition of premature or irrelevant responses, and working memory capacity.

The most elementary test ever used in psychological research is the *Simple Reaction Time* which is a measure of sensorimotor speed. It gives information on the participant's reaction time (RT) and it is completely discharged from any cognitive load. The term Reaction Time is usually used as a supplementary term of speed of processing. While speed of processing is primarily a function of the brain, i.e. the nerve conduction velocity, and is therefore subjected to the containment of the brain's hardware parameters, we define speed of information processing as the speed at which an individual completes basic cognitive functions such as item identification or simple discrimination. Reaction time is the expression of speed in quantifiable terms: higher speed is manifested via shorter reaction time. The obtained measures of speed of processing are only estimations of the true value of the nerve conduction velocity. The simpler the cognitive test and the less intrusion of distracting parameters in the experimental process, the more precise the estimation of speed of processing will be. Sensorimotor variance is unavoidably present; yet, it can be eliminated when the test procedure minimizes the dependence on sensorimotor parameters.

Inspection Time is a measure of perceptual processing speed needed to identify a stimulus and it is determined by estimating the briefest exposure time an individual needs to process new information accurately. The stimuli used for this task are simple pictures, for example two lines of either the same or different length, which carry the minimum amount of information so that no conceptual weight will be imposed on the system. In *Discrimination Reaction Time* the participant is confronted with the possible occurrence of either of two (or more) different reaction stimuli. This test consists of all the processing components of the simple RT plus the additional time required for discriminating the stimuli. The *Choice Reaction Time* includes the processes necessary for discriminating stimuli and the processes for making a choice between two (or more) different response alternatives. Making a choice is another cognitive process that adds to the total time over and above pure discrimination time. These tasks can be more complex by adding rules and restrictions which will add on the cognitive load, and thus tap on more complicated processes, as is the case with the information control processes. As tests get more complex their association with the general intelligence factor is better established as they allow for more variance to be observed. As a result, some tests are more *g-loaded* than others, i.e., they share more common variance with the general intelligence factor than other tests do.

Deary (2000) reports that the correlations for the RTs obtained from the most common ECTs with IQ are rather modest ranging between -0.10 to -0.40, going from simple RT, to discrimination RT, to choice RT. Jensen (1998) reports that the measures of speed of processing obtained from various ECTs are correlated, on average, with various measures of psychometric IQ with -.35. The correlation gets bigger as tasks get more complicated since more cognitive processes are involved and therefore, a greater part of the general cognitive ability variance is exposed. Furthermore, in the case of dual tasks, where two different ECTs run in tandem and the RT for each test is measured separately, the correlation of each separate RT with IQ is increased. Dual tasks address not only the speed of information processing, but also the executive control and the capacity of working memory for the short-term retention of information. Persons with high IQ succeed in the dual task by making a wiser allocation of their time and their cognitive resources. They inhibit premature responses to allow time for processing input information and to make the right decisions. This is time consuming and can result in the decay of the neural traces of the recently input information. Some information is unavoidably lost, unless care is taken to transfer the information into long-term memory by immediate repetition or rehearsal. Effective strategy use, which is highly related to IQ, may also contribute to higher accuracy and to a more prudent time management. Nevertheless, attention (Hutton, Wilding, & Hudson, 1997), motivation (Larson, Succuzzo, & Brown, 1994), and personality (Stough, Brebner, Nettelbeck, Cooper, Bates, & Mangan, 1996) are found not to be responsible for the relation between ECTs' RT and intelligence measures.

Generally speaking, complex tasks put greater burden on inhibition processes and on working memory, than do simple tasks. In the case of a quick succession of input information, there is a trade-off between processing and storage and a faster information processing becomes an unambiguous advantage. Therefore, performance on complex tasks reflects a broader spectrum of mental abilities, and as a result it shares more common variance with IQ. In addition to these, it is suggested that the magnitude of the relation between mental speed and reasoning ability could too be regarded as a function of task complexity (Larson, Merritt & Williams, 1988). The more complex a mental speed task is, the higher its correlation with reasoning will be (Hunt, 1980; Stankov & Roberts, 1997). Thus, individual differences in processing efficiency, working memory and reasoning are better traced when complex tasks are used.

The use of tasks which differ in complexity and which address a broad spectrum of processes is not only important in obtaining higher correlations with IQ, but it is significant in obtaining time measures of each cognitive process as such. This idea originated from Donders, back in the beginning of 1860s. He argued that by subtracting simple RT from the RT of a more complex process, one gets a measure of the time required for the complex process as such. Donders's subtraction method has been used in studying the time the system requires for executing various cognitive processes, such as discrimination, choice, decision, and information retrieval from memory. For example, it is found that in young adults the average simple RT is about 200 milliseconds (ms) while the discrimination time (the difference of discrimination RT and simple RT) varies, on average, from 30 to over 100 ms, depending on the complexity of the stimuli. As the cognitive process gets more complex, the obtained RT measures have a larger variance, implying that individual differences get bigger when more complex processes are involved in the process of the task solution.

The psychometric, cognitive and developmental aspects of each of the various mental processes (namely information processing speed, information control mechanism, working memory and reasoning) as well as their relation with general intelligence will be discussed in the next section.

Speed of Information Processing

Speed of processing is the speed with which the neuronal communication between different areas of the brain takes place. Though little is known about individual differences in the design aspects of the brain, the working hypothesis is that all biologically normal persons have the same neural 'hardware'. Differences among individuals are located in the efficiency of brain activity. Specifically, nervous impulses which are triggered any time a cognitive task is presented to the individual, travel considerable distances with a finite nerve conduction speed, making the communication between separated regions of the brain possible. Cognitive tasks are solved as a result of the efficient communication of different brain regions. Therefore, nerve conduction speed is an important parameter defining the efficiency of the communication between the various brain regions and consequently, it defines performance on all mental functions. As it is posited by bottom-up theories, individual differences in higher mental functions are a manifestation of individual differences at a more basic level of brain activity, namely neural and synaptic attributes that determine the speed and efficiency of information processing. Therefore, speed of processing is the process that is thought to underlie all other cognitive functions and it is the basic source of individual differences in knowledge acquisition and, therefore, in learning and in use of strategy. Though nerve conduction speed is not measurable via the standard psychometric tests, researchers in cognitive and psychometric psychology have considered speed of processing as the speed with which the simplest elementary cognitive task is completed. Therefore, the term "speed of processing" refers to the speed with which an individual responds to the simplest stimulus with the minimum possible demand on other cognitive resources, such as stimuli discrimination, perceptual and conceptual control or working memory.

Mental speed is highly related to the general intelligence factor *g*. Vernon (1989) calculated the N-weighted average correlation of the g-loading of an IQ test and the speed of information processing based on the results reported in five different studies, conducted by Vernon himself. This average correlation is found to be equal to -.52. Moreover, Vernon (1983) has reported that the correlation of IQ scores with speed of processing is no longer significant after partialling out the *g* factor from the IQ factor which indicates the strong relation between the general intelligence factor and the mental speed. Finally, the strong relation between the general intelligence factor and the mental speed is revealed in the case of non-speeded, highly g-loaded, tests, such as the Raven Advanced Progressive Matrices (RAPM). The IQ score extracted from the RAPM tests has the highest correlation with the RT extracted from a set of ECTs (Vernon, 1983). Additionally, it is suggested that the correlation of mental speed with both crystallized and fluid intelligence independently, provides further support to the thesis that it also correlates with the general intelligence factor, as *g* is the common factor residing higher than the crystallized and the fluid intelligence factors and it highly correlates with both of them (Jenkinson, 1983).

The strong relation between mental speed and the general intelligence factor is revealed under two conditions. First, when measurements on complex speed tasks are used, since they can be assumed to include substantial variance due to individual differences in inhibition ability and working memory capacity which are strongly related to reasoning (Kyllonen & Christal, 1990), and, second, when reasoning tasks, which are also considered as good indicators of the general intelligence, are administrated under speeded conditions. The time pressure favors individuals with high mental speed because the greater the mental speed the greater the number of items they can work on. According to Wilhelm and Schulze (2002) most of the studies reporting a strong relationship between reasoning ability and mental speed are based on at least one of these two conditions. But, according to Wilhelm and Schulze, to achieve a more objective estimation of the correlation between speed of processing and reasoning, simple mental speed measures and unspeeded reasoning tasks should be used. The intensity of the relation between mental speed and reasoning ability is better estimated when mental speed is not intruding in the measurement procedure as a spurious factor biasing the results. When time restricted measurement of reasoning ability is used, then the results mirror not only the functions ascribed to working memory and reasoning per se but, additionally, mental speed is present thus altering the picture. Time restricted reasoning tasks result in an overestimation of the correlation between mental speed and reasoning.

Various theories have been proposed regarding the speed of processing and the general intelligence factor correlation. The most prominent one, the general strategies hypothesis (Belmont & Mitchell, 1987), states that persons with higher IQ are better at discovering more efficient strategies for solving particular problems and that they use efficient strategies even when dealing with simple ECTs. These individuals show good management of their intellectual resources based on their good knowledge of the structure of the task or the problem they need to solve. According to the general strategies hypothesis, individual differences in reaction times reflect individual differences in choosing and successfully applying the optimum strategy. While no empirical data have been demonstrated reinforcing the strategy hypothesis, it is assumed that individuals with high IQ have been endowed by a general ability to find, learn and exert the optimum strategy at every case independently of the task specifics. Additionally, the conclusion deriving from this theoretical hypothesis on the relation of speed of information processing and general intelligence places much importance on the role of strategy use and strategy application, both of which are highly related to learning ability. Furthermore, it is implied that intra-individual differences in speed of processing are getting smaller in the course of strategy application practice and that inter-trial individual differences are not consistent since each task's requirements evoke different strategy use, something that directly affects processing speed.

The general strategies hypothesis has been challenged by various researchers yet, the most reliable study, was conducted by Alderton and Larson (1994). This study examined whether the strategy use is present in a consistent way across tasks of increased complexity. Strategy switching was extremely beneficial in the successful completion of the tests. The results that showed no correlation ($r = .026$) between strategy use and intelligence, and no correlation ($r = -.006$) between the strategies used, led the researchers to the conclusion that strategy use is strongly depended on the situation and the domain specificities "with little explanatory power for *general* ability findings" (p. 74) and that the hypothesis of consistency in the use of strategies across tasks is not confirmed. Jensen (1998) disputes general strategies hypothesis, and describes it as a behavioristic approach to things which overlooks both the biological substrate of intelligence and the role of the basic processes. He proposes two alternative explanations in regards to the correlation between efficient strategy use and IQ. The first explanation is that the strong relation between efficient strategy use and IQ simply reflects the individual differences in the use of a more or less efficient strategy or individual differences in the number of trials needed to discover and use an efficient strategy. The second explanation attributes the correlation of efficiency in strategy use and IQ to the biological substrate of intelligence, namely the neural efficiency, an important aspect of brain functioning.

Closely related to speed of processing are the notions of learning ability and experience acquisition. In as far as the relation between speed of processing and learning ability is concerned, what is evident in the literature is an acknowledgement of a relation between reaction time and learning ability as well as of a relation of learning ability with the general intelligence factor. The efficiency of information processing, expressed as speediness of processing, is the source of common variance between reaction time, learning ability and general intelligence factor. Faster learners learn more quickly how to deal with various cognitive tasks and how to decrease their reaction times than do the slower learners. Furthermore, deeply related to the general learning ability is the notion of practice as well as the antagonist notions of automatized versus controlled processes. Practice and experience acquisition can be accounted for changes in speed of processing. Experience and specific knowledge acquisition result in a more elaborate domain-specific comprehension and in a more cohesive memory. More entries are added to the long-term memory as a result of specific knowledge acquisition and more links between these entries are installed as a result of practice and experience, resulting in an increase in the number of certain types of representations in memory. These extensive connections are expected to lead to more rapid access of information (Chi & Ceci, 1987). Logan (1988) considers experience acquisition as the main force shifting the individual from the algorithmic, and time consuming, level to an automatic level where responses are retrieved instantly. Automatized processes free up working memory, are relatively effortless and result in very low correlation between speed of processing and IQ, whereas controlled processes require focused attention and mental effort, thereby leaving room for the speed of processing and IQ correlation to emerge.

A study conducted by Neubauer and Freudenthaler (1994), aimed at investigating, among other things, the effects of prolonged practice to near-perfect performance on the correlation between RT and IQ. The ECT that was used was the Sentence-Picture Verification Test (SVT), a task which is neither extremely novel nor completely automatized for the participants. Their results showed significant decline of the RTs after the 9-hour practice, a characteristic of tasks that can be largely automatized (Ackerman & Schneider, 1985), and significant declines in the correlation of RT and IQ early in practice, probably due to the assignment of a not so efficient strategy at the beginning of the 9-hour session. However, during approximately the last 1200 trials (over the course of more than 2500 trials) the correlation stabilized at an asymptotic level, as a result of the presence of a controlled process which requires focused attention, mental effort, and the assessment of various strategies at the beginning of the practice course until an efficient strategy is applied. After more than 2500 trials and nine hours of practice, RT correlated -0.39 with IQ (initially the correlation was -0.46). The researchers concluded that the biologically based bottom-up explanations of the 'mental speed' theory of intelligence, which considers mental speed as the most important basis of variation in intelligence, is strongly supported by their data.

The observed discrepancy in the reported correlations between speed of processing and the *g* factor is due to the use of tasks that differ in terms of their context and their complexity. When tasks of similar context and complexity, but which differed in terms of their content, were used, the reported correlations did not differ (Thorndike, 1987) suggesting that speed of processing is a content-free general ability that is differentiated by the complexity of the given information – not the content as such. Hale (1990) reached the same conclusion when she tested adolescents of various ages using a battery of four different content processing speed tasks. Her study revealed no difference in the processing speed as a function of the content of the tasks. Kail (1991) found that changes in processing speed are very similar in all task domains, suggesting that changes in speed of processing are reflecting changes in processing capacity rather than the result of some kind of learning and that these changes are driven by a global processing speed mechanism. Kail (2000) also suggests that this global mechanism limits the speed of processing, as it is a characteristic of the developing information processing system.

Individual differences in speed of processing, when exogenous factors, such as expertise, task complexity, familiarity with the context and the content of the tasks, are controlled, are observed as a function of age. Age-related changes in speed of processing will be studied in the next section.

The Development of Speed of Processing

The developmental profile of the processing speed has been thoroughly examined by the method of systematic relations which looks for a consistent relation between the mean response times in groups of individuals of different ages by calculating the slowing coefficient, which is the factor by which individuals at one age are slower (or faster) than individuals at another age. A number of studies including children, adolescents and adults were conducted in order to calculate the slowing coefficient. Salthouse (1993) examined speed differences in various age groups of adults between 18 and 80 years of age. The results of his study indicate that there is a highly systematic relation between the reaction times of adults of different ages and that the magnitude of the differences in speed increases with age. Hale (1990) tested children at the age of 10, 12 and 15 years and a reference group of young adults, on a battery of four different content speed tasks. Her study showed that speed increased with age, a finding which strengthens the assumption for a global developmental trend in processing speed, and that as we move from childhood to adolescence speed of processing gradually approaches the speed of young adults.

Kail (1991) conducted a meta-analysis of 72 studies on speeded performance to provide additional evidence on the relation between the mean response times in groups of different ages. This meta-analysis included 1826 pairs of mean RTs for children, adolescents and adults. Kail showed that the mean reaction time of young children and adolescents is equal to the mean reaction time of the young adults, which is the age with the smallest reaction time recorded, multiplied with a slowing coefficient. The value of the slowing coefficient became smaller with age, in a nonlinear fashion: it changed substantially in early and middle childhood and more slowly thereafter. The reaction time at a certain age (RT*i*) is related to the reaction time of the young adults (RT*a*) in the following fashion: RT*i*=m*i*RT*a*, where m*i* is the slowing coefficient. The slowing coefficient is described by the exponential function $m_i = a + be^{-ci}$ where m_i is the slowing coefficient at a certain age i, a is the asymptote, e is the base of natural logarithms, $a+b$ is the intercept (for $i = 0$, $e^{-ci} = 1$) and c is a 'decay' parameter that indicates how rapidly the function approaches the asymptote. This function captures the fact that processing speed shows initially rapid and then progressively more gradual improvements throughout childhood and adolescence. It is not until the middle of adolescence that adult levels of speeded performance are achieved.

Cerella and Hale (1994) conducted a literature review to further assess the usefulness of exponential functions in describing age-related changes in speed throughout life span. They showed that one exponential function can be used to describe age-related change during childhood and adolescence and another exponential function can be used to describe change during adulthood. When the two functions are combined, they form a single U-shaped function describing the gradual improvement in speed during childhood followed first by a plateau and then by an even more gradual decline during adulthood.

The second method of examining the possibility that a relatively general mechanism contributes to the age differences in processing speed is the use of statistical control procedures. Specifically, it is assumed that if processing speed changes are driven by a global mechanism, then the observed age-related changes in higher cognitive processes will be affected by the presence of this mechanism in a global way and, thus, all cognitive domains will be affected. If, on the other hand changes in the speed of processing are differentiated according to the domain specificities then, performance on cognitive tasks within different domains (controlling for complexity and special knowledge) will, accordingly, be differentiated. Therefore, the relation of speed of processing with age and with the performance on various cognitive tasks is partialled out from the relation of age with the cognitive performance. In a study conducted by Salthouse (1992), which involved 910 adults between 18 and 84 years of age, as well as in a study conducted by Kail (1992), with 9 year-olds and adults, it was revealed that age-related differences in cognitive performance are attenuated substantially after variance associated with processing speed is eliminated. These findings suggest that speed of processing has a substantial general influence in age-related changes in many domains.

On the other hand, Anderson (1992) studied the relation between speed, as obtained by Inspection Time ECTs, and intelligence, as obtained by raw scores and performance IQ from the WISC-R, on 6-, 8- and 10-year-old children. His results led him to the conclusion that relatively little of the total age-related variance in raw score intelligence is mediated by speed. Specifically, when the effect of speed was statistically controlled, the correlation between age and raw scores on the WISC-R dropped only slightly, from 0.82 to 0.78. Thus, despite the moderately strong relationship between age and speed, Anderson's data suggests that maybe the role of speed in the variance of general intelligence is not as substantial as some other theorists suggest.

The Relation of Speed of Processing with Intelligence

The significant relation between speed of processing and general intelligence, as well as its relation with IQ measures which have already been presented, need to be further analyzed under a developmental perspective. The hierarchical models of intelligence

(Carroll, 1993) take into account speed of processing as an important factor. Kail and Salthouse (1994, p. 221) refer to the factor of speed of processing as a “cognitive primitive” meaning that it is a fundamental part of the architecture of the developing mind. Kail (2000) refers to three bodies of research in support for the central role of speed of processing in intelligence. Specifically, he uses the results from the studies on populations with intellectual impairment to show that children known to differ in general intelligence differ in their speed of processing and that RTs of peers with and without mental retardation were related in the same fashion as the RTs of children with adults. In the case of mentally retarded individuals, the slowing coefficient *m* is decreased as a function of their IQ. The second body of research used to support the structural role of speed of processing in the architecture of intelligence, is the developmental cascade proposed by Fry and Hale (1996). Age-related changes in speed of processing of children and adolescents (7- to 19-year-olds) are associated with increases in the capacity of working memory, and in turn, these increases are associated with increases in fluid intelligence, namely reasoning and problem solving. Finally, measures of speed of processing (based on eye movement) in three and a half month-old infants are related to their IQ when 4-years-old (with a correlation of -.44) according to Dougherty and Haith (1997), though infant measures are not highly reliable. All these studies indicate the central role of speed of processing in intelligence.

The study of the developmental changes in the relationship between speed of processing and intelligence is usually misleading, due to the confounding of maturational changes in speed with individual differences in speed. This confounding of changes in speed of processing may inflate the correlation between speed and raw intelligence scores and attenuate the correlation between speed and IQ scores. When children of different ages are tested, data reflects age-related differences in speed and general intelligence as well as individual differences among children in the same age group, in both speed and intelligence. The synergy of both kinds of differences increases the variance shared between speed and general intelligence compared to their variance in an age-homogeneous sample. As a consequence, the correlation between speed and raw intelligence scores is increased, resulting in an inflated correlation. Besides, any correlation between speed and age-normed scores (i.e., IQ scores) is possible to be correspondingly attenuated by the effect of age differences in speed.

The relationship between speed and intelligence in age-heterogeneous groups of school-age children was examined by several studies. Most of these studies confounded age-related differences with ability-related differences in speed of processing. The most consisted set of findings is provided by Anderson (1992) who conducted assessments on 6-, 8- and 10-year-old children for whom he obtained raw scores and performance IQ from the WISC-R and two speeded measures on inspection time, a measure of perceptual processing speed determined by estimating the briefest exposure time an individual needs to process new information accurately. Anderson reported significant correlations between age and speed (-0.41), age and raw score intelligence (0.82) and speed and raw score intelligence (-0.52). With age statistically controlled, the correlation between speed and raw score intelligence dropped to -0.35 (which agrees with the correlations obtained from the age-homogeneous studies). The difference between the full and partial correlations suggests that a considerable portion of the total speed and intelligence relationship in Anderson's sample can be attributed to age-related differences in speed.

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The results from the study of the developmental profile of speed suggest that developmental changes are driven by a global mechanism which sets limits in the functioning of speed of processing. Besides, the basic assumption from neurocognitive research is that the neural conduction velocity is finite and therefore upper boundaries exist. Furthermore, the research on the developmental aspects of speed of processing suggests that the maximum processing capacity is reached towards the end of adolescence and at the beginning of adulthood. Based on all these findings on the limited capacity of the system in regard to its response on speed demands, it is suggested that a mechanism which protects the system from inefficiently allocating its resources exists. This inhibitory control mechanism which secures better standards in processing efficiency is presented below.

The Executive Functions: Attention, Control of Information

Executive function (EF) is an umbrella term for various cognitive processes that subserve goal-directed behavior (Miller & Cohen, 2001), in novel or demanding situations (Stuss, 1992), which require a rapid and flexible adjustment of behavior to the changing demands of the environment (Zelazo, Müller, Frye, & Marcovitch, 2003). Denckla and Reiss (1997, p. 283), suggest that EF "refers to a cognitive module consisting of effect or output elements involving inhibition, working memory, and organizational strategies necessary to prepare a response". Different aspects of executive functions have been emphasized by different researchers, such as working memory (Baddeley, 1996), inhibition (Diamond, 1996) and aspects of attention (Posner & Rothbart, 1998). The nature of EF and its organization have been widely studied and two main approaches have been deployed. Some researchers have suggested that EF is a unitary system with no distinct sub-functions or sub-components (e.g. Duncan, Emslie, Williams, Johnson, & Freer, 1996). Others view EF as a multi-faceted system which involves several discrete cognitive processes that have a relatively focal neural representation (e.g., Baddeley, 1986; Stuss, Shallice, Alexander, & Picton, 1995).

The multi-faceted nature of EF is suggested both by behavioral and neuroimaging studies. Behavioral studies were based on batteries of widely used EF tasks, such as the Wisconsin Card Sorting Test (WCST) and the Tower of Hanoi (ToH) task. Low or non-significant correlations between these tasks are demonstrated and multiple factors are yielded from exploratory factor analysis (Brocki & Bohlin, 2004) suggesting the existence of distinct EF sub-functions. The argument on the separability of the EF constructs is reinforced by the neuroimaging studies on the multi-faceted nature of EF. Specifically, different components of EF seem to rely on different parts of prefrontal cortex (PFC). The ability to maintain information in working memory has been found to mostly activate lateral PFC (Narayanan, Prabhakaran, Bunge, Christoff, Fine, & Gabrieli, 2005; Smith & Jonides, 1999). Switching between tasks is thought to rely on medial PFC (Rushworth, Walton, Kennerley, & Bannerman, 2004). Finally, the ability to inhibit responses was found to rely on orbitofrontal cortex (Aron, Robbins, & Poldrack, 2004; Roberts & Wallis, 2000). Thus, different regions within PFC subserve different components of goal-directed behavior. MacDonald et al. (2000) suggest that EF processes may not be attributable to a single unitary brain system; rather, they emerge as a result of the interaction of distinct brain systems, responsible for complementary control functions. Moreover, the great reliance of these processes on working memory, since information about the task demand and goals must be temporarily maintained in working memory (Baddeley, 1992), suggests the involvement of different brain networks that support the functioning of working memory, such as prefronto-parietal and prefronto-temporal networks and left-hemispheric speed areas (Gruber & Goschke, 2004).

Behavioral and neuroimaging studies using multiple EF tasks often face the *task impurity* problem (Burgess, 1997; Phillips, 1997) which refers to the fact that a single indicator of a given construct cannot be safely considered as a pure measure of that construct. Most measures are contaminated by random error and systematic error (Kline, 1998) which, in turn, contaminates the results reported. The task impurity problem is highly relevant to EF research, as executive functions necessarily manifest themselves by operating on other cognitive processes that are not directly relevant to the target executive function (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). Therefore, performance on a single executive test does not purely reflect executive functioning. As a consequence, the observed (low) correlations between tasks, or the manifested multiple separable factors, are not an absolute proof of the existence of discrete executive functions (Miyake & Shah, 1999). Another important problem in studying the multi-faced nature of EF is associated with the use of complex executive tasks like the WCST and ToH. The construct validities of such complex tasks are not well established (Phillips, 1997; Rabbitt, 1997; Reitan & Wolfson, 1994). Many prevalent executive tasks seem to have been validated only based on the criterion of being, to some extent, sensitive to frontal lobe damage while the precise nature of executive processes implicated in the performance of these tasks is underspecified. According to Miyake et al. (2000, p. 53) “this unclarity of the underlying abilities tapped by these complex executive tasks is reflected in a proliferation of terms and concepts used to characterize the task requirements of different executive tests”. Miyake and his colleagues (2000) propose using multiple tasks to measure each EF component and adopting a latent variables approach to extract the common variance of the tasks, as a means to addressing the task impurity problem. Latent variables refer to what is shared among tasks tapping a given EF. In a study conducted to specify the extent to which the three frequently postulated executive functions of shifting, information monitoring and updating (usually identified with working memory), and inhibition are unitary or separable, Miyake et al. (2000) used the latent variables method they suggest, in order to overcome the serious problems with interpreting the results of typical correlational and exploratory factor analysis. Young, healthy, adults were tested on multiple tasks tapping shifting, working memory, and inhibition, and on several standard but complex, neuropsychological tasks, including the WCST and the ToH. The results of their analysis showed that, although moderately correlated, working memory, shifting, and inhibition were separable constructs. Latent variables approach was also adopted by Lehto, Juujaervi, Kooistra and Pulkkinen (2003) to extract the common variance between the various tasks used to tap EF component processes. Letho et al., who were the first to assess the patterning of EF component processes in children by using structural equation modeling, have observed the same factor structure in a group of 8–13-year old children as previously found by Miyake et al. (2000) in young adults. Huizinga, Dolan and van der Molen (2006) have also studied the multi-faceted nature of EF. Participants, children, adolescents and young adults were tested on three tasks for each EF, the WCST, and the ToL. Confirmatory factor analysis was used to extract latent variables. Two common factors were yielded: Working memory and shifting. However, the variables assumed to tap inhibition were unrelated. The results of this study provide further support for the non-unitary nature of EF. The two latent factors of working memory and shifting seem to reflect distinct EF constructs while inhibitory control seems to be a broad construct which needs to be further analyzed. The findings yielded from all the above mentioned studies are protected from the task impurity problem since multiple EF tasks were used and latent variable analysis was applied to the data.

According to Zelazo and his colleagues (Zelazo, Qu, & Müller, 2005) the different proposals on the aspects of EF as they have been emphasized by different researchers, such as working memory by Baddeley (1996), inhibition by Diamond (1996) and attention by Posner and Rothbart (1998), fail to capture the diversity of the processes associated with executive functions. Zelazo, Carter, Reznick and Frye (1997) base their model of EF on Luria’s (1973) approach to neurological systems, according to which prefrontal cortex and other neurological systems consist of interactive functional systems that involve the integration of subsystems. Subsystems interact, each maintaining its own role and function within the larger system of which they are part. Executive function is conceptualized as a function which is defined by its outcomes, namely the deliberate problem solving. He proposes a distinction between hot and cool aspects of executive function manifested in the functioning of each subsystem during any deliberate problem solving procedure. Hot executive function is required for problems that involve the regulation of affect and motivation and it is associated with ventral and medial regions of prefrontal cortex. Cool executive function is a more purely cognitive aspect. It is required in relatively abstract, decontextualized problems and it is associated with dorsolateral prefrontal cortex. Zelazo’s proposed problem solving framework (Zelazo et al., 1997; Zelazo, Qu & Muller, 2005) proceeds from problem representation to planning to execution to evaluation. Inflexibility can occur at each of these phases. Systematic changes in the various phases of problem solving are identified during the preschool years and beyond. These changes are hypothesized to be bidirectional in the sense that "intelligent activity can be reflected back into earlier phases of problem solving, where it can come to precede execution and contribute to the development of EF as a whole" (Zelazo, Qu, & Muller, 2005, p. 462).

Hot EF is often identified with the theory of mind. Theory of mind refers to having a good understanding of human action in terms of plans, desires, intentions, and beliefs. According to Perner, Stummer and Lang (1999) theory of mind is an integral part of EF, responsible for inhibiting incorrect responses or actions. Performance on EF tasks that involve some kind of conflict between two perspectives of a situation, can predict with much accuracy performance on tasks on theory of mind (Carlson & Moses, 2001). The strong relation between executive function and theory of mind is not affected even when the effects of age, IQ, and gender are controlled. Theory of mind is a developmental phenomenon, as is executive function, and it unfolds itself on the spectrum of complexity. Therefore, theory of mind and, subsequently, inhibitory control and executive functions, go through a big developmental change at the age of 4 years when metarepresentations emerge (Perner, 1991). Metarepresentations are conscious understanding that representations represent mental states and act in a causal way, driving people's actions and guiding problem solving.

Attention

Attention is considered to be an important constituent of intelligence (Schweizer, Moosbrugger, & Goldhammer, 2005). Different types of attention have been proposed by various researchers, such as the *perceptual attention* manifested in the form of alertness, sustained attention, focused attention, attentional switching and divided attention (Coull, 1998; Sturm & Zimmermann, 2000; Zomeren & Brouwer, 1994), the *supervisory attention* manifested in the functioning of the central executive of working memory in order to guarantee appropriate behavior in situations where the rapid execution of automatic processes is not enabled (Baddeley, 1986), and the *information processing attention* (Neumann, 1992; 1996) which includes inhibition of action, spatial attention, planning of action, skill-based interference and arousal. Supervisory attention will be presented when working memory is discussed while information processing attention will be presented when inhibitory control is discussed.

Perceptual attention, and specifically attentional switching, has been extensively studied using the task switching paradigm in which participants rapidly switch between two or more speed tasks that are usually performed on the same set of stimuli. The ability to flexibly switch between task demands, or the ability to select the appropriate rules for subsequent behavior, is a complex function that requires task rule retrieval (Mayr & Kliegl, 2000) and overriding the previously relevant rule that corresponded to the stimulus–response association (Meiran, 1996). Various manipulations in the delay between consecutive trials of the switching paradigm, or between the task signal and the target trials have been made in order to test whether performance decrements are associated with an inability to override the previously relevant stimulus–response association rule, or with difficulty in retrieving and activating the upcoming rule.

Switching between tasks is associated with some kind of mental cost reflected in performance decrement (Schweizer, Moosbrugger, & Goldhammer, 2005). Mental cost is manifested as mixing cost and switch cost. Mixing cost refers to response time increase when performance on task repetitions in a mixed task block is compared to performance on task repetitions in a single task block (Los, 1996). Switch cost refers to response time increase when performance on switching between tasks is compared to performance on repeating tasks within a mixed task block (Meiran, 1996).

Inhibitory Control

Controlling the incoming information and inhibiting, or suppressing, irrelevant associations and premature reaction tendencies is a cognitive process that has a central role in the study of information processing. Research from the neuropsychological, cognitive, and developmental literature makes it evident that inhibitory control, one of several processes involved in "executive functioning", plays a significant role in determining how various mental processes work together in the successful execution of a task.

In general, *control* refers to how efficiently the system handles the vast amount of conflicting information, how it focuses its attention to the pieces of information that are relevant to its current goal, and how productively goal-irrelevant information is filtered out. *Inhibition* refers to the function which obstructs the system from reacting to the incoming information in a premature way, that is, without taking into account all aspects of the situation at hand. The *control* and *inhibition* terms are usually used interchangeably to describe the process of efficient handling of information, which permits the focusing of attention and the processing of goal relevant information, while filtering out the irrelevant information, and suppressing premature responses that emerge before a process is completed. The two terms seem to describe the two sides of the same coin, though the more general term *inhibitory control* is frequently used replacing both of these terms.

Inhibitory control covers a variety of constructs and at least two theoretical models have been suggested. The first is the interference model which postulates that inhibition refers to hierarchical control of a lower force by a higher force. Dempster (1993) proposes a synthesis between developmental and neuropsychological research (suggesting that resistance to interference contributes to diverse expressions of cognitive development), with both indicating that the frontal lobes are critically involved in interference-sensitive tasks. Thus, the prefrontal cortex plays an important role in executive functions and the active suppression is understood as a key construct of the model. The second model of inhibition is the inefficient inhibition model. It denotes a competitive relation between qualitatively equivalent powers in which one force leads to the temporary arrest of the other force. Bjorklund and Harnishfeger (1995) conceptualized inhibition in terms of a process that blocks the spread of activation and hypothesized that inhibitory processes become more efficient during childhood, resulting in less irrelevant information entering the system and, therefore, increasing its functional capacity. The inefficient inhibition model seems to emphasize the notion of competitive interaction rather than active suppression.

The process of inhibitory control is mainly studied under conditions where an individual is required to identify an aspect of a stimulus when this aspect is incongruent with other aspects of the stimulus as well as when the relevant to the task aspect is not the dominant aspect of the stimulus. In such experimental conditions the concepts of automatization and of selective attention are interweaved. Routine procedures are formed when processes are repeatedly activated within the same context and the same content and in turn are transformed into automated processes. The most known experiment for studying the nature of automatic and controlled cognitive processes (Posner & Snyder, 1975), the neurocognitive architecture of selective attention (Rebai, Bernard, & Lannou, 1997), and age related declines in inhibitory processing (West & Alain, 2000) is the paradigm designed by Stroop (1935). According to this paradigm a word referring to a color name is written in some ink color, which in the congruent condition is the same as the color to which the word is referring to and in the incongruent condition is different from the color to which the word is referring to. The word stimulus is presented under two different conditions: reading the word and naming the color of the ink with which the word is written. According to Stroop (1935) the second condition, i.e. naming the ink color, demands a longer reaction time and this additional need in processing time results from the interference of the dominant aspect of the stimulus, which is the tendency to read the word, with the weaker, yet goal-relevant aspect, which is naming the ink-color. This increase in response latency when an individual is required to identify an aspect when this aspect is incongruent with other aspects of the stimulus, compared to the time required to identify a neutral aspect or an aspect congruent with the other aspects of the stimulus is known as the Stroop interference effect or the Stroop phenomenon.

The Stroop phenomenon has been extensively studied using different stimuli (verbal, numerical, spatial) and various conditions, aiming at proposing information processing models which can explain the function of inhibitory control mechanism. Navon (1977) conducted a series of studies on inhibitory control using the nested letter identification task. Large letters composed of several smaller letters are presented to the individual who is instructed to identify either the larger letter (global condition) or the smaller letters (local condition). Navon supported this experimental design by the idea that objects have salient and non-salient features which help individuals form a holistic impression of the object when all features are combined together. He referred to the salient features as global features whereas the non-salient ones were called local features. The relative salience of the information from the local features and the global configurations influences the control exerted. Navon´s experiments showed that global features were identified more quickly than local features and that response latency to identify the local features were affected by the global features. In the case where the global and the local features of the stimulus (i.e., the large and the small letters) were the same, the identification of the local feature was facilitated. On the contrary, when the global and the local features mismatched, the identification of the local features was inhibited. On the other hand, response latency to identify the global feature was not affected by the identity of the local features. Based on these findings Navon proposed a serial model in which global analysis precedes that of the local analysis. He advanced the *global precedence hypothesis*, in which global processing is considered as a necessary stage of perception, one that cannot be skipped. When the global and the local features of information are in conflict, then the global features interfere in the processing of the local features, whereas, the local features do not interfere with the identification of global features. This serial processing of information in stimuli is met in conditions where the stimuli are hierarchically organized is such a way that the local level is defined by small individual bits of information, which are then used to configure a larger bit of information in a global level. Navon argued that “the global precedence has a number of possible advantages such as utilization of low-resolution information, economy of processing resources, and disambiguation of indistinct details" (1977, p. 381). His notion on the allocation of processing resources as well as his suggestion that research interest should focus on studying the control on the complexity of global and local features are in line with contemporary information processing research.

On the other hand, other models in which processing is assumed to proceed in a parallel rather than in a serial mode, seem to support the idea that the information from both dimensions (global and local) is simultaneously received. The relative strength of each dimension and the current focus of attention, affect the processing of the information resulting in individual differences. Verbal, numerical and spatial stimuli have been used in various experimental designs aiming at studying inhibitory control and parallel distributed processing. Research studies using verbal stimuli (a color naming word written in some ink color) have resulted in some computational (Cohen, Dunbar, & McCelland, 1990) and mathematical (Lindsay & Jacoby, 1994) models. According to these models, color and word information are processed in independent pathways that converge on a common response system. In congruent trials, when the word denotes a color which is the same as the ink color with which the word is written, responding is facilitated, as the same response level representation is activated by the color and the word information. The Stroop effect emerges on incongruent trials when information from the color and the word activate competing response level representations. The activation of more than one response level representation requires additional time for input by the stimulus's less salient information, which in the case of a word-color situation is the color information, to accrue enough activation to become differentiated from input by the word pathway and guide a response (West & Alain, 1999).

The Stroop effect, according to Demetriou, Christou, Spanoudis and Platsidou (2002b), is an additive function of three fundamental processes, namely dimension selection, dimension identification and inference control. In a study conducted by Demetriou and his colleagues, measures of dimension selection, dimension identification and interference control were taken to test Stroop effect model. Multiple regression analysis revealed that dimension identification is the first best predictor, dimension selection the second and interference control the third best predictor of the Stroop effect. Efficiency in dimension identification is the most important component because it is always present and it provides the substance for understanding and decision making. Dimension selection is needed only when there are alternative dimensions to choose from and interference control is needed only when one or more dimensions interfere with any of the other two processes. These results are in accord with contemporary brain research findings according to which large differences in response latency between the congruent and incongruent trials are better explained by distinguishing the process of evaluation from the process of response selection and that interference is related to conflict in the response selection rather than in the stimulus evaluation process. Dimension identification is included in the evaluation process while dimension selection and interference control are vital parts of the process of response. As Demetriou et al. (2002b) suggest, dimension selection could be executed before the activation of any of the other processes and that the other processes pop in before a final decision is made about the dimension to be responded to, thereby slowing decision making in relation to the dimension to be attended to. Data from the neurocognitive literature which lend support to the additive Stroop-effect model proposed by Demetriou, will be presented shortly afterwards. Moreover, brain research, and especially research using functional magnetic resonance imaging (fMRI) and event related potentials (ERPs), providing important information on the function of inhibitory control under stroop-like conditions, will also be presented in order to shed some light on the debate on serial and parallel processing.

Duncan-Johnson and Kopell (1980) suggest a dual-pathway model of the verbal stroop-like tasks according to which two different neural pathways are activated to process different kinds of information. Moreover, they reported no differences in the latency or amplitude of the P3 elicited by congruent, neutral, or incongruent trials in the stroop-like task and large differences in response latency between the congruent and incongruent trials. These findings suggest a distinction between the processes of evaluation and response selection and that interference is related to conflict in the response selection rather than in the stimulus evaluation process. Consistent with these findings are the findings of a study conducted by West and Alain (1999) using ERPs. Specifically, a number of ERP modulations were recorded reflecting differential neural activity when the word pathway could support task performance on congruent trials and when the color pathway could support task performance on incongruent trials. The ERPs elicited by congruent and neutral trials were quite similar indicating that similar neural processing supported task performance in congruent and neutral conditions. The incongruent trials were associated with two frontally distributed ERP modulations suggesting that conflict detection and conflict resolution are separate processes supported by different neural generators located within different regions (the lateral prefrontal and anterior cingulate, respectively). Furthermore, the ERPs from the incongruent trials revealed that processing in the color pathway (that is the less salient or local aspect of the incongruent stimulus) was modulated by conflict resolution processes (as they were recorded from the fronto-central slow wave).

These findings on the verbal stroop-like tasks indicate that in the congruent and neutral conditions, where perceptual color and word pathways converge on a common conceptual level system, task performance is better and faster facilitated. When the system detects conflict due to incompatible color and word information, a dynamic process is activated in order to modulate the perceptual color pathway and, as a result, the conceptual level system is attenuated or suppressed, as suggested by the decreased neural activity observed over the left parietal region for incongruent trials (Lindsay & Jacoby, 1994). Increased response latency on incongruent trials is due to the time required by the conflict resolution processes to activate the color pathway to a level sufficient to guide a response (West & Alain, 1999).

Closely related to the Stroop interference effect observed in digit tasks, is the nature of number representation which, in turn, is strongly associated with the number distance effect. Dehaene (1997) suggests that individuals form an abstract mental representation of quantity along a mental number line regardless of the external representation of numbers. This theory can explain the distance effect (Fias & Fischer, 2005) which postulates that when two numbers are compared as to their relative value the smaller the distance between the two numbers, the closer they are marked along the mental number line, and therefore, the harder it is to discriminate them. Nuerk et al. (2001) found that during a number comparison task with two-digit numbers, individuals responded more slowly when the unit digits were incongruent with the decade digits in terms of their relative magnitudes, although the distance effect between the numbers was controlled. This Stroop-like effect indicates that individuals process the number digits in parallel, instead of holistically.

Additional neuroimaging evidence for such a parallel processing model was provided by the two-digit number comparison study conducted by Liu, Wang, Corbly, Zhang and Joseph (2006). The Stroop interference effect was traced in the behavioral results of the study: individuals responded more slowly to incongruent pairs of numbers (in which the decade digit was greater, but the unit digit was smaller, in the larger number than those in the smaller number, respectively, with the mental distance between the digits of the two numbers being constant) and to pairs of a smaller mental number line distance. Activation of the attentional network, typically associated with such an interference effect, was also identified. To overcome the interference imposed by the incongruent relative sizes of the unit digits (e.g., the larger unit digit in the smaller number), individuals need to shift attention to the decade digits and rely more on the decade digits to make the correct comparison. Due to the interference caused by the unit digits in the incongruent pairs, it is assumed that individuals shift their attention to the left and enhance processing of the decade digits in order to overcome the interference from the unit digits (Liu, Wang, Corbly, Zhang, & Joseph, 2006). These results lend support to the parallel processing model of the decade and unit digits modulated by attentional selection. The results also suggest that Stroop effect activates distinct subregions along the right hemisphere intraparietal sulcus (IPS) which are involved in attentional selection and numerical comparison.

Parallel processing is also supported by research in visual object perception. However, the complexity of the visual stimuli has often been accounted for the controversial research outcomes and the variety of the proposed models. Some models claim that the ventral pathway, a set of visual cortical areas responsible for object recognition, can process only one or very few objects at a time whilst other models suggest a massively parallel processing of objects in a scene. According to Rousselet, Thorpe and Fabre-Thorpe (2004) the ventral pathway seems to be able to encode high-level diagnostic information about visual stimuli and perform complex analyses on them in parallel, but only during a short period of time and under the limitations imposed on the system by competitive interactions which strongly limit the number of detailed representations available. Subsequently only one or very few stimuli are explicitly selected and consciously processed. Rousselet, Thorpe and Fabre-Thorpe propose a model according to which the dynamic network comprising prefrontal and parietal cortices seems to select an object by first performing a short high-level parallel analysis and then rapidly zooming in on one or a few objects without processing all objects in a scene in detail.

The Development of the Executive Functions

Children become increasingly more able to control their thoughts and actions (Huizinga, Dolan, & van der Molen, 2006). Their ability to select input from the environment that is relevant to their goals and suppress distracting or conflicting information, to hold that information in mind and to process it according to the demands of the task at hand, to inhibit inappropriate or premature reactions, and to maintain alertness during the problem solving procedure is increasingly developed (Diamond, 1990) as they enter adolescence and early adulthood. All these processes are usually referred to with the use of the hypothetical constructs of selective attention, working memory, inhibition and sustained attention or alertness and are part of the generic construct of executive functions (Polderman, Posthuma, De Sonneville, Stins, Verhulst , & Boomsma, 2007). Davidson et al. (2006) place much value on the functions of working memory, inhibition, and cognitive flexibility and they postulate that mature cognition is characterized by the specific abilities which refer to these functions.

Developmental studies are often faced with some problems reflected in their findings. In illuminating the diversity in the developmental trajectories of the processes, the standard neuropsychological tasks used, such as the WCST and ToH, have a central role. But, the use of different tasks across studies to measure the same EF component as well as the complexity of the EF tasks allow for a deviance in the recorded results. For example, analysis of perseverative errors on the WCST indicates that the performance of children reaches the performance of young-adults by the age of 11-12 years, whereas, analysis of failure-to-maintain set indicates that adult levels of performance are not reached before the age of 13–15 years (Levin, Culhane, et al., 1996; Welsh, Pennington, & Groisser, 1991). On the ToL task, performance based on errors appears to continuously improve from middle childhood into young-adulthood; whereas, performance based on errors and time, reaches adult levels of performance by the age of as 13 years of age (Baker, Segalowitz, & Ferlisi, 2001; Levin & Fletcher, 1996). These findings give rise to various explanations as for the source and nature of change in EF component processes and as a consequence, a straightforward interpretation of the developmental trends of the EF component processes is impeded.

Furthermore, many developmental studies focus on a single EF component process, and as a consequence, assessment of developmental change across EF component processes is not reliable as differential rates might be due to different samples rather than components. On the other hand, the functions referred to as constructs of EF are often functionally interrelated during the problem solving procedure making the developmental study of each separate function a difficult endeavor since the tasks used in such studies are not clear measures of the functions ascribed to each construct solely. For example, inhibitory control measures are "contaminated" by working memory and attentional shifting flexibility to a more or lesser degree, according to the specificities of the tasks. Moreover, it is unclear whether the question of measurement invariance is secured (Meredith, 1993). Most probably, it is the case that children at various ages use different strategies when performing on EF tasks, and therefore, it might be the case that not the same construct is being measured across age (Huizinga, Dolan, & van der Molen, 2006). Finally, it should be noted that developmental research findings are often under the confinement of studying heterogeneous age groups simultaneously, rather than studying a group longitudinally, in the course of time. The cross-sectional design of most developmental studies cannot guarantee the homogeneity of the groups and cannot illuminate the developmental trajectory of the processes longitudinally. Thus, a reliable assessment of the developmental patterning of EF component processes requires measuring homogeneous age groups in the various EF component processes and applying latent variable approach to the data.

Having these research confinements under consideration, we will present developmental data for the EF in general and developmental data for attentional shifting (cognitive flexibility) and inhibitory control, in specific.

The findings from various developmental studies provide further support to both the unity and diversity of these EF processes. EF component processes seem to develop at different rates (Huizinga et al., 2006) beginning in early childhood and continuing into adolescence when adult-level performance is attained. For example, working memory and inhibition are present from early infancy (Davidson, Amso, Anderson, & Diamond, 2006). Selective attention, including the ability to suppress distracting information, improves significantly during childhood (Ridderinkhof & Van der Stelt, 1999). Processing speed, a core process present in all EF components, becomes faster and storage capacity increases (Kail, 1992).

A recent developmental study conducted by Huizinga et al. (2006) has revealed the developmental trajectories of the three most commonly used EF components, namely working memory, shifting, and inhibition of responses, and their relation to performance on standard, complex, neuropsychological EF tasks, the WCST and the Tower of London (ToL), a variant of the ToH task. The study aimed at assessing the developmental trajectories for each task and determine when the latent components of working memory, shifting, and inhibition reach adult levels. A multi-group design was adopted for providing an assessment of developmental change in EF component processes. Participants were 7-, 11-, 15-, and 21-year olds and were tested on three tasks for each EF component process, the WCST and the ToL. The performance analyses revealed different developmental trends in working memory and shifting, a finding in accordance with earlier literature (Cepeda, Kramer, & Gonzalez de Sather, 2001; Gathercole, Pickering, Ambridge, & Wearing, 2004). Working memory continues to develop into young-adulthood, whereas shifting attains mature levels during adolescence.

The distinct developmental trajectories of the various EF component processes have led to the proposal of various developmental theories of EF. Specifically, some researchers have explained age-related changes in EF based on the construct of inhibition (Luria, 1966; Carlson, Moses, & Hix, 1998; Dempster, 1992). Many researchers have in an ad hoc manner considered EF as synonymous to inhibition and, consequently, have measured EF using an interference paradigm. In so doing, failures on EF tasks are manifested or explained as perseverative errors, i.e. errors in inhibiting behavior (Zelazo et al., 1997). EF deficits are explained as inability in suppressing interfering response tendencies because of an immature or inefficient inhibition mechanism. Nevertheless, such explanations are unable to support predictions regarding the various developmental situations and they are therefore limited in post hoc explanations. Moreover, the construct of inhibition fails to address how one decides what is to be inhibited (Zelazo & Müller, 2002). Other researchers have explained changes in EF based on changes in actual or functional capacity of working memory (e.g., Case, 1985b). This approach probably has its origin in the work on PFC impairment and its close relation with working memory deficits. Developmental studies have shown that there are regular age-related increases in working memory throughout childhood (Gathercole, 1998). These increases seem to be particularly important for planning and execution. Diamond (1991) has suggested that the development of EF involves both constructs of working memory and inhibition. All three attempts to model EF development are fairly simple and not able to capture the full range of phenomena that are covered by the term EF.

An attempt to capture the complexity of the full range of EF phenomena was made by Zelazo and Frye (1997) who have proposed a more complex, hierarchical theory on the development of EF, including the theory of mind. They propose the cognitive complexity and control theory which explains age-related changes in executive function as a consequence of changes in the maximum complexity of the rules individuals formulate, in an ad-hoc fashion, and use under various conditions. These rules are subjected to constant evaluation in respect to other rules via the mechanism of rule reflection, and as a consequence, rule hierarchies are formed. Age related increases in individuals' metacognition, reflection and deliberate selection among their rules, result in increased control over thought and action (Zelazo, Frye, & Rapus, 1996). In these hierarchies reside the conditions under which rules are valid, too. The more rules and the more conditions reside in a hierarchy, the more complex the rule hierarchy becomes. Increases in rule complexity result from developmental changes in conscious reflection on information which, in turn, results to increased control over thought and action. Complex hierarchies allow for more flexible selections of rules according to the underlying condition that must be satisfied and, accordingly, more flexible responding is succeeded. According to Zelazo and Müller (2002, p. 454), "dissociations between knowledge and the ability to use that knowledge occur (under conditions of interference) until incompatible pieces of knowledge are integrated into a single, more complex rule system via another degree of reflection". In the case where integration into a more complex rule system is not attained, behavior is controlled and limited by the local associations of the particular knowledge. As a consequence, representational inflexibility (Zelazo, Qu, & Müller, 2005) and difficulty in overriding or inhibiting a prepotent response (Diamond, 1996), are observed. A big increase in rule complexity takes place between the age of 3 and 5 years when metarepresentations emerge. Children are increasingly becoming more able to reflect on their rules, subordinate them to a higher order rule and successfully employ them in situations where any residing incompatibility is controlled. According to Frye, Zelazo, and Palfai (1995), these increases in control strongly affect children's reasoning in social and nonsocial domains. The control of reasoning is constrained by the level of rule complexity. Such limitations are overcome when a higher level of complexity is achieved through an ongoing process of rule reflection and rule assessment. Halford, Wilson and Philips (1998) suggest that the systematic construction of increasingly complex relations is a major dimension of cognitive development. Furthermore, rule reflection, rule assessment and rule employment are strongly associated with the functioning of working memory, a construct closely related to the generic term of EF, and its development.

Researchers have been interested in studying the degree to which genetic and environmental variation are responsible for individual differences in executive functioning during childhood. Stins, De Sonneville, Groot, Polderman, Van Baal and Boomsma (2005) designed a study using 5-year-old mono- and dizygotic twin pairs to investigate the extent to which heritability and common environmental influences are responsible for variance in processing speed of selective attention and working memory. Though familial influences on task performance were observed, no clear distinction could be made between genetic and common environmental influences. On the other hand, strong genetic influences were observed on their performance on inhibition tasks, while no significant common environmental influences were present (Groot, De Sonneville, Stins, & Boomsma, 2004). A longitudinal analysis of the variance in working memory was conducted by Polderman, Stins, Posthuma, Gosso, Verhulst and Boomsma (2006) who used the same twins as Stins et al. (2005) and Groot et al. (2004) used when the twins were 12 years old. Half of the working memory variance (43–56%) was explained by genetic variance, a finding comparable to findings from studies with young adults (Ando et al., 2001) where genetic variance contributed for 43–48% to the variance in WM performance. In a study conducted by Polderman, Posthuma, et al. (2007) the developmental stability in executive functioning during childhood and the question of whether the causes of developmental stability are of genetic or environmental origin, were investigated. This study examined the variance of EF components and the contribution of genetic influences at age 5 years and at age 12 years. In the longitudinal design of the study, 237 twin pairs were tested on executive functioning when they were 5 years old and approximately 75% of these twins were tested again when they were 12 years old. The correlations between age 5 and age 12 years for processing speed of selective attention, working memory and sustained attention (0.37, 0.37 and 0.39, respectively) were "quite substantial considering the time interval of 7 years and dramatic brain development throughout this period of childhood" as the researchers note (p. 18). Dynamic changes in brain happen between age 3 and 15 years leading to large developmental differences observed between children of different age groups. Thompson, Giedd, Woods, MacDonald, Evans and Toga (2000) report that very fast growth of the frontal networks, that regulate alertness and the planning of actions, was detected early in childhood, between age 3 and age 6 years, while substantial changes in parietal regions, which are related to association and language function, occur between age 11 and 15 years. Moreover, significant changes in cortical thickness throughout several regions of the brain take place between ages 7 and 16 years (Shaw, Helmes, & Mitchell, 2006). Therefore, the age homogeneity of the samples used in the study conducted by Polderman, Posthuma, et al. (2007) suggests that cognitive developmental divergence due to age differences is less likely. The most important finding of that study was the substantial heritablity estimates of selective attention, working memory and sustained attention at age 5 and at age 12 years, and the suggestion that stability of these traits is mediated by genetic factors. Common environmental factors, as well as unique environmental factors, did not play a significant role for the stability over time of any of the EF components.

Developmental studies on attentional shifting have examined the cost of shifting back and forth between tasks and have demonstrated that the cost of shifting decreases with age (Diamond, 2002; Zelazo, Craik & Booth, 2004). This developmental pattern is closely related with the maturation of the PFC (Casey, Davidson, Hara, Thomas, Martinez, Galvan, Halperin, Rodriguez-Aranda & Tottenham, 2004), which is the area of the brain that is mostly critical for the control processes (Crone, Wendelken, Donohue & Bunge, 2005). The ability of attentional shifting is complex, and it seems to depend on various other cognitive processes that may rely on different neural mechanisms (Crone et al., 2005) and, consequently, different mechanisms may affect performance on task-switch at different ages. Recent research findings suggest that the ability to shift task sets does not reach young-adult level of performance until the age of 15 years (Cepeda et al., 2001; Crone, Bunge, van der Molen, & Ridderinkhof, 2006; Kray, Eber, & Lindenberger, 2004).

Research interest has been focused on examining the developmental trajectory of task switching with the use of several task manipulations, such as varying the delay between consecutive trials of the switching paradigm, or between the task signal and the target trials. Cepeda et al. (2001) used these manipulations and examined age related differences in switching task performance in respect to age-related changes in 'passive' dissipation of cognitive sources during the interval between response in trial *n* and signal on trial *n+1* and to 'active' preparation during the interval between the signal and the target. The results of their study showed that increasing the interval between the signal and the target had the same effect on all age groups. On the other hand, increasing the interval between response in trial *n* and signal on trial *n+1* resulted in a decrease in switch costs for young adults, but not for children. These findings suggest that the 'passive' dissipation of cognitive sources is stronger for younger children since they are more susceptible to interference from the stimulus-response rule of the previous trial. Moreover, younger children are more prone to carry-over effects from the previous trial because the binding between stimuli and responses is stronger in children than in adults (Smulders, Notebaert, Meijer, Crone, van der Molen, & Soetens, 2005).

Carry-over effects are also reflected in the process of automatic facilitation, a phenomenon observed when a task is repeated, the interval between the response in trial *n* and stimulus in trial *n+1* is short, and individuals (young children more than adults) benefit from response repetition. Carry-over effects and automatic facilitation are studied as sequential effects, that is, changes in speed of response as a function of the sequence of preceding tasks and responses. Closely related to the carry-over effects are two other effects, namely the repetition benefit effect and the reverse repetition effect. The repetition benefit effect is manifested when individuals repeat the same response in task repetition trials, whereas, the reverse repetition effect is manifested when individuals are hindered by repeating the same response in task switch trials. In a study conducted by Smulders, Notebaert et al. (2005), it was shown that adults demonstrate repetition benefit, but are also prone to the reversed repetition effect. Younger children demonstrate larger reversed repetition costs, while they benefit from the repetition effect more than adults do. When there is rapid succession of trials in a single task conditions, greater automatic facilitation is observed in children more than in adults (Kerr, Davidson, Nelson, & Haley, 1982; Soetens & Hueting, 1992). Smulders, Notebaert et al. (2005) suggest that children may adjust associations between responses and tasks more strongly, resulting in benefits when the tasks repeat and in costs when the tasks switch (Meiran, 2000). The developmental differences in task switch costs can be largely explained by the assumption that younger children experience greater carry-over effects which interferes with their ability to switch to currently intended rules. This is more likely an automatic rather than an endogenous process.

The age-related change in the ability to shift task sets has been interpreted in terms of two shift cost hypotheses. The first hypothesis argues that the larger shift costs in young children reflect immature levels of executive control (Cepeda et al., 2001; Zelazo, Craik, & Booth, 2004). It is proposed that children have larger switch costs because they cannot efficiently inhibit their responses to the previously activated task (Diamond, 2002; Kirkham, Cruess, & Diamond, 2003; van den Wildenberg & van der Molen, 2003) and, therefore, they cannot suppress or inhibit the rules previously activated. When children have to switch from one rule to another they experience attentional inertia (Kirkham et al., 2003) which reflects their failure to inhibit responding based on the previously learned and applied rule and which results in perseveration. The second hypothesis argues that the larger shift costs in children reflect working memory deficiency in retrieval of the rule which describes stimulus and response association (Crone, Bunge, van der Molen, & Ridderinkhof, 2006).

Rougier, Noelle, Braver, Cohen, and O'Reilly (2005) propose a model that provides an explanation for the development of cognitive flexibility based on the functioning of neurobiological mechanisms specific to the PFC. Specifically it is proposed that these PFC neurobiological mechanisms result in the self organization of abstract representational rules that support flexible cognitive control. Experience is given a primary role in the development of these representations and the cognitive flexibility that arises. The functioning of the neurobiological mechanisms is assumed to rely on some fundamental properties of the PFC, such as its capacity for "active maintenance of patterns of neural activity over time and against interference from distracting inputs, so that currently relevant information can be held in working memory" (p. 7338), its adaptive ability to update these neural activity patterns by "dynamically switching between active maintenance and rapid updating of new representations" (p. 7338), and its ability to maintain extensive interconnectivity with other cortical areas. The interaction of active patterns of neural activity with experience produces abstract representational rules in the PFC which lead to significantly higher levels of generalization by guiding processing according to abstract dimensions of the stimuli. Generalization, as Rougier et al. (2005) say, is an important measure of cognitive flexibility and it is effected as a result of the search and use of the appropriate learned pattern of activity rather than the need to learn a new set of connection.

Resistance to interference and competing response inhibition define a key dimension of development and reflect cognitive ability in general (Kipp, 2005). Age-related changes in cognitive control are often examined in terms of developmental changes in inhibitory control (Diamond, 2002; Kirkham et al., 2003). The general pattern of inhibitory control development is that it increases throughout childhood (Klenberg, Korkman, & Lahti Nuuttila, 2001), and it reaches adult level of performance in late childhood (Van den Wildenberg & Van der Molen, 2004), or in early adolescence (Williams, Ponesse, Schachar, Logan, & Tannock, 1999).

In a developmental study on age-related changes in simple and selective inhibition conducted by Van den Wildenberg and van der Molen (2004), it was found that the cognitive cost, reflected in the time they allocated to inhibit a prepotend response when an incompatible response was required, was greater for 7 year olds relative to 10 year olds and young adults. Moreover, speed of inhibition of the prepotend responses, which occur in the form of rapid transient activation of the compatible response to a stimulus (Hommel & Prinz, 1997), increased with age. Specifically, the RT in the selective stop signal task used in the study, decreased from 327ms in the 7 year olds, to 300ms in the 10 year olds, to 237ms in the young adult group. Van den Wildenberg and van der Molen suggest that their findings on developmental changes in inhibition are consistent to findings on the developmental trends in the speed of processing and to the conclusion that a global mechanism limits the speed of information processing (Kail, 1993; Hale, 1990).

It is obvious that time is an important parameter of inhibitory control for two reasons: First, rabid occurrence of prepotend responses may lead the system to erroneous responses and failure of the inhibitory control process. Second, speeded responses are considered as a manifestation of efficiency and, therefore, a measure of inhibitory control ability. Though the findings from the study of Van den Wildenberg and van der Molen (2004) clearly show a decrease in RT in inhibitory control tasks, these findings reflect developmental changes from childhood to young adulthood. The developmental pattern of inhibitory control changes throughout adulthood till the later end of the developmental spectrum in relation to the speed of processing factor have been studied in individuals ranging from 6 to 82 years of age by Christ, White, Mandernach and Keys (2001). Their study has demonstrated that age-related differences in inhibitory control performance between children and young adults are sufficiently explained by differences in processing speed; however, age-related differences between young and older adults cannot be sufficiently explained by speed. The findings from this study suggest that the ability to inhibit a prepotend response and generate an incompatible response develops quite early and declines at the later end of the developmental spectrum. Processing speed plays a mostly significant role in the efficiency of inhibitory control functioning at the early stages of development, while later in life, age-related differences in inhibitory control are mostly driven by the specificities of this process.

Similar conclusions were reached from a more recent study conducted by Huizinga, Dolan, and van der Molen (2006) on the developmental trends in EF task performance. This study revealed that age-related differences in EF cannot be explained in terms of a global change in basic processing speed. Specifically, all speeded tasks used in the experimental design, i.e., the three shifting tasks and the two of the three inhibitory control tasks, were specified to load on the basic processing speed factor, which was indexed by median RT of the pure blocks of the Stroop task, to correct for within-group individual differences in processing speed. The correction for within-group individual differences in basic processing speed did not remove the age related trends in task performance. This finding indicates that the developmental trends in EF task performance cannot be explained in terms of a global change in basic processing speed and that an important part of the developmental changes in inhibitory control need to be attributed to parameters exclusively related to the process as such.

Mental rules of varying complexity are the building blocks of cognitive control. Inhibitory control and discrimination learning, the ability of individuals to control their actions in order to apply the appropriate rule and respond differently to different signals, appear to be closely linked (Schachar & Logan, 1990). Studies of discrimination learning in young children make it evident that children less than 6 years of age have difficulty mastering discrimination learning tasks. Specifically, children aged 3 to 6 years were unable to execute or withhold motor responding, although they understood the rules of the task and they could verbally describe them (Bell & Livesey, 1985). In another study by Livesey and Morgan (1991) young children were able to give the appropriate response in a verbal response condition, indicating an understanding of the task rules, but in an active performance condition, they were unable to execute or withhold a motor response in accordance with the current rule. Zelazo, Reznick and Pinon (1995) referred to these findings as a result of children's inability to use the rules required for correct performance. They called this dissociation between the correct verbal response and the wrong motor response as *abulic* dissociation, meaning abnormal lack of ability to act or to make decisions. According to Zelazo et al. (1995) these abulic dissociations are relative to the child's cognitive capacity to reflect on the rules provided to control behavior.

Diamond (1990; Diamond, Zola-Morgan, & Squire, 1989) argues that age-related changes in children's ability to control responding can be attributed to the development of the PFC. However, the neural structures underlying inhibitory control constrain children from demonstrating an ability to withhold motor responding despite their cognitive capacity to learn the rules and demonstrate correct verbal response (Livesey & Morgan, 1991; Zelazo et al., 1995; Zelazo & Reznick, 1991).

Zelazo and Reznick (1991) and Zelazo et al. (1995) argue that rule reflection and the purposeful selection of the most appropriate rule necessary for successful task performance, depend on representational flexibility, working memory, selective control of attention, and proficiency at error correction. Executive errors due to representational inflexibility or forgetting or malfunctioning of the executive processes, in general prevent the individual from reflecting on the rules available and acquiring a more complex rule system which, in turn, lead to inefficiency in control over thought and subsequent action. Zelazo et al. (1996) indicate that as a consequence of changes in the complexity of children's rule structures, dimensional understanding may be acquired. As an example, it is mentioned that although children at the age of 3 years use rules for sorting a group of objects by a dimension, such as color, it is not until the age of 4 or 5 years that they can reflect on these rules and compare them with rules for sorting according to different dimensions, such as shape.

Lifespan cognitive changes are closely related to the processes of representation and control, and their interaction (Craik & Bialystock, 2006). The type and quality of the accumulated representations in terms of knowledge, crystallized schemas, reflecting experience, judgment and wisdom, influence the way the system constructs its rules and employs them in inhibitory control situations. Representational knowledge and inhibitory control follow a common developmental path from childhood to early adulthood, when they both reach their maximum point, while they follow separate trajectories as individuals move from maturity to old age. Specifically, representational knowledge maintains relatively stable in old age, whereas thereafter inhibitory control declines gradually in terms of power, speed, and complexity (Craik & Bialystock, 2006). The same developmental trajectory is followed by fluid intelligence which reflects the ability to identify and understand complex relations, and draw inferences based upon them. The gradual development of the inhibitory control process during childhood and its gradual decline in the elderly are better explained by Casey (2004) who argues that the executive control functions are mediated by the frontal lobes of the brain which are the last cortical areas to mature and among the first to be impaired in aging.

Donald (1991) explains the development of knowledge representations in terms of the phylogenetical evolution of the internal systems that formulate and maintain representations. These systems are hierarchically organized. Children formulate and retrieve lower representational knowledge and, as they progressively enter maturity, they build higher-order, abstract representations, free of any contextual reference. During elder age, representational knowledge can be formulated and retrieved, though the external context of the representations is needed to help the process.

In a study conducted by Dowsett and Livesey (2000) 3-, 4-, and 5- year old children received repeated exposure to tasks facilitating the acquisition of increasingly complex rule structures with the hypothesis that, if rule reflection capacity was present, children deficient in inhibitory control would benefit from exposure to complex rules. The results of the study showed that with repeated exposure and reflection on complex rules, the capacity for inhibitory control can be accelerated, even in children 3 years of age. Dowsett and Livesey explain these findings with respect to an analysis of the varied executive demands of the training tasks. Specifically, they argue that “representational flexibility, attentional control, working memory, error proficiency, motivational factors, and response control, strengthened the structural characteristics necessary for inhibitory control, producing more generalizable response capabilities” (2000, p. 173). Nevertheless, Case (1985) argues that experience has a limited role in the acquisition of executive skills. Specifically, he explained that practice in a novel operation increases operational efficiency and speed, up to some asymptotic value which is set by the age-related constraints in the efficiency of their psychological system. Thus, ceiling effects in performance will be produced. Zelazo et al. (1996) view advancement in general executive function performance from a different point and suggest that “increases in the ability to reflect on one’s rules ought to permit widespread increases in self understanding, self control and social interaction” (p. 58). Demetriou et al. (2002b) make similar suggestions when, based on their findings, they argue that practice in dimension identification and interference control tasks and growth of processing potentials interact to produce cognitive changes that underlie developmental changes in different domains of thought (Case, 1992; Demetriou, Efklides, & Platsidou, 1993), and influences the formation of the self-concept and the ability to control socially relevant impulses (Demetriou & Kazi, 2001).

The Relation of the Executive Functions with Intelligence

Research on the relationship between EF and intelligence has focused on the relation of the different types of attention with the *g* factor. Complex EF tasks have often been used in such studies, therefore yielding a high association between EF processes, such as divided attention, sustained attention, attentional switching, focused attention, stimulus discrimination, and intelligence (Roberts, Beh, Spilsbury, & Stankov, 1991; Schweizer & Moosbrugger, 2004; Stankov, Roberts, & Spilsbury, 1994; Schweizer, 2001; Schweizer & Koch, 2003). Schmidt-Atzert and Bühner (2000) conducted a meta-analysis of six studies on the relationship between attention measures and intelligence and yielded a mean correlation of .29.

Schweizer, Moosbrugger and Goldhammer (2005) investigated the relationships between the individual types of attention and intelligence as well as the identification of the model which best represents the overall relationship between attention and intelligence. Their analyses led them to the observation that each type of attention was substantially linked to intelligence. Specifically, latent variables of attention were formed based on the individual measurements of each type of attention which served as manifest variables for each individual type of attention. The latent correlations obtained for the link relating each latent variable of attention to the latent variable of intelligence varied between .20 and .49 (all of them reaching the level of significance). According to the researchers, these latent correlations suggest dependence among the types of attention, which provides the basis for a hierarchical structure of attention, and a high degree of overlap between the types of attention in predicting intelligence. Dependence among the latent variables of attention is the precondition for the existence of higher level latent variables termed the "*stages*". Stages are the various sources or fields of research into different broad cognitive constructs related to attention, such as perceptual processing, higher mental processing, and executive and control processing.

According to the theory of multiple resources (Wickens, 1980) a major source of dependence among different types of attention is their association with the same or related resources. Important resources are the areas of human information processing where a higher degree of dependence is to be expected and these areas are the individual stages of human information processing, perceptual processing, higher mental processing, and also executive and control processing (Wickens, 2002). Schweizer et al. (2005) suggest that a higher degree of homogeneity in processing can be assumed within these stages than between these stages. The degree of overlap between the attention types is larger within the stages than between the stages. Nevertheless, the stages can have common resources, as is the case between the stages of higher mental processing and executive and control processing.

In identifying the model that best represents the attention-intelligence relation, Schweizer et al. (2005) first assigned to each stage the latent variables according to previous research findings by Sturm and Zimmermann (2000), Neumann (1992; 1996) and Baddeley (1986). So, the stage of perceptual processing was related to focused attention (Sturm & Zimmermann, 2000), to attentional switching (Sturm & Zimmermann, 2000), to alertness (Sturm & Zimmermann, 2000) and to spatial attention (Neumann, 1992; 1996). The stage of higher mental processing was related to supervisory attention (Baddeley, 1986) and to sustained attention (Sturm & Zimmermann, 2000). Finally, the executive and control stage was related to inhibition (Neumann, 1992; 1996), to planning (Neumann, 1992; 1996), to divided attention (Sturm & Zimmermann, 2000) and to interference (Neumann, 1992; 1996). The structural model that best fitted the data was the one in which the stages of higher mental processing and executive and control processing were merged into one latent variable. This latent variable and the perceptual processing latent variable were linked to the latent variable representing intelligence. This model suggests that higher mental processing and executive and control processing have common resources, namely the resources of control processing since higher mental processing and executive processing activated during dealing with complex tasks require control processing. Moreover, it is suggested that attention is an important source of general intelligence.

Executive control functions have a prime role in the functioning of working memory (Baddeley, 1986; 2000). The mechanisms for regulating thought and behavior, the mental control of prepotent or over learned stereotypical responses (Baddeley, Emslie, Kolodny, & Duncan, 1998) and conscious awareness (Baddeley, 2000) are omnipresent in the functioning of working memory. Complex mental tasks which pose high demands on working memory are implicitly demanding to the supervisory attentional system. Success in such tasks is closely dependent on the efficiency of the EF, in general, and the supervisory attentional system (De Jong & Das- Small, 1995; Schweizer & Koch, 2001, 2003; Kyllonen & Christal, 1990).

Working Memory

Working memory is a hypothetical construct which comprises mental processes that keep a limited amount of information in an especially retrievable form, long enough for it to be used in ongoing mental tasks (Cowan, Morey, Chen, & Bunting, 2007). Information is kept in working memory only seconds after it has been presented (Baddeley, 1986; Gathercole, 1998) and unless it is preserved there via conscious rehearsal, coding of its aspects which will be registered, and retrieval into long-term memory (Atkinson &

Shiffrin, 1968), it decays. Therefore, the flow of information into the system and the extent to which information is lost due to decay are affected by these control processes. Working memory is also considered to comprise the processes of focusing attention, and transformation and mental manipulation of information received from the environment or retrieved from long-term memory traces (Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004). Ackerman, Beier and Boyle (2005) suggest that working memory is related to executive and attentional control capacity, but it does not account for all of the individual differences in these capacities. This assertion implies the dual nature of working memory; storage and executive control. While most theorists focus on working memory in terms of either its storage capacity or its attentional aspect, Conway, Cowan, Bunting, Therriault and Minkoff (2002) emphasize that working memory is a more complex construct which consists of a storage component as well as an attention component. Therefore, a consistent understanding of the function of working memory should address both issues by studying its function in maintaining memory representations in the face of concurrent processing and under the plausible distractions and attention shifts (Engle, Tuholski, Laughlin, & Conway, 1999; Miyake & Shah, 1999).

Conway et al. (2002) have identified the storage component of working memory with short-term memory, which "is a storage buffer, the capacity of which is determined by practiced skills and strategies, such as rehearsal and chunking" (p. 164). Short-term memory can be measured using simple span tests which place zero demand on the attention component of working memory. A correlation of .68 was reported by Engle, Tuholski, et al. (1999) between latent variables of short-term memory and working memory, while Conway et al. (2002) reported a correlation of .82 between these latent variables. Though highly correlated, the two memory constructs are separable because, as Conway et al. claimed, a two-factor structural equation model with these two latent variables fit the data better than a single-factor solution where short-term memory was combined with working memory into one factor. It can, therefore, be asserted that short-term memory capacity is not identical to working memory capacity, and that each represents a different facet of memory. The separability of the capacity of short-term memory from the capacity of working memory which draws on attentional resources is further supported by research findings based on the study of individual differences in memory capacity and of the development of memory capacity from early childhood to adulthood. Daneman and Merikle (1996) have found that complex working memory measures addressing the attentional capacity of working memory show consistently higher associations with language comprehension than do simple, short memory, span measures. Morra (1994) found that individual differences in complex span are independent from the variability observed in the simple memory capacity across children. Furthermore, Siegel (1994) asserts that complex and simple span tasks show separable developmental changes in adulthood. Specifically, complex span diminishes from early to late adulthood, whereas simple span is maintained.

Individual differences in working memory capacity allocated during a mental task can account for the individual differences in task performance. Specifically, when the demands of a mental task exceed the maximum amount of the system's available capacity, then the storage and the attention components of the working memory collapse giving rise to individual differences (Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004). Individual differences in working memory capacity appear within any task domain (Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle, 2005; Daneman & Merikle 1996; Kane, Hambrick, Tuholski, Wilhelm, Payne, & Engle, 2004), they are better observed in performance variability on complex span tasks such as the operation span (Turner & Engle, 1989) and the counting span (Case, Kurland, & Goldberg, 1982) and they reflect individual differences in the overall capacity of available resources and efficiency of mental processes (Jensen, 1998; Cowan, 1995; Engle, Tuholski, et al., 1999; Conway et al., 2002). Engle, Kane and Tuholski (1999) argue that individual differences in performance on complex span tasks are attributed to differences in the central executive component of working memory, while individual differences in performance on simple span tasks should be attributed to the variability observed in domain-specific abilities such as chunking and rehearsal (in the case of span tasks that address the phonological component of memory). Conway, Cowan, et al. (2002) note that though the dissociation of short-term memory capacity from working memory capacity is theoretically sound, no task is a ‘‘pure’’ measure of either capacity and that “all span tasks, simple and complex, will tap each capacity to some extent” (p. 165). All tasks activate, to a more or lesser degree, the engagement of controlled effortful processing as well as the automatized skills. As a consequence, even the simplest short-term memory tasks address temporary storage with some involvement of attention control. The confounding of the temporary storage and the executive processing in working memory measurements alters the estimation of the relation of working memory with the higher cognitive abilities and the general intelligence factor. In order to overcome this difficulty, Colom, Rebollo, Palacios, Juan-Espinosa and Kyllonen (2004) suggest that different tasks addressing temporary storage and controlled processing as separate abilities should be developed.

On the other hand many tasks incorporating both storage and executive processing have been developed to examine individual and developmental differences in working memory (Baddeley & Hitch 1974; Baddeley 1986; Baddeley & Logie 1999; Gathercole & Hitch 1993; Hitch, Towse, & Hutton 2001) as well as to investigate the relation between working memory and intelligence (Barrouillet, Bernardin, & Camos 2004; Conway, Cowan, et al., 2002; Engle, Tuholski, Laughlin, & Conway 1999; Kyllonen & Christal 1990). It is even suggested that working memory tests should also engage transformation, supervision, and coordination processes (Ackerman, Beier, & Boyle, 2005). Such tests yield strong correlations with general intelligence measures in a way that some researchers have used them as an index for distinguishing between individuals with higher or lower intelligence (Conway, Cowan, Bunting, Therriault, & Minkoff 2002; Engle, Tuholski, Laughlin, & Conway 1999; Kyllonen & Christal 1990). A possible drawback of this approach is the strategy use and the employment of other resources beyond the ones considered in the original design of the study, such as the involvement of a long-term retrieval strategy. Strategy use hinders understanding the real processes activated during task performance since the real need to use basic working memory capacity on storage and executive processing is confounded with the mechanics of strategy use. Consequently, the effort of understanding intelligence and its relation with working memory per se is obscured (Cowan et al., in press). In order to circumvent strategy use Cowan et al. propose the use of tasks that leave little time for rehearsal and chunking between processing episodes as these are more effective measures of working memory (Barrouillet, Bernardin, & Camos 2004; Conlin, Gathercole, & Adams 2005; Friedman & Miyake 2004; Lépine, Barrouillet, & Camos 2005).

An alternative approach as to the most appropriate working memory measure was recently proposed by Cowan, Elliott et al. (2005). They suggest the use of scope-of-attention measures that do not include a separate processing component, but nevertheless prevent rehearsal or grouping of items to be recalled. The researchers argue that attention can be discerned in (at least) two dimensions: the control of attention and its scope, though most research on the relation between working memory and attention has focused primarily on the control of attention. They suggest that an emphasis should be put on the scope of attention as a special form of storage limit as this was proposed by Cowan (2001). Cowan, Elliott et al. (2005) posit that individuals who excel at controlling attention could also have the largest scope of attention and this is effected with an adjustable attention which allows individuals to “zoom in to hold on to a goal in the face of interference” and when the task specificities permit “to zoom out to apprehend multiple items at once” (p.

50). Zooming out allows for more information bits to be covered, but with less intensity or precision of processing of each piece, than a zoomed-in setting. Measuring the scope of attention refers to the number of objects or chunks that can be extracted and held at one time in the focus of attention. The focus of attention is of limited capacity and “it extracts chunks of information from a field of activated features in memory in order to allow an explicit memory response” (p. 51) by constructing representations. The scope of attention measures provide a reasonable alternative or supplement to the storage and processing measures already used in the working memory research. According to the results of the Cowan, Elliott et al. (2005) research, both types of measures correlate with each other and with measures of aptitudes in children and adults. Moreover, the simple digit span test correlates well with aptitudes in second and fourth grade children, but not in older children or adults, since young children are typically unable to rehearse automatically the way that adults do and therefore, their performance on simple digit spans is of high predictive value as for their aptitudes.

It is obvious that the different types of measuring working memory mirror the discrepancies in the notion of working memory capacity. Therefore, before examining some of the models of working memory, a brief account on the contemporary notion of working memory capacity will be presented.

Engle (2002) rejects the notion of capacity as the limited number of items or chunks that can be stored. Working memory capacity reflects individual differences “in the ability to control attention to maintain information in an active, quickly retrievable state” (p. 20) and therefore, it is about maintaining or suppressing information by activating attention. According to this view, greater capacity does not indicate a larger memory store; rather it directly suggests that more items can be maintained as active and thus are in a retrievable state, and it indirectly signifies greater ability to control attention and to efficiently use it to avoid interference and distraction. WM capacity is important in the retention of representations and in determining how many representations can be maintained. Therefore, Engle suggests that measures of working memory capacity should reflect both memory processes and executive attention. Engle, Tuholski, et al. (1999) used structural equation modeling analysis to test whether working memory processes, as they are reflected in the traditional measures of short-term memory span, and working memory capacity can be represented distinctively in a model of the general fluid intelligence. When the variance common to working memory capacity and short term memory span was statistically removed, working memory capacity still correlated with general fluid intelligence, while the left-over short term memory span variance did not correlate with intelligence. This finding strongly suggests that the common variance of the two constructs was due to the common memory processes (such as rehearsal and chunking) underlying the two constructs. The residual variance in working memory capacity would constitute executive attention and it is strongly related to general fluid intelligence.

The strong relation of working memory capacity with the ability of executive attention is evident through various experimental designs where people with varying working memory spans are compared as to their ability to control distracting information and to maintain a goal. When individuals with high and low WM capacity were tested on an highly demanding executive attention task, namely the antisaccade task, the data suggested that the relation of the working memory capacity with the performance on higher-order cognitive tasks is mediated by a domain-free executive-attention system (Kane, Bleckley, Conway, & Engle, 2001). In another study conducted by Kane and Engle (2003) using the Stroop paradigm, it was found that differences in the inhibition ability of individuals with high and low span come to surface only when the context of the task is demanding in attentional resources. The same conclusion was reached in another study conducted by Conway, Cowan, and Bunting (2001) where individuals with low working memory spans were less capable than individuals with high working memory spans of doing the mental work necessary to block distracting information in a highly demanding task, namely the dichotic-listening task, where individuals repeat aloud words presented to one ear while ignoring information presented to the other ear.

Working Memory Capacity

The understanding of working memory capacity has evolved in the last 40 years or so from mere number of items recalled from short term memory, without taking under consideration any other parameters, to introducing a distinction between construct and processes, to distinguishing levels of information processing, and to addressing working memory processing and attentional control as component processes of the general EF construct. George Miller (1956) reviewed the literature on the limitation on short term memory span and came up with ‘the magical number seven, plus or minus two’. His research had led him to the conclusion that healthy adults are able to recall at least five items but no more than eight. He found that expertise can help to overcome working memory limits by associating several information items to form one larger, meaningful group or *chunk*. Miller’s notion of short-term memory capacity was later differentiated from the notion of working memory capacity where emphasis was placed on the processing component of working memory and on the system’s limitations in maintaining information in an active, quickly retrievable state albeit any distraction or shift of attention (e.g. Engle, 2001).

Atkinson and Shiffrin (1968) proposed a seminal model of memory which included three memory stores: a sensory register, a short term store, and a long term store. The short term store was a component analogous to working memory where conscious mental processes are performed (Lachman, Lachman, & Butterfield, 1979). Atkinson and Shiffrin suggested that individuals can successfully recall information that was early or late presented in a serial mode (primary effect and recency effect, respectively) and this phenomenon holds for every number of information presented. In a free recall situation, the items recalled first will be the last few in the item list (recency effect), followed by the first few in the item list (primary effect). If rehearsal is not suppressed, then the first few items will be copied in long term memory from where they will be retrieved, after the other items which had not been copied in the long term memory, will be recalled. In the case where the item recall is delayed, the primary effect is not abolished, unlike the recency effect, since the first presented items had been copied in long term memory and their traces do not decay. Following the Atkinson and Shiffrin modal model other theories on working memory have proposed “shifting the emphasis from the underlying store as the most important factor to the type of processing that was performed” (Neath & Surprenant, 2003).

The first theoretical shift of the emphasis from the working memory store structure to the working memory processing was attempted by Craik and Lockhart (1972). Their thesis was based on the assumption that memory is the result of a series of analyses performed on the information. Each analysis is performed at a deeper level than the previous one. Levels are conceived as points on a continuum which goes from shallow processing, focusing on perceptual features, to deeper semantic meaning processing. When information is analyzed in a deeper level involving meaning then the resulting memory of that information is more durable and can be retrieved more successfully. On the role of rehearsal, Craik and Lockhart point out that when it is limited to simple rote repetition, known as *maintenance rehearsal*, then no memory improvement is observed, no matter how long information had been rehearsed. Rather, when rehearsal induces a deeper level of analysis, known as *elaborative rehearsal*, then memory is drastically improved. Hyde and Jenkins (1973) have experimentally supported most of the assumptions Craik and Lockhart had proposed on the processing perspectives of working memory. Of great importance is their finding that when the participants were involved in a deeper level of information analysis (like reporting how pleasant or unpleasant a word was) they could recall that information more successfully compared with the cases where information was analyzed in a more shallow level (like rating the word frequency). Hyde and Jenkins suggested that when the system is engaged in reflecting on the meaning of the information, then the whole working memory mechanism is activated in a more substantiated way and the resulting memory is more durable. Moreover, in the cases where the participants knew that they would have to recall the information presented, i.e. when the whole working memory process became intentional, there was no significant difference in the information that was recalled compared with the cases of incidental working memory process, where participants were not informed that they would have to recall the information presented to them.

A different view on the relation between level of processing and performance on memory tasks, was suggested by Morris, Bransford and Franks (1977) who demonstrated that it is not always the case that the deeper the level of processing the better the performance. Rather, they claim that what is crucial in the way information is retrieved is the so called *transfer of appropriate processing*. According to this view, better memory performance is a function of how appropriate (for the particular test or the particular kind of information) the type of processing is. The individual uses a variety of processes to deal with the incoming information. The resulting memory largely depends on how appropriate processes were used. Appropriate processes lead to either organization of the incoming information in clusters via *relational processing* or distinctiveness of the information and creation of competing items via *item-specific processing* (Hunt & McDaniel, 1993). Differentiation of the item-to-be-remembered from competing items of information is crucial during the encoding phase, while similarity as a product of organization is mostly important during the retrieval of the information. According to the *encoding specificity principle* proposed by Tulving (1983), this interaction of the processes taking place during encoding and retrieval of information, called ecphory, from a Greek word meaning “to be made known”, determines the outcoming memory result.

Just and Carpenter (1992) have proposed a theory on working memory capacity in which individual differences in the working memory are the consequence of differing levels of available activation. The greater the capacity of an individual’s working memory, the more information the individual has simultaneously available for use when solving problems. As children mature they develop an increase in activational levels and working memory capacity that ultimately results in improved intellectual functioning (Cohen & Sandberg, 1980; Cornoldi, Vecchia, & Tressoldi, 1995). One basic assumption underlying Just and Carpenter’s framework is that the processing demands of a task must be high in order to distinguish individual differences in more complex abilities. Moreover, the theoretical model proposed by Just and Carpenter assumes that different domains of processing (e.g. verbal, quantitative, and spatial) may draw on different pools of activation and thus have different capacities with respect to working memory.

Working Memory Models

Baddeley proposed an influential multi-component model (Baddeley & Hitch, 1974; Baddeley, 1992; 2000) which encompasses a central executive which is an attention controlling system that coordinates and processes the information of the other components of the model, two unimodal storage systems, namely the phonological loop and the visuospatial sketchpad which manipulate and store acoustic information and visual images, respectively, and a multimodal limited capacity system capable of integrating information into unitary episodic representations, the episodic buffer. Repovš and Baddeley (2006) note that the model suggests the fractionation of working memory into independent stores and processes, sheds light on the nature of representations in individual stores, tracks the mechanisms of their maintenance and manipulation, assumes the way the components of working memory relate to each other, and reveals the role they play in other cognitive abilities. Although the model was originally devised to account for adult short-term memory performance it adequately represents the development of memory during the childhood years.

The phonological loop is considered to be the most important contributor to memory span. It consists of two components, a phonological store and an articulatory or subvocal rehearsal process analogous to subvocal speech (Baddeley, 1986). The phonological store can be directly reached via auditory presentation of speech stimuli, and it can also be indirectly reached via phonological codes generated internally for nonauditory stimuli, such as printed words or familiar visual objects (Gathercole, 1998). Conrad (1964) and Wickelgren (1965) argue that the main code in working memory is acoustic, suggesting that individuals use some form of inner speech to remember the sound of the to-be-remembered items. Baddeley conducted a serious of experiments that support the idea that acoustic, as a form of inner speech, is the dominant code in working memory (Baddeley, 1966). Individuals use the second component of the phonological loop, namely the articulatory rehearsal, to rehearse and maintain information in the phonological store of working memory, or even transfer it to long-term memory. Murray (1967) used the procedure known as articulatory suppression to prevent rehearsal and reached the conclusion that inner speech is a mechanism the system uses to rehearse and maintain information in working memory.

Phonological representations decay rapidly in the phonological store, within about 2 seconds, unless they are rehearsed in real time (Baddeley, Thomson, & Buchanan, 1975). Articulatory rehearsal of the decaying phonological representations occurs serially and in real time. Its function is to retrieve and re-articulate the information held in the phonological store by controlling the subvocal rehearsal of it and refresh the memory trace. Thus, the information that can be retained in the working memory is a trade-off between the decay rate and the rehearsal rate. Further, articulatory rehearsal is used to recode or translate information from other modalities in a speech-based code and deposits it in the phonological store. Speech input enters the phonological store automatically.

The capacity of the phonological store is limited by the number of items that can be articulated in the time available before their memory trace decays. However, the actual capacity of the phonological store depends on the characteristics of the items and the phonological nature of the store. Research has shown that similarity in the phonological structure of stimuli gaining access to the phonological store via auditory or visual presentation, substantially impairs the process of information recall, whereas, similarity of meaning has little effect on the recall process. Specifically, Baddeley (1966) conducted a study comparing the performance on recalling four lists of words, two of which were the control lists and the other two had words that were acoustically and semantically similar, respectively. Similarity of sound resulted in very poor performance while similarity of meaning had very little effect on the performance when compared to the performance on the respective control list. On the other hand, similarity of meaning affects the long-term learning of such information, whereas the similarity of sound has no such effect on learning (Baddeley, 1966). Therefore, information is maintained within the phonological loop in terms of its sound characteristics.

The key role of articulatory rehearsal in maintaining the information and preventing its decay is supported by two prevalent phenomena that have been extensively studied and replicated by different researchers and under various conditions. The first one is the *word length effect* which refers to the direct effect the length of the words has on the ability of the individual to recall a list of words in terms of time and accuracy. As the length of the words in terms of pronunciation time, increases, the ability to recall those words, declines (Baddeley, Thomson, & Buchanan, 1975). This phenomenon was interpreted as reflecting the result of the subvocal rehearsal component of the phonological loop as the delay between successive rehearsals of lengthier words within the phonological store, allows for more loss of information. An interesting equation relating memory span with articulation rate and the duration of the word (verbal) trace has been proposed by Schweickert, Guentert, and Hersberger (1990). They suggest that memory span, *s*, for verbal verbs of type *i* is a linear function of the pronunciation rate, *r*, and the duration of the verbal trace, *t*. The relationship is described in the equation $s_i = r_i t$. From this equation the duration of the verbal trace has been yielded in various studies, with consistent mean 1.6s. This time value is close to the estimation of Baddeley et al. (1975) on the maximum time phonological representations of memory items can remain in the phonological store before they decay. Specifically, it is proposed that phonological representations decay rapidly within 2 seconds if unrehearsed. As Cowan (1995) comments, the word-length effect is "the best remaining solid evidence in favor of temporary storage" (p. 42).

The imperative role of time as a catalytic factor in the decay of phonological representations of memory items is reflected in the vast amount of research findings on the relation of memory span with speed of processing. Kail and Salthouse (1994) suggest that throughout the life span age-related changes in working memory and other cognitive abilities result from a developmental increase, and then decrease, in the speed of processing, reflecting the improvement of neural efficiency with maturation in childhood and its decline later with aging. It is proposed that individuals with high working memory span rehearse information more quickly before it can decay from the phonological store, and therefore speed of processing may be a sound criterion distinguishing between individuals in terms of their working memory. In a study conducted by Cowan, Wood, Wood, Keller, Nugent, and Keller (1998), a more refined approach was followed in order to demystify the role of speed of processing in the functioning of working memory. Using structural equation modeling the researchers found that retrieval and rehearsal speed were unrelated to each other. However, they both were related to working memory (digit) span with path coefficients equal to .41 and .49, respectively. These relations, together, accounted for 87% of the age-related variance in digit span and 60% of its total variance. Though these correlations are by no means evidence of causation, they provide a strong argument on the role of processing efficiency in working memory.

The word length effect is eliminated when articulatory rehearsal of the to-be-remembered items is disabled by requiring individuals to engage in irrelevant articulation during the memory task, a procedure known as *articulatory suppression* (Baddeley, Lewis, & Vallar, 1984; Baddeley et al., 1975). It is argued that in articulatory suppression, the rehearsal process that would take place in real time to refresh the decaying memory traces within the phonological store cannot be engaged and so the word length effect is abolished.

Under the articulatory suppression condition the ability to remember items, still exists, though significantly impaired, suggesting that "there are other possible ways of storing verbal information, one candidate being the episodic buffer" (Repovš & Baddeley, 2006, p. 8). But, in the case of auditory presentation of list items the phonological similarity effect is not abolished under the articulatory suppression condition suggesting that speech has automatic access to the phonological store, bypassing the articulatory rehearsal process. Visually presented items cannot bypass the articulatory rehearsal process, and are therefore, subjected to the effects related to it.

The visuospatial sketchpad maintains and manipulates visual and spatial information such as shape, colour, and movement. Logie (1995) has proposed that this working memory component has two subcomponents: a visual store and a spatial mechanism. Although memory material cannot be decisively characterized in terms of either visual or spatial features, the separability of the visuospatial sketchpad into these two distinct subcomponents for discrete processing of visual and spatial features is consistent with findings from the neuropsychological and cognitive research on the dissimilar ways with which the system preserves visual and spatial memories (Farah, Hamond, Levine, & Calvanio, 1988; Hanley, Young, & Pearson, 1991). For example, Della Sala, Gray, Baddeley, Allemano and Wilson, (1999) have shown that a spatial interference task disrupts performance on a spatial working memory test (the Corsi block), while it has no effect on a visual working memory test (the visual patterns), while a visual interference task has the opposite effect.

The visual subsystem preserves representations that are based on a small number of different basic features such as shape, color, and orientation, in parallel stores specific for each feature. Then, the system binds together the stored individual features into integrated object representations and activates attentional mechanisms to maintain those representations (Repovš & Baddeley, 2006). The encoding of visual information in working memory is related to the perceptual features and the visual imagery which is shaped based on previous experience such as category learning. Wagar and Dixon (2005) explored whether the specific features involved in category judgment and learning, affect visual encoding and maintenance in working memory. Their findings suggest that previous experience and learning significantly affects the encoding of information into working memory.

Visual information that enters the visuospatial sketchpad of working memory is mediated by bottom-up features of visual information such as visual cues that automatically influence the transfer of visual information into working memory (Schmidt-

Atzert & Bühner, 2000), perceptual organization of visual input based on the gestalt principles of proximity and connectedness (Woodman et al., 2003) and object-based feature binding (Xu, 2002). The maintenance of information in visual – not spatial – working memory is disrupted when irrelevant pictures, causing visual noise, are presented to the individuals (Della Sala, Gray, Baddeley, Allemano, & Wilson, 1999) indicating the dependence of visual memory on the perceptual features of the stimuli. McConnell and Quinn (2000; 2004) showed that the degree of interference caused by the interfering display is determined by the complexity of the visual noise. McConnell and Quinn suggest that the visual subcomponent of the visuospatial sketchpad is directly accessible by externally presented visual interference, bypassing higher-level knowledge-based analysis.

On the other hand, spatial working memory is closely related to spatial attention Baddeley (1986). Studies of visual search reveal the close relation between spatial working memory and attention (Woodman & Luck, 2004; Oh & Kim, 2004). The efficiency of visual search and the accuracy of the visual working memory task were not affected by the concurrent presence of a visual working memory task, but the concurrent spatial working memory task reduced both the efficiency of visual search and the accuracy of the spatial working memory task. It is suggested that visual search and active maintenance of information in spatial working memory rely on a common resource, which could be spatial attention or a common system for representing spatial information. The role of spatial selective attention in spatial working memory was studied by Awh and Jonides (2001) who concluded that spatial attention contributes to keeping spatial information active in working memory since it functions as a rehearsal mechanism. Eye (Baddeley, 1986) and body movements (Pearson, Logie, & Gilhooly, 1999) cause shifts of spatial attention, resulting in interference within spatial working memory (Smyth, 1996). Though Lawrence, Myerson, Oonk and Abrams (2001) suggested that all spatial movements produce similar effects on spatial working memory, and therefore, a common mechanism of interference, such as the shifting of spatial attention, is proposed, Pearson and Sahraie (2003) and Lawrence, Myerson, and Abrams (2004) suggested that the interference associated with eye movements cannot be explained only in terms of shifts of attention.

The least empirically studied component of the multi-component working memory model is the central executive (Baddeley, 1986; 1996). It was initially conceived as a limited capacity pool of general processing resources, but its role in the functioning of working memory, its interaction with the phonological loop and the visuospatial subsystems, and its relation with other cognitive functions remained vague for many years (Gathercole, 1998). Baddeley (1996) suggests that the central executive can be f*ractionated in four functions:* the ability to focus attention, to divide and to switch attention, and the ability to relate the contents of working and long-term memory. The ability to relate the content of working memory to long-term memory has been subsequently transferred to a new component of working memory, the episodic buffer (Baddeley, 2000). The central executive of the multi-model proposed by Baddeley is closely related to the functions ascribed to the EF, which were presented earlier. It is strongly involved in the manipulation of information within the stores. While simple representation and maintenance of the information are independent processes, the central executive is involved when the complex binding and integration of information is needed. The central executive acts as a source of attentional control in complex cognitive abilities. The other components of working memory act supportively to the function of central executive. The phonological loop maintains execution programs or representational rules, while the visuospatial sketchpad is involved in guiding visual and spatial attention.

The episodic buffer was added to the multicomponent model of working memory in order to accommodate research findings and theoretical questions that the other components of the model could not address. It is assumed to be “a limited-capacity temporary storage system that is capable of intergrading information from a variety of sources” (Baddeley, 2000, p. 421) into unitary multi-dimensional representations using a multi-modal code. It integrates information from the other working memory components and the long-term memory into more complex structures, namely scenes or episodes. It serves as a mediator between subsystems with different codes. The limited capacity of the attentional system, namely the central executive, affects the integration and maintenance of information within the episodic buffer. The process of retrieving and binding information from multiple sources and modalities is primarily based on conscious awareness. Repovš and Baddeley (2006) suggest that in order to explore the episodic buffer and its role in cognition two classes of tasks must be developed, namely measures of capacity and interference tasks. Prabhakaran, Narayanan, Zhao and Gabrieli (2000) devised a task that required concurrent maintenance of presented letters and locations. The results of their study confirmed the existence of a memory buffer which allows for the reflection on the retrieved information, its manipulation, its modification and integration, and its short-term maintenance.

The Development of Working Memory

Developmental changes in working memory are observed over the course of childhood and through adolescence where adult levels of performance are reached (Hitch, Halliday, Dodd, & Littler, 1989; Luna, Garver, Urban, Lazar, & Sweeney, 2004). Phonological memory increases significantly over the early and middle years of childhood. The memory spam of the 4-year-old children is about two or three items and it increases to about six items at 12 years (Gathercole, 1998). At the other end of the continuum, age-related declines in verbal, spatial, and visual working memory have been observed leading to the conclusion that older adults consistently recall fewer items (see Shaw, Helmes, & Mitchell 2006).

Though in school-aged children developmental changes in the ability to maintain information online are observed (Cowan, 1997), the most impressive changes are observed when children have to manipulate information, or activate control functions during this process (Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006). Neuroimaging studies have shown that development of working memory co-occurs with functional age-related changes of lateral PFC (Klingberg, Forssberg, & Westerberg, 2002; Kwon, Reiss, & Menon, 2002). Luna, Garver, Urban, Lazar and Sweeney (2004) have studied cognitive maturation by addressing the developmental profile of processing speed, voluntary response suppression, and spatial working memory and their functional interplay in 245 individuals aged from 8- to 30-years-old. Steep improvement of development was observed in the younger ages followed by stabilization in adolescence when adult level performance began. Specifically, for processing speed, response inhibition, and working memory adult level performance was attained at approximately 15, 14, and 19 years of age, respectively. The study revealed, in accordance with other studies (Demetriou et al., 2002) that processing speed influences the development of working memory. Moreover, it was revealed that the development of response suppression and working memory were interdependent.

Based on Baddeley's model, the phonological working memory has two sub-components, the store and the rehearsal, which seem to have distinct developmental courses. The phonological store component is present from early childhood, while the subvocal rehearsal process does not emerge until about the age of 7 years (Gathercole & Hitch, 1993). Prior to that age, serial recall performance is mediated by the phonological store component of the phonological loop. The developmental change in the use of the articulatory rehearsal strategy to maintain the contents of the phonological store is well documented. Research studies have shown that children between 3 and 5 years of age are prone to the word phonological similarity and the word length effect when tested in a serial word recall of auditorily presented items. But, when the items are presented to them in pictures, the recall of their labels, even if they are lengthy in articulatory duration or are phonologically similar to one another, is not impaired, relative to children aged 7 years and older (Ford & Silber, 1994; Gathercole & Adams, 1994; Hitch & Halliday, 1983). It seems that picture stimuli are not recoded into the phonological form, and therefore, young children try to remember these memory items in terms of their visual characteristics (Hitch, Halliday, Schaafstal, & Schraagen, 1988; Longoni & Scalisi, 1994). Further evidence on the development of articulatory rehearsal is provided by studies in which measures of both auditory memory span and of the articulation rate of the memory items were taken. These studies revealed a non-positive correlation between articulation rate and memory span for children below 7 years of age (Cowan, Keller, et al., 1994; Gathercole & Adams, 1993; Gathercole, Adams, & Hitch, 1994; Henry, 1994), whereas strongly positive associations are found when adults are tested under the same conditions (Gathercole et al., 1994).

After the age of 7 years, children begin to use the rehearsal strategy and employ it to maintain items in the phonological store. Non-auditory memory items are recoded into a phonological code and are subjected to the articulatory rehearsal process. As a result, the phonological store span increases. However, developmental increases in memory span are observed in children younger than 7 years of age. Gathercole and Adams (1994) tried to explain this memory span development based on changes in articulation rates at recall and, consequently, the reduction of the decay of memory items in the phonological store prior to output. Two studies have tested this hypothetical explanation, and found that changes in articulation rates can only partially account of the increase in memory span during early childhood (Henry & Millar, 1991; Roodenrys, Hulme, & Brown, 1993). Both studies have concluded that even after controlling the differences in the articulation rates between younger and older children, residual differences in memory span still existed. A promising explanation as to what accounts for these residual differences in memory span comes from research on the *lexicality effect* which refers to the substantial recall advantage to verbal memory sequences containing familiar words, over sequences containing nonwords, when the stimuli do not differ in articulatory duration or in the amount of phonological information (Hulme, Maughan, & Brown, 1991). In a series of studies conducted by Hulme and colleagues it was suggested that although both the phonological knowledge and the non-phonological features of the words are knowledge stored in long-term memory, the lexicality effect is mediated by the phonological knowledge about the sounds of words rather than by the non-phonological features, such as the meaning (Brown & Hulme, 1992; Hulme et al., 1991). Moreover, it is suggested that long-term knowledge about the structure of the native language and the probabilistic structure of sound combinations in the language mediates memory performance (Gathercole, 1995; Gathercole & Martin, 1996; Gathercole, Willis, Emslie, & Baddeley, 1991). As children grow, their native language vocabulary expands and, thus, they acquire better knowledge about the phonotactic properties of the language. As a result, phonological loop representations are enhanced and item retrieval is improved. Vocabulary acquisition (Gathercole & Baddeley, 1989; 1993; Gathercole, Willis, Emslie, & Baddeley, 1992; Michas & Henry, 1994) and speech production (Adams & Gathercole, 1995; 1996) also account for the high degree of variability of phonological memory capacity across children at any chronological point. This finding suggests that language learning is primarily supported by the function of the phonological loop (Gathercole & Baddeley, 1993).

Younger children are more dependent than older children or adults on using the sketchpad in recalling visual material from working memory as they are not able to generate phonological codes for visual items (Hitch et al., 1988). Contrary to younger children who rely on their recall of the purely visuospatial characteristics of the memory stimuli, older children use the phonological loop to mediate recall of visual memory items that were verbally recoded and sent to the phonological store. In order to assess the development of visuospatial memory the tendency to verbally recode visual information must be controlled or diminished. To this end, memory tasks need to present stimuli that do not correspond to familiar items so that the individual will not be able to recode it into phonological form. Wilson, Scott and Power (1987) studied the development of the visual component of the sketchpad using one such memory task, namely the pattern span task. Participants were presented with a two dimensional pattern composed of squares. Some were filled and some were unfilled. In the partial recall variant of the test, which was used by Wilson, Scott and Power, the participant needs to identify the original location of a missing filled block in a pattern that is identical to the original pattern except from the missing block. The number of blocks in the test pattern is progressively increased until the participant's memory accuracy falls below a criterion level. Memory span is assumed to be reflected in the number of blocks reliably remembered. Wilson et al. (1987) showed that visual memory span increases substantially and regularly between 5 years, when the mean pattern span was about 4 blocks, and 11 years when adult levels of performance are achieved with mean pattern spam around 14 blocks. Miles, Morgan, Milne, and Morris (1996) reached similar developmental patterns of visual span in a study they conducted using two other variant of the visual pattern task, namely the recognition (in which the participants had to judge which of a pair of patterns had been previously presented) and free recall (in which a blank matrix was presented, and participants had to point to the squares that were filled in the originally presented pattern). Both variants of the test yielded the same developmental profile of the visual memory span across groups of children aged 5, 7, and 10 years, and adults. In all age cohorts studied, span estimates were lower in the free recall condition of the test.

Despite the seemingly nonverbal nature of the pattern span findings resulting from these studies, Wilson et al. (1987) tested the hypothesis that the developmental increase in pattern span can be attributed to the contribution of memory components other than the visuospatial sketchpad. Specifically, Wilson et al. found that the visual memory span was significantly decreased when the pattern span test was tested under concurrent task conditions by introducing a 10-second interval of spoken arithmetic related activity (backward counting for older participants, forward counting for the youngest age group) between presentation of the pattern and recalling it,. Moreover, it was found that the magnitude of this disruption increased progressively between 5 and 11 years. These findings strongly suggest that the involvement of the central executive by forcing the participants to engage in irrelevant mental arithmetic (Baddeley & Hitch, 1974), and the articulatory suppression forced by the irrelevant articulation (Baddeley et al., 1975) affect working memory in the pattern span task for older children and adults. Therefore, the developmental increase in visual span can be partly attributed to an increase in the sketchpad capacity per se and partly to the use of nonvisual strategies emanating from the phonological loop and the central executive.

The development of spatial memory has been mainly studied by using the Corsi blocks task. A three dimensional display of nine blocks is placed in front of the participant. The aim is to reproduce, the pattern of the blocks previously tapped by the experimenter by tapping the same blocks in the same sequence. A span estimate is obtained as the number of blocks reliably reproduced in the correct sequence. Isaacs and Vargha-Khadem (1989) used the Corsi task to study the development of spatial memory spans of children aged between 7 and 15 years. Children were tested on both the forward and the backward recall of the pattern blocks. An important finding of this study was that Corsi spatial span is equivalent in both variants of the test indicating that spatial order information is extracted in a fundamentally different manner than verbal and visual order information.

In another study on the relationships between children's capacities to retain phonological, visual, and spatial information in short-term memory (Pickering, Gathercole, Hall, & Lloyd, 2001) measures of the pattern span, the Corsi block recall, and digit span were taken. The yielded scores were uncorrelated with one another, suggesting that the phonological, visual, and spatial memory capacities are dissociable since early childhood. Subsequently, the researchers used versions of the pattern span and Corsi blocks tasks that were comparable in terms of information content and paradigms employed. The obtained scores from the two tasks were uncorrelated with one another, suggesting that different memory capacities may underpin visuospatial memory. Age-related increases in span were observed in both tasks. Visual span, obtained from the pattern span task, was much steeper than the spatial span task, though the two span estimates were similar in the youngest age groups. The sheer increase in pattern span with age may reflect the increasing use by older children of nonvisual strategies to enhance their visual memory, as it was proposed by Wilson et al. (1987) and Miles et al. (1996). These findings could reflect a more basic functional distinction in the way information is processed. It could be the case that verbal, and probably visual, information is serially processed whereas spatial information is submitted into parallel processing. Furthermore, it could be the case that there are different developmental rates for the brain systems that accommodate serial versus parallel processing.

The Relation of Working Memory with Intelligence

The nature of the relation of working memory with intelligence is a most important issue within the cognitive and the developmental literature. Various research studies have been conducted aiming at elucidating this relation and giving answers to the questions raised in regards to this relation and its parameters. Working memory relations with general intelligence factor or Spearman's *g*, fluid intelligence, and reasoning ability, have been used as means to unravel intelligence and understand its relation with working memory. Through this procedure the central role of working memory in the architecture of human intelligence is exemplified.

Of great importance to understanding the relation between working memory and intelligence is the study conducted by Oberauer, Süß, Schulze, Wilhelm and Wittmann (2000) which provides important insights into the specificities of this relation. A set of 23 working memory tests that represented a sampling of stimulus content (verbal, numerical, and spatial-figural) and the underlying simple and executive functions of working memory (storage and transformation, supervision, and coordination), and a set of 45 ability tests were administered to 128 participants. Three WM factors (a verbal-numerical factor, a spatial-figural factor, and a supervisory functions factor reflecting a mixture of variance due to mental speed and to supervisory functions of the central executive) and various intellectual ability factors (reasoning ability, content abilities (verbal, numerical, and spatial), and processing speed) were derived. Specifically, processing speed had a correlation of .31, .19, and .61 with the three working memory factors, namely the verbal-numerical, the spatial-figural and the supervisory-functions, respectively. All intellectual content ability factors, namely the numerical, the verbal, and the spatial, significantly correlated with all three working memory factors (correlations ranging from .28 to .58) with the only exception being the correlation between the verbal ability factor with the spatial-figural working memory (.08), a correlation that could be explained by the absence of the articulatory rehearsal strategy in processing spatial memory items. Finally, the reasoning ability factor had a correlation of .42, .56, and .41 with the verbal-numerical, the spatial-figural and the supervisory-speed memory factors, respectively. The extracted correlations suggest that working memory, as a multifaceted construct that is better represented based on the memory contents and the complexity of the activated processes, has a differentiated pattern of relations with the various intellectual abilities (Oberauer et al., 2000).

In as far as the relation of working memory with the *g* factor, Ackerman, Beier, and Boyle (2002) provide an interesting pattern of correlations. Specifically, working memory had a correlation with the *g* factor of .70, while when the performance on the Raven test, a test highly tapping inductive reasoning, was excluded from the *g* composite, the correlation dropped to .47. Furthermore, based on a meta-analysis of 86 independent samples and 9,778 participants conducted by Ackerman, Beier and Boyle (2005) the hypothesis of an isomorphic relationship between working memory and *g* was rejected, since their maximum correlation, corrected for unreliability, was .614. As Ackerman et al. (2005, p. 34) note “the opinions regarding the isomorphic relationship between WM and *g* (or *gf*) are changing”.

Oberauer, Schulze, Wilhelm and Süß (2005) provide a coherent explanation as to why the search for correlation between working memory and the *g* factor is characterized by much discrepancy in the reported correlations. Oberauer et al. (2005) note that working memory (Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980) was first conceptualized as short-term memory. The tasks used to measure working memory capacity have been constructed to reflect processes postulated in the various working memory theories, and therefore much variability is observed in the tasks used, while, at the same time, there is an ongoing discussion on what makes a good measure of working memory. In line with the Oberauer et al. (2005) rational, Colom, Rebollo, Palacios, Juan-Espinosa and Kyllonen (2004) study the relation of working memory (as a construct comprising executive processes) and *g* (as it is reflected in crystallized and fluid intelligence, spatial ability, and psychometric speed). Though a high correlation (.93) was yielded between working memory and the *g* factor, the researchers are skeptical in characterizing the most basic component of working memory as the essence of *g*. This component is responsible for monitoring the operations performed on working memory and maintaining the rule representation necessary for any problem solving task. However, Colom et al. (2004) suggest that working memory tasks should be able to separate the effect of temporary storage from executive control processing so that those two facets of working memory will be independently correlated with *g*. Then the isomorphic relation between working memory and *g* will be better tested.

The discussion as to what the *g* factor seems everlasting. From Spearman's (1904) initial theory of intelligence and the general mental ability factor, which he believed to correspond to a fixed amount of "mental energy" an individual can assign to different mental tasks, to the inductive approach that *g* is implied by the positive correlations between several ability measures, intelligence researchers happened to construct and use over a century, and that it represents the general efficacy of the individual's intellectual processes, "*g* reflects a mixture of the mostly implicit theories of intelligence various researchers have endorsed and their intuitions about ways to test it" (Oberauer, Schulze, Wilhelm, & Süß, 2005, p. 64). No theory-based procedure for measuring it and no single test with which *g* can be identified with exist. Nevertheless, many researchers have used the Raven's Progressive Matrices Test as a marker for fluid intelligence (since it is considered an outstanding measure of reasoning about spatial features and relations) and a good approximation to *g*, to study its relation with working memory, even if the yielded correlation can be contaminated by test-specific variance (Ackerman et al., 2005).

The radical claim of Kyllonen and Christal (1990) that reasoning is a little more than WM capacity, based on the high estimates of the correlation between WM and reasoning ability (.80 to .90), clearly suggested an isomorphic relation between working memory and fluid intelligence and a close dependency of reasoning and problem solving on the conscious contents of working memory. Since the publication of the Kyllonen and Christal (1990) paper, much research has been done in order to clarify what mediates the working memory and reasoning relation.

Salthouse (1993) examined the correlation between each item on Raven with both age and a composite measure of working memory. He found that the correlation between the accuracy on each Raven item and working memory was fairly constant across all items and that the correlation of age with Raven performance was again constant. The fact that Raven items are hierarchically presented based on their complexity, makes these findings mostly interesting. Item complexity seems not to mediate the working memory and Raven performance relation. In a subsequent study Salthouse (2000) found that more difficult items do share some unique variance with age. Salthouse suggests that item complexity accounts for a small part of the shared variance in both working memory and age and that some other factor mediates the relation between working memory and reasoning.

In an attempt to find which that mediator factor is Carpenter, Just, and Shell (1990) attempted to distillate the notion of item complexity. Specifically, they performed a thorough item complexity analysis of the Raven test and found that the number of rule tokens an individual needs to complete a task defines each item's complexity. Therefore, the most difficult problems are those requiring the most rule tokens. Based on the substantial role of working memory in maintaining representational rules, it is obvious that the most difficult problems place a heavy load on working memory resources. Therefore, as Carpenter et al. (1990) suggested, the number of items that can be maintained in working memory accounts for the common variance between reasoning and measures of working memory. Babcock (2002) reached the same conclusion as the one proposed by Carpenter et al. (1990) by investigating developmental changes on reasoning ability in adults (using the Raven test) and by examining the rules required to solve each task. Babcock suggested that developmental differences on reasoning are due to quantitative rather than qualitative differences in the overall amount of processing resources available and, thus, the amount of memory items that can be maintained in working memory. In a recent study, Unsworth and Engle (2005) examined the role of individual differences in working memory capacity and reasoning (using the Raven test) and tested the hypothesis that the correlation between working memory and measures of fluid intelligence is mediated by the number of representational rules that can be held in working memory. A total of 160 participants between the ages of 18 and 35 were tested. The results, consistent with the work of Salthouse (1993), demonstrated that item variations in complexity do not account for the shared variance. Individual differences in working memory capacity did not result in differential performance in terms of item complexity. The inconsistency of the results in regards to the role of item complexity and working memory load in the relation of working memory with reasoning suggests that this relation is probably mediated by other factors too.

Some theorists posit that processing speed accounts for the relationship between working memory and fluid intelligence (Fry & Hale, 1996; Jensen, 1998; Kail & Salthouse, 1994; Salthouse, 1996) since encoding, transforming, and retrieving information within working memory takes time and the faster the rate of processing, the greater the amount of information that can be processed. Other theorists posit that the real contribution of working memory in fluid intelligence can be traced when a subtle distinction between the short-term memory and working memory constructs is achieved (Engle, Tuholski, et al., 1999).

Conway, Cowan, Bunting, Therriault and Minkoff (2002) explored the complex relationship that exists between working memory capacity, short-term memory capacity, processing speed, and fluid intelligence and aimed at identifying the primary contributor to individual differences in fluid intelligence. A very strong correlation between working memory capacity and general fluid intelligence was observed, in accordance to previous findings (Carpenter et al., 1990; Engle, Tuholski, et al., 1999; Kyllonen, 1996; Kyllonen & Christal, 1990), while short-term memory, clearly distinguished from working memory capacity, did not correlate significantly with fluid intelligence. Sheer speed of processing measures, that place minimal demands on memory and attention, do not significantly correlate with fluid intelligence. The absence of significant correlation between short-term memory capacity and speed of processing with fluid intelligence stand opposite to the results of previous studies (for reviews, see Jensen, 1998). Conway et al. (2002) suggest that the main reason for this discrepancy lies in the methodological considerations of those studies. Specifically, they may not have administered pure measures of short-term memory capacity and of speed of processing; rather, it is assumed that their measures were contaminated by their attention control variance.

Cowan and his associates (Cowan et al., 2007; Cowan, Elliott et al., 2005) investigated the nature of the executive function that probably acts as a mediator in the working memory – fluid intelligence relation. They suggest that the general ability to focus attention according to the task demands and the flexibility to *zoom out* to capture the maximum number of items, or *zoom in* to maintain its attention on the target diverting any possible interference, mediate the relation of working memory with fluid intelligence (Cowan et al., 2007). Other theorists provide a more specific account on the nature of the mediator (Engle, Tuholski, et al., 1999; Kane et al., 2001; 2004; Unsworth & Engle, 2005). They suggest that the ability to control attention, which strongly relies on the central executive component of working memory, is responsible for the relation of working memory with intelligence. The central executive component maintains activation to goal-relevant information and inhibits goal-irrelevant information. When the central executive is not actively involved in memory span tasks, that is, when automatized routines and well-learned strategies, such as rehearsal and chunking, are activated, then individual differences in performance cannot be related to fluid intelligence variance. According to Conway et al. (2002), complex tasks, such as the Ravens, highly correlate with fluid intelligence because they demand the discovery and maintenance of goal-relevant rules while processing new rules and filtering out irrelevant features. Engle (2002, p. 20) postulates that “greater working memory capacity does mean that more items can be maintained as active, but this is a result of greater ability to control attention, not a larger memory store. Thus, greater working memory capacity also means greater ability to use attention to avoid distraction”. Therefore, the missing link between working memory and fluid intelligence is the ability to keep a representation active (Engle, Tuholski, et al., 1999) via controlled attention.

Finally, it should be noted that domain-specific experience could be associated with a more sophisticated repertoire of strategies, a notion known as the *long-term working memory* (Ericsson & Kintsch, 1995), allowing for more efficient knowledge representations, and more flexibility in strategy deployment (Ericsson & Delaney, 1999). Individual differences in strategy deployment contribute to the variance observed in working memory and fluid intelligence (Mathews, Hunt, & MacLeod, 1980; Rogers, Hertzog, & Fisk, 2000). The domain-specific experience and the accumulated knowledge on when and how to use strategies are closely related to learning ability. Verguts and De Boeck (2002) suggested that learning the correct solution strategies and then utilizing them across future problems of a similar type can explain a part of the shared variance between working memory and intelligence. Consistent with this view is the evidence obtained by Carlstedt, Gustafsson, and Ullstadius (2000) that an intelligence test made up of homogenous items loaded higher on a general intelligence factor than did a similar test made up of heterogeneous items.

Reasoning Ability

During the course of history humans developed, in terms of reasoning, a self-constrained thinking based on justifiable, logical inferences (Moshman, in press). They moved from using myths to describe and understand the physical world to attempting to reason about the world’s systems and phenomena, and to reason about their own reasoning. At the core of reasoning lies the ability for logical argumentation, that is, the ability to produce and to evaluate arguments using their validity as the only criterion. The validity of an argument depends on its logical structure as opposed to the content of the propositions. All arguments are based on the claim that a group of propositions, namely the premises, provide some grounds for accepting another proposition, namely the conclusion. Philosophers have classified arguments into two broad categories based on the nature of the relationship between premise and conclusion. Deductive arguments assert that their premises provide absolute grounds for accepting the conclusion while inductive arguments assert that their premises provide only limited grounds for accepting the conclusion. By definition, a valid deduction yields a conclusion that follows necessarily from true premises and inductive arguments assert that the conclusion follows not necessarily but only probably from the truth of the premises. Inductive arguments are deductively invalid. The premises of an inductive argument are believed to support the conclusion but do not entail it, i.e. they do not ensure its truth. A strong induction is thus an argument in which the truth of the premises would make the truth of the conclusion probable, but not definite. An argument which is deductively invalid may be understood as an inductive argument which attempts to affirm a probable conclusion.

Induction and deduction can be distinguished in terms of the semantic information they convey. Induction is a thought process that aims to draw a plausible conclusion from particular observations or premises. It increases semantic information, although it is a *deductively closed* process, that is, there is not sufficient information to undeniably determine the truth value of the semantic information introduced by the conclusion. Deduction is a systematic process that leads to the formulation of a conclusion based on the assumption that the given premises are true. Deduction does not increase semantic information and the conclusion within the deductive argument is not influenced by any additional premise. On the other hand, additional premise may alter the strength of an inductive conclusion.

Inductive Reasoning

Induction is the reasoning process that encompasses various, seemingly different, inferential laws that are activated in order to induce a conclusion. All inductive inferential laws have a common characteristic, namely they produce assumptions that are transformed into certainties. As a result emanating from this transformation, the conclusion is not undeniably true. As the possibility that the conclusion is true is getting bigger, the inductive argument is getting stronger. An inductive argument can never be deductively valid, since the possibility of a true conclusion will, in the best case, be asymptotically approaching unity, but it will never really reach it. During the inductive reasoning process, the individual formulates laws and makes generalizations based on specific propositions that refer to individual instances, observations and experiences. This process is identified via different inferential types, namely generalization, statistical syllogism, simple induction, argument from analogy, causal inference, and prediction.

An inductive argument leads to a generalization when it proceeds from a premise about a sample to a conclusion about the population. In other words, it induces the universal from the particular. The strength and the credibility which the premises provide for the conclusion, is dependent on the number of individuals in the sample group compared to the number in the population and on the randomness of the sample. Hasty generalization is a fallacy in which an individual either reaches a generalization based on insufficient evidence or bases a broad conclusion upon the statistics of a survey of a small group that fails to sufficiently represent the whole population. Another fallacy related to inductive generalization is the biased sample, where the statistical sample of the underlying population is not a reasonable approximation to a random sample. A second type of inductive reasoning is the statistical syllogism which proceeds from a generalization (usually accompanied by a qualifying term e.g. “some”, “many”, “often” etc.) to a conclusion about an individual based on that generalization. Simple induction is a third type of inductive reasoning which proceeds from a premise about a sample group to a conclusion about another individual. This type of reasoning is a combination of a generalization and a statistical syllogism, where the conclusion of the generalization is also the first premise of the statistical syllogism.

An analogy is a common type of inductive reasoning. It proceeds from known similarities between two entities to a conclusion about an additional attribute common to both entities. The more relevant the similarities are the more probable the conclusion is. *False analogy* refers to a fallacy where the two entities may be similar in one respect but not in another. Finally, causal inference and prediction are two other types of inductive reasoning that are often used. In causal inference, the individual draws a conclusion about a causal connection between two entities based on their coexistence or their correlation, while in prediction a conclusion about a future event is drawn based on a past sample.

According to Polya (1968), inductive reasoning is based on various inferential schemas two of which are mostly important because they are used in deductive reasoning as well. The first inferential schema is the so called Denying the Antecedent where a conjecture A, that is, a proposition (or a set of propositions) presumed to be true based on inconclusive grounds, implies a consequence B. If B is proven to be wrong, then the conjecture A is proven to be wrong too. The second inferential schema is the so called Affirming the Consequence where if consequence B is proven to be true, then the conjecture A is getting more reliable. This is the most important inferential schema in inductive reasoning. Conjecture A is becoming increasingly more reliable as a function of the number and the nature of its consequences that are proven true. Specifically, as more consequences are proven true, the conjecture A is getting stronger. Moreover, the more different (or less probable to happen) from the other consequences a newly confirmed consequence is, the more reliable the conjecture becomes. Polya also suggests that the reliability of a conjecture can be determined in respect to the true value of another conjecture that is analogous to the first one. Specifically, if conjecture A, is analogous to conjecture B, then conjecture A is becoming more reliable if conjecture B is proven to be true. Moreover, if conjectures A and B are incompatible and conjecture B is proven to be wrong, the conjecture becomes more reliable.

Most of the studies on inductive reasoning in children use tests which strongly activate the categorization skills and the conceptual repertoire. Inductive inferences are strongly based on individual's knowledge of the properties the typical members of a category process and on the range of the conceptual repertoire they have. Inductive inferences can be made very early in life. Gelman studied the ability of 2-, 3-and 4- year olds to perform inductive inferences about the properties of typical and atypical members of a familiar category, in two different studies (Gelman & Coley, 1990; Gelman & Markman, 1986). The results of these studies suggest that young children are primarily capable of successfully applying inferential processes based on typicality. They make their inferences according to typical member inclusion in a category based on strong perceptual similarities, even though they are also capable (to a lesser degree) to infer based on relational similarity and general knowledge. Older children (Gutheil & Gelman, 1997), at the age of 8 to 10 years, begin to be affected by the sample size effect, which is the number of observations upon which the inductive inference is based, yet they are still more affected by the category inclusion properties rather than by the number of observations. Category inclusion properties drive the reasoners' inferences in a differentiated way according to the nature of the properties.

Another form of inductive reasoning, which is also based to a significant extent to the available knowledge of properties and relations, is analogical reasoning. Analogy is based on the comparison of the structure of two (or more) relational representations (Hummel & Holyoak, 1997), thus it is greatly based on the functions of working memory and especially on the functions of its central executive component. Central executive controls which pieces of relational information will be retrieved from long-term memory and which will remain active throughout the whole reasoning process. This process is greatly affected by the way the relational information is structured in long-term memory and the extent to which the individual appreciates the fine differences that exist between different mental representations that are relationally similar. Central executive also monitors the correspondences between elements of the source and elements of the target.

Analogical reasoning in children is supported by the perceptual similarity between the elements of an analogy though it often works as a bound in their inductive reasoning (Gentner & Toupin, 1986). For this reason, researchers often use tests where perceptual similarity is controlled in order to study a different level of similarity, namely the relational similarity, and how it constraints the analogical reasoning process. Goswami and Brown (1989; 1990) have studied the analogical ability of preschool children (4- to 5-year olds) as well as of school-age children (6- and 9-year olds). They have concluded that children can reason based on relational similarities and they can protect their inferences from the perceptual similarity. An important conclusion was that analogical reasoning covaries with age as well as with the individual's repertoire of relational knowledge. The range and the depth of knowledge seem to play a crucial role in the process of inductive inference. As Goswami (2002, p. 295) notes "investigations of whether children reason inductively on the basis of perceptual attributes, lower-order relations, or higher-level causal or systematic relations are better understood as a sensitive index of their depth of understanding of a domain, rather than as an indication of their developmental status per se".

Psychological research on analogical reasoning has extensively used geometric and verbal analogies. Verbal and geometric analogies provide an excellent tool in measuring individual differences in knowledge on relationships between concepts. Various models on geometric analogy performance have been proposed (Mulholland, Pellegrino, & Glaser, 1980) and tasks of varying complexity have been used to test strategy use. Tasks involving multiple transformations on a single element (shape) are found to be harder than tasks involving the same transformations on single, separated, elements (shapes). In the case where multiple transformations are made on a single element the individual has to retain in working memory the shape and apply on it a series of transformations whose intermediate products must also be maintained in working memory (Mulholland et al., 1980). In as far as strategy use and strategy shifting are concerned, it is suggested that low-ability individuals shift to a different, more time consuming strategy sooner than high-ability individuals do. Moreover, analyses of eye fixations showed that when individuals faced more complex analogies they often used repeated lookbacks to the given relationship of the first pair of shapes, as an integral part of the strategy they used (Bettell-Fox, Lohman, & Snow, 1984).

The most salient difference between the geometric and the verbal analogies is the big number and the subtle nature of the transformation rules regarding verbal analogies. Verbal analogies consist of one pair of related words and another word without its pair. The target is to find the missing word that has the same relationship to the word as the first pair so that the second pair of words is completed. Two major semantic types of verbal relational schemas, namely the intentional and the pragmatic, are suggested (Bejar, Chaffin, & Embretson, 1991). These types include a number of semantic relations that are based on the meaning of the word-elements used (intentional-type relations, such as class inclusion, similarity, attribute, contrast, and nonattribute) and sometimes they extend beyond the meaning of the word- elements to a broader knowledge (pragmatic-type relations, such as event, cause-purpose, space-time, part-whole, representation). Bejar et al. (1991) analyzed a big number of GRE verbal analogies and concluded that pragmatic relations are easier than the intentional items with the only exception being the class of contrast relations. Though these findings were not replicated on SAT items (Diones, Bejar, & Chaffin, 1996) an item complexity analysis of SAT verbal analogies (Buck, Van Essen, Tatsuoka, Kostin, Lutz, & Phelps, 1998) revealed that semantic complexity is greatly determined by the number of meanings a word can have and by the degree of a word's abstractness. Pellegrino and Glaser (1982) suggest that a key source of verbal analogy complexity is what they call representational variability which refers to the initial ambiguity in the rule that the individual must generate based on the relationship of the stem of the analogy (i.e., the relationship between the pair of the given words).

More demanding verbal analogies have been studied in respect to the strategies individuals use in order to solve them. One such strategy was studied by Alderton, Goldman and Pellegrino (1985) and it referred either to *reason forward*, that is individuals base their reasoning on the information provided by the stem of the analogy, or *reason backwards* that is, they base their reasoning on the information provided by the alternative answers from which they will choose the right one. *Reason backwards* has been suggested by the researchers as a good strategy since the alternatives constrain the search for relationships between the terms in the stem and, therefore, the cognitive load from this task is reduced. Generally speaking, high ability individuals tend to be more flexible in choosing and applying different strategies and on monitoring and assessing the strategy use throughout the task solving procedure. These metacognitive skills (Gitomer, Curtis, Glacer, & Lensky, 1987) as well as the specific knowledge an individual has (Horn, 1972), are major sources of individuals differences in verbal analogical reasoning.

Deductive Reasoning

Though both induction and deduction are based on establishing and applying inferential laws and constructing models for representing the premises and reaching for a conclusion, they are two distinct processes whose difference is reflected in Frege's position: "However much we many disparage deduction, it cannot be denied that the laws established by induction are not enough" (Frege, 1884/1974, p. 23). The deductive reasoning process is an austere process which is based on well-grounded rules.

Deductive reasoning, often called logical reasoning, has been mainly studied by using conditional reasoning tasks that involve a major premise of the form "if p then q" and one of four possible inferences, namely "p is true", "q is false", "p is false", and "q is true", leading to a conclusion. In the first two cases a logically correct conclusion can be reached. These are the cases known as Modus Ponens and Modus Tollens. Modus Ponens (MP) is the inference that involves the premises "if p then q" and "p is true" and leads to the logically correct conclusion "q is true". Modus Tollens (MT) is the inference that involves the premises "if p then q" and "q is false" and leads to the logically correct conclusion "p is false". In the other two cases no logically correct conclusion can be reached with certainty. Denial of the Antecedent (DA) is the inference that involves the premises "if p then q" and "p is false" and leads to no logically correct conclusion, though most often the false conclusion "q is false" is reached. Affirmation of the Consequent (AC) is the inference that involves the premises "if p then q" and "q is true" and leads to no logically correct conclusion, though "p is true" is mistakenly considered to be the conclusion quite often. MP and MT are called *determinate arguments*, since they lead to a logically correct conclusion, while DA and AC are called *indeterminate arguments*, since they do not lead to a logically correct conclusion.

Researchers have extensively studied the development of logical reasoning. Piaget's theory had been the dominant theory for years. This theory postulated that a key aspect in cognitive development is the development of the formal operational logic that emerges in early adolescence (Inhelder & Piaget, 1958). Contrary to Piaget's theory, two other theories, with seemingly inconsistent findings, have been developed: the *early competence theory*, postulating that even preschool children are basically logical, and the *adult irrationality theory*, postulating that even adults are nonlogical and irrational. The perceived inconsistencies between these theories reflect the dissimilarity of two notions, mistakenly used interchangeably, namely *logic* and *rationality*. Rationality represents something more than logic (Bickhard & Campbell, 1996). It goes beyond the typical rules of formal logic and it reflects the development of metalogical and metacognitive awareness.

Developmental research in deductive reasoning indicates that preschool children can routinely make deductive inferences (Braine & O'Brien, 1998; Pillow, 2002) though they are not aware that they have actually made an inference, and they are not aware about the status of its logicality (Moshman, in press). Moshman (2004, p. 223) argues that "what develops beyond early childhood is not the basic ability to make logical inferences, but metalogical knowledge about the nature and justifiability of logical inferences, and metacognitive awareness, knowledge, and control of one's inferential processes". It is noted, however, that the development of this metacognitive ability may never attain a definitive state of maturity (Kuhn, 2000; Moshman, 1994). Such a metacognitive conception of rationality diminishes the perceived inconsistencies between the early competence and the adult irrationality theory and it clarifies the cognitive developmental theory from the paradox of logical children and illogical adults. Based on this understanding of the difference between logic and rationality, the development of metacognitive awareness is realized through the progress in the quality of the individual's thinking. Moshman (2004) argues that the ability to reflect on one's own reasoning, and to use the product of this reflection to organize complex reasoning processes is what accounts for a major part of the individual differences between reasoners of the same age, as well as for the age-related differences between children and adults. Metacognition refers both to the ability to think about thinking, and to explicitly control the organization of one's reasoning processes.

Strongly related to the ability of metalogical understanding is the concept of logical necessity, which, according to Moshman's (1990) model of the development of metalogical reasoning, develops in three stages. In the first stage, *explicit content–implicit inference*, preschool children make correct inferences based on a set of given premises, but cannot distinguish probable from logically necessary conclusions. By the second stage, *explicit inference–implicit logic*, school-aged children can understand the necessity of deductive arguments, but are still bound from the truth or falsity of its content that acts as a crucial impediment in focusing on the internal logical structure of an argument (Moshman & Franks, 1986). By the third stage, *explicit logic–implicit metalogic*, most 12- and 13-year-olds, when given examples, instructions, and feedback, and most adults, are able to distinguish arguments on the basis of their validity.

Miller, Custer, and Nassau (2000) conducted a study on the development of the conception of necessity in a group of 100 children aged 7, 9, and 11 years old. The participants were asked to make judgments about logical, mathematical, and definitional necessities, physical laws, social conventions, and an arbitrary fact. The judgments were made in regards to the spatial universality of their inference, its changeability, and the imaginability of any alternative. The results of this study revealed that even the younger children were able to understand the universality of necessary truths and their nonchangeability. As children make it through childhood they become increasingly more capable to apprehend the refined distinctions between necessity, possibility, sufficiency, and indeterminacy (Klahr & Chen, 2003; Morris & Sloutsky, 2001). Though the conception of necessity is, to an elementary level, present from childhood, they are still constrained by the content of the argument and their knowledge on the content (Simoneau & Markovits, 2003), and they are unable to identify and accept the logical form of the inferences. As children approach adolescence they can increasingly distinguish form from content, and can recognize valid hypothetico-deductive arguments based on their forms, rather than on their content (Morris, 2000). To summarize, preschool children are able to make inferences though they are unaware of their doing so. At about the age of 6, children become aware of inference, they begin to understand that some inferences are better than others, and they begin to recognize the necessity of deductive inferences, and identify universality, possibility and impossibility. Just before entering adolescence, they reach a more explicit appreciation of the role of logical form in guaranteeing the validity of deductive arguments and can increasingly handle with more efficiency hypothetical and false premises.

Yet, another important aspect in the development of reasoning is the knowledge acquisition about the logical properties of propositions, inferences, and arguments. As children get older they better understand the laws containing their own and others' inferential processes. Awareness of inference emerges at about the age of 6 and continues to develop through the childhood years (Miller, Hardin, & Montgomery, 2003; Pillow, 1999; 2002). In a study conducted by Sodian and Wimmer (1987) aiming at assessing the level of awareness of inference in children aged 4 to 6 years, it was found that children of 4 or 5 years can produce correct inferences but could not recognize that another person could produce correct inferences too. This inability to recognize the other person's ability or inability to make correct inferences was diminished at the age of 6 years. Moreover, awareness of inference is functionally related to the individual's cognitive flexibility which allows for the consideration of the possibility that some inferences are more justifiable than others. Pillow (2002) assessed the ability of children aged from 5 to 10 years compared to college undergraduates, to produce conclusions on the basis of partial information and pure guessing, in a set of inference-related tasks that included deductive inference, inductive inference, and guessing. All participants were confident of their conclusions in the case of deductive inferences and less confident in the case of inductive inferences and guesses. Pillow (2002; Pillow, Hill, Boyce, & Stein, 2000) suggests that children as young as 5 or 6 years of age are, to a certain degree, intuitively confident about the greater certainty associated with deduction, and that intuition is progressively substituted by an understanding of various metalogical parameters.

Theories on Reasoning

Three major theories have been developed to account for the cognitive and developmental findings on reasoning performance. Each of these theories has approached reasoning from a different viewpoint (or perspective). Two of the proposed theories, namely the mental rule theory and the mental model theory are considered to be standing on totally opposite grounds, while the third theory, namely the pragmatic reasoning schemas, stands in the middle.

Mental Model Theory. Mental model theory postulates that reasoning is based on constructing and manipulating mental models. This theory was proposed by Johnson-Laird (1983; Johnson-Laird & Byrne, 1991) as an attempt to merge structure and semantics into one construct, namely the mental models. A mental model is a content-specific analogical representation of the structure in the premises. It requires spatial manipulation and search and it can be experienced as a visual image whose structure corresponds to the structure of the information that is represented. Mental model theory postulates that reasoners have an underlying competence knowledge of the *meaning* of the logical terms or connectives of the language (e.g. *all*, *some*, *if…then*, *and*) and use this language knowledge to construct models. The entities of the information are represented by symbols which maintain the properties and the relations between the entities of the information. Mental model theory opposes the idea that deduction depends on formal rules of inference; rather, it postulates that "to deduce is to maintain semantic information, to simplify, and to reach a new conclusion" (Johnson-Laird & Byrne 1991, p. 22). Maintaining semantic information and simplifying the amount of information given in the premises are two important aspects of the deduction process which are closely related to the efficient allocation of cognitive resources, namely working memory and attention control. Since the result of the deduction process must be something new that is not explicitly stated in the premises and, at the same time, something that corroborates all information given in the premises, it is important for the system to maintain all pieces of information and ensure that the conclusion is completely deduced from it. Furthermore, the extracted conclusion needs to carry less amount of information, be clearly in a *reasoner-friendly* manner so that it can be stored to long-term memory for further use.

The main assumption of the mental models theory is that reasoning process takes place during a three-stage procedure of model construction (Johnson-Laird & Byrne, 1991). The three stages correspond to understanding the meaning carried in the premises and constructing internal models based on it, formulating a parsimonious description of the so far constructed models in which information not explicitly stated in the premises must be included and, searching for alternative models of the premises which falsify the parsimonious description which was deduced earlier. If such models exist, the reasoner returns to the second stage searching for a new conclusion which no constructed model can falsify. If the set of possible models is exhausted without reaching for a conclusion then the reasoner must conclude that nothing follows from the set of the given premises. According to Johnson-Laird and Byrne (1991) the major cause of difficulty during deductive reasoning is the necessity to construct models of alternative possibilities and the most errors occur when the reasoner overlooks such alternatives.

Deductions that depend on quantifiers and connectives have a finite number of possible mental models and, subsequently, the search for alternative models can in principle be exhaustive. Despite this, reasoners do not tend to exhaust the search for alternative models. Rather, they construct a minimum number of models and reach for a conclusion based on a subset of the possible models. This tendency can be explained in terms of processing efficiency and working memory resources and can be a major factor in explaining individual differences in deductive reasoning performance. As Johnson-Laird and Byrne (1991) put it, “the model theory predicts the general pattern of performance and it could account for these individual differences in terms of such factors as the processing capacity of working memory” (p. 62), thus virtually admitting that their theory offers no essential theoretical connection between reasoning performance and cognitive resources and no real answers can be given as to explaining the nature of individual differences in deductive reasoning. Moreover, mental model theory provides a very thoroughly hypothetical analysis of how an adult would perform in the various conditional reasoning inferential patterns, but no answers are provided in respect to the developmental pattern of reasoning ability.

Mental Rules Theory. Mental rules theories (Braine, 1978; Rips, 1994) postulate that deductive reasoning is a rule governed process and that reasoners have an underlying competence knowledge of the *inferential role* of the logical terms of the language (e.g. *all*, *some*, *if…then*, *and*). Internal representations of arguments are built based on the structural properties of the entities in the premises, rather than on their meaning. Using this as a starting point, some theorists have proposed that inference rules are innate; they are naturally built into the human cognitive architecture (Braine, 1978; Macnamara, 1986; Rips, 1983) and they are abstract and of general purpose in nature. There are supposed to be separate rules for each logical connective. Theories of deduction that are based on mental rules assume that verbal premises are first translated into an internal representation of their logical form. Then, an inferential mechanism is applied to these rule-based representations to draw a conclusion. Specifically, the mental repertoire of inference rules is accessed so that a mental derivation or a proof of a conclusion can be made. Lastly, the content-free conclusion is translated into the content of the premises (Braine; 1978).

The repertoire of inference rules that humans process, consists only of elementary rules, so when a more complex rule is needed the system selects a number of elementary rules, which are combined in the derivation process to reach for a conclusion. The ease of access to the mental rule and the number of steps in the derivation of a conclusion from the premises, are taken to be the two factors which define the difficulty of the inferential process (Rips, 1983). According to mental rules theories, errors arise when there is no available inference rule or when the inference rule is available but inaccessible. Errors may also arise during the encoding procedure due to comprehension deficit (Braine & O'Brien, 1991) or due to premise misinterpretation (Rumain, Connell, & Braine, 1983).

Mental rules theories have failed to explain individual differences and developmental trends on the process of premise translation in an abstract syntactic structure or the process encoding or translation of the conclusion back to the natural language.

Pragmatic Schemas Theory. An attempt to bridge the gap between mental models and mental rules theories was made by Cheng and Holyoak (1985) who had proposed that reasoning is based on pragmatic reasoning schemas, which mainly concern causation, permission, and obligation and are induced from life experience and memories of particular experiences. They are formulated as the distillation of accumulated experience on particular instances and they acquire general validity once they have been applied and tested under various specific occasions. These knowledge structures are at an intermediate level of abstraction and their validation procedure may lead to the so called *case-based reasoning*. Case-based reasoning is reasoning based on previous cases (Riesbeck & Schank, 1989), a kind of thinking which according to Johnson-Laird and Byrne (1991) "has nothing to do with logic" (p. 34). Nevertheless, when the reasoning process is based on previous cases and when the same experience has been repeated often enough, a content specific rule can be established and applied on future demands.

The accumulated knowledge and the formulated rules are entering the reasoning procedure in a way that may influence the outcome. Specifically, the content of the premises activates in an abductive way relevant information and facts that are connected to it. This activated information triggers the activation of a relevant rule which is used in the reasoning procedure. The theory of pragmatic reasoning schemas postulates that people learn to reason in certain contexts and formulate schemas to abstract their knowledge. Schemas facilitate reasoning by analogy. Their abstract structure is mapped onto the structure of related situations and related rules are activated and applied.

Neurocognitive Data on Reasoning

Recent neurocognitive research on the neural basis of reasoning conducted by Goel and his colleagues (2007; Goel, Buchel, Frith, & Dolan, 2000; Goel & Dolan, 2000; 2001; Goel, Gold, Kapur, & Houle, 1997) revealed some interesting findings regarding the differentiation between mental logic and mental model theories and about the dissociation in the neural mechanisms underlying the two different forms of reasoning. This data also provides insights into the role of prefrontal cortex (PFC) in logical reasoning. Both mental model and mental logic theories make explicit localization predictions on the systems actively involved in the reasoning process. Specifically, if mental model theory provides the correct hypothesis on the role of the visuo-spatial system in the functioning of logical reasoning as a necessary and sufficient condition, then the neural structures for visuospatial processing must be actively involved during reasoning process. On the other hand, if mental logic theory provides the correct hypothesis on the role of the language (syntactic) system as a necessary and sufficient condition in logical reasoning, then the neuroanatomical mechanisms of language (syntactic) processing must be involved in reasoning.

Contrary to both of the preceding predictions, mental logic theories that predict that the language (syntactic) system is necessary and sufficient for deductive reasoning, and mental model theories that predict that the visuo-spatial system is necessary and sufficient for logical reasoning, Goel et al. (2000) found evidence for the engagement of both systems. The presence of semantic content engages the language and long-term memory systems in the reasoning process. The absence of semantic content engages the visuo-spatial system in the identical reasoning task. Goel (2007) notes that the mental models and mental rules theories of deductive reasoning differ with respect to the knowledge they draw upon, the mental representations they postulate, the mechanisms they invoke, and the neuroanatomical predictions they make.

As far as the dissociation in the neural mechanisms underlying the two forms of reasoning is concerned, Goel and his colleagues (Goel et al., 1997) put under test two accounts regarding the nature of reasoning in terms of underlying cognitive processes and computational mechanisms. The first account postulates that there exists a differentiation between deduction and induction. Specifically, this account assumes that deduction is a formal rule-governed process where internalized rules similar to those of formal logic are used to construct valid arguments. This view also claims that when individuals draw valid arguments, their reasoning competence is revealed, while when errors are made, then cognitive resources shortcomings, such as memory limitations and attentional deficits, are revealed. Induction is considered as a process of hypothesis generation and testing, which is effected by searching the data and establishing a mapping on to the situation at hand. Establishing a mapping and suggesting a generalization requires a big repertoire of general knowledge and experience. Goel et al. (1997) hypothesize that if deductive reasoning is a rule-governed process that is strongly based on the structure of language it will activate the left hemisphere more than the right hemisphere and some of the same structures involved in language processing will be also involved during deduction. Moreover, it is hypothesized that if inductive reasoning is a process that activates the mechanisms of generalization and abstraction, then the left prefrontal cortex will be activated during induction.

The second account postulates that no dissociation between the two reasoning forms exists and that a unitary account of human reasoning must be assumed. Mental models theory and the pragmatic reasoning schemas theory propose a unitary account for reasoning. Specifically, mental models theory opposes the idea of internalized logic rules; rather it proposes that individuals are able to "semantically comprehend an argument and construct non-linguistic mental models that are structurally isomorphic to the situation described in the premises of the argument" (Goel et al., 1997). Mental model theory offers an explanatory framework that can accommodate both induction and deduction. Successful model construction and alternative models search is directly related to the application of the formal rules of logic. Searching for alternative models can lead to necessary conclusions and to conclusions about possibilities. A conclusion is *necessary* if it holds in all alternative models of the premises; and a conclusion is *possible* if it holds in at least one model of the premises. A conclusion that holds in most alternative models is a probable conclusion; a conclusion that holds in only one model of the premises is a possible. Probable and possible conclusions are reached through the process of induction. According to mental model theory, induction differs from deduction in the fact that the former allows for the addition of information not included in the premises. Pragmatic reasoning schemas theory suggests that both deductive and inductive reasoning rely on general-purpose reasoning knowledge extracted from content-specific schemas.

Results from neurocognitive research (Goel et al., 1997) strongly suggest that deductive and inductive reasoning are clearly differentiated and they involve the left prefrontal cortex in a different way. Deduction may be primarily a linguistic, rule-governed activity rather than a process of constructing and searching mental models. Inductive reasoning activates the left prefrontal cortex, a region associated with the processes of generalization and abstraction. Moreover, this region is associated with the storage of huge amounts of knowledge structures (Grafman, 1994) that are essentially needed in reasoning process. Goel et al. (1997) suggest that the classical distinction between deduction and induction has a neurophysiological basis. Deduction is associated with language (syntactic) processing rather than spatial modeling, a finding that is consistent with the formal rules theory, and induction activates the medial region of the left prefrontal cortex, a region associated with generalization and abstraction over world knowledge.

The differentiated profile of inductive and deductive reasoning is further supported by recent cognitive and developmental data on the role of specific knowledge, context and conceptual substrate in the course of reasoning and on the differentiated need of inductive and deductive reasoning on various cognitive resources. While both types of reasoning develop in a continuous fashion across lifespan (Goswami, 2002), reasoning is not an all-purpose general ability with general strategies applicable to all domains; rather its outcomes depend on various exogenous and endogenous factors which shall be analyzed below.

Exogenous Factors Affecting Reasoning

The content and, therefore, the meaning of the premises are strongly related to the reasoning procedure where their role in each type of reasoning is clearly differentiated. In deduction, knowledge and belief biases may intrude in the process and eradicate the effect of the logic form of the argument on the extraction of the outcome. In induction, the content of the premises defines the outcome since it activates the retrieval of knowledge stored in long-term memory. Most of the research on the effect of content to the reasoning process was conducted by using conditional reasoning, i.e. deductive reasoning based on at least one premise that included the “if … then” connector. The way the content and the meaning of the conditional premises influences reasoning performance on the four logical inference types (MP, MT, AC, DA), has been also used as an instrument for criticizing the mental rules and the mental models theories. The former proved unable to explain how individuals apply rules after decontextualizing the given premises and how they reach for a content-based conclusion, while the latter has been criticized for not explaining individual and developmental differences in reasoning performance.

Mental models theory provides some explanations as to the way individuals produce valid and invalid inferences when the content of the argument is not abstract. Specifically, according to mental models theory individuals can produce valid arguments by providing uncertainty responses to AC and DA inferences when the content of the premises supports searching for many possible alternative models and when accessibility to possible alternatives is easily achieved. Accessibility to alternatives depends on the volume and diversity of knowledge stored in long-term memory, as well as on the way this knowledge is structured in long-term memory. The latter parameter strongly affects the strength of associations between premises and stored knowledge. Children (Janveau-Brennan & Markovits, 1999) and adults (Cummins, 1995) can more easily produce uncertainty responses to the fallacies AC and DA when the content of the given conditional premises allows for many possible alternatives. When individuals search for more alternatives they are less likely to give a biconditional inference to the premises, since they evaluate the antecedent of the conditional not as a necessary condition but as a sufficient condition for the consequent (Staudenmayer, 1975).

When many possible alternatives are activated due to the large amount of stored knowledge in long-term memory or the strong associations between the premises and the stored knowledge, the chances that some bits of disabling knowledge will also be activated are not negligible. Disabling knowledge may lead to the suppression of MP and MT inferences by producing logical wrong conclusions (Byrne, 1989; Markovits, 1984; Rumain, Connell, & Braine, 1983). The suppression of the valid inference schemas is less probable to happen in children than in adults, since children do not engage in deep search for alternatives as they stop the process right after the activation of the complementary information, and even when they are engaged in deeper search for alternatives, their limited knowledge repertoire, their limited working memory capacity which hinders processing of many alternatives and the not-so-strong associations between knowledge bits, do not allow the activation of disabling knowledge. Thus, a U-shaped performance in logically valid inferential schemas can be viewed: children performing higher, adolescents or even young adults performing lower because of the activation of disabling information and, older adolescents and adults performing higher, as their ability to inhibit disabling information is protecting the system from extracting logically wrong conclusion (Handley et al., 2004).

According to Rumain et al. (1983), the suppression of the logically valid inferences as well as the fallacies according to the content of the premises, indicates that reasoning is depended on the ability of the individual to search for alternatives, to process the activated alternatives and to control disabling alternatives from entering the reasoning process, rather than on stored inference rules. Therefore, it is suggested that reasoning is strongly depended on endogenous factors, such as working memory, inhibitory control, and speed of processing.

In the case where the content of the premises is abstract, mental models theory is unable to explain the reason why MP and the two fallacies are almost always made, while MT inference is not so often drawn. Abstract content tests often use premises with familiar terms involved in an arbitrary relation, in order to control the effects caused by previous knowledge and belief biases (Evans, Newstead, & Byrne, 1993) which will be extensively discussed latter. In this case, individuals are constrained by the limitations imposed by the lack of a relational underpinning and, consequently, the search and activation of alternatives, as well as the inhibitory control process, are restrained. The relation between antecedent and consequent becomes a relation between two variables; variables P and Q (the values of which are specified by the propositions p and q in the conditional "if p then q", respectively) and the fact that the antecedent (p) and the consequence (q) are familiar terms allows for the retrieval of at least some possible values they can have. Markovits and Barrouillet (2002), note that the nature of the semantic space of variables of P and Q and, therefore, the range and domain of their possible values, are of crucial importance in reasoning process. Specifically, they suggest that if one or both of these variables are of binary nature, i.e., if they can only have two possible values, then the process of retrieving alternative values and maintaining them in working memory becomes drastically easier. Generally speaking though, when the variables P and Q have no binary nature the cognitive load imposed on the system by the construction and maintenance of mental models representing arbitrary co-occurrence of P and Q values is big. As a consequence, reasoners tend to construct fewer models and younger children find it harder than older children to construct models based on arbitrary relations.

The additional cognitive load imposed by the arbitrary relational schema suppresses the number of models individuals at various ages can construct. According to the variation of mental models theory proposed by Markovits and Barrouillet (2002) younger children, at the age of 5- to 8- years old can, under the constraint of an arbitrary relational schema, construct only one model: the initial model as it is stated in the conditional premise. In this case the model constructed assumes that "p is true" and "q is true" and therefore MP and

AC inferences are made while MT and DA are refused since they carry negative values. Older children at the age of 9 years old to early adolescence are able to construct a second model too, usually that being the model based on the complementary information: “not p” and “not q”. This model is complementary to the initial model and their combination results in a biconditional interpretation of the given conditional premise. As a result, all four inferences of both the logical (MP and MT) and the non-logical (AC and DA) are accepted. The increase in the cognitive capacity of older adolescents and young adults opens the way for the construction of a third model based on the alternative class of information according to which there are instances for which “p is not true” and “q is true”. The activation of the alternative information and the construction of the third model, leads reasoners at a conditional interpretation of the premise “if p then q” and the acceptance of the MP and MT inferences while the fallacious AC and DA inferences are rejected. In a nutshell, the conditional interpretation of the premises “if p then q” evolves from one-model to two-model to three-model interpretation (Lecas & Barrouillet, 1999). All the above theoretical hypotheses proposed by the Markovits and Barrouillet model (2002) are supported by the findings of research on children’s, adolescents’ and adults’ reasoning based on arbitrary relation, conducted by Barrouillet and Lecas (1998) and Barrouillet, Grosset, and Lecas (2000).

The absence of an underpinning relation between p and q in the “if p then q” premise and its substitution by an abstract relation impedes the activation of disabling instances during the retrieval process which follows the construction of the initial model and the activation of the complementary and alternative instances. As a consequence, the U-shaped developmental curve of the MP inference observed in the case where the relation of p and q is not arbitrary is not followed. In fact, Barrouillet and Lecas (1998) have observed a ceiling effect from the beginning of adolescence.

Endogenous Factors Affecting Reasoning

Reasoning process draws on the functioning of other cognitive processes and is strongly depended on them. As Halford and Andrews (2006) note, reasoning is no longer considered as application of the laws of logic, but as an emergent property of more fundamental processes. Halford, Cowan and Andrews (2007) propose that reasoning is closely related to working memory capacity through their common requirement to bind elements to a coordinate system using attention. Further, it is proposed by Halford et al. (2007) that the common demand for attention could serve as a possible explanation for common capacity limitations in working memory and reasoning. Handley et al. (2004)

indicate the lack of developmental research examining the role of inhibitory control and executive function.

Markovits and Barrouillet (2002) have attempted to examine reasoning vis-à-vis working memory, and they proposed a model based on three assumptions. First, they assume that when dealing with a conditional statement, the reasoner constructs a simple representation of the relation between the antecedent and the consequent of the “if-then” premise. This representation will initiate the activation of the associated knowledge. This activation gets to be more refined once the second (minor) premise is added to the given information. The strength and the result of knowledge retrieval and activation are a function of the available knowledge and the efficiency of the retrieval processes, both of which constitute prime factors of individual differences. This assumption is in line with Cowan’s (2001) levels of activation as a model explaining the nature and function of working memory. Markovits and Barrouillet (2002) assume that “only elements that are activated sufficiently strongly enter working memory and will be available for further processing” (p. 10). Further, some pieces of the activated information must be inhibited if they are not linked with the represented relation between the antecedent and the consequent, as well as with the situation described by the minor premise, in a direct way. The second assumption on which Markovits and Barrouillet base their model is that mental models for conditionals are representational structures (Barrouillet & Lecas, 1998). Within these representational structures the retrieved pieces of knowledge are organized. The relation between antecedent and consequent becomes a relation between two variables; variables P and Q. The retrieved knowledge is bound with the relational structure between the variables in such a way as to offer the reasoner a broad spectrum of the alternate values each variable in the relational schema can get.

The number of the available alternatives and their relevance to the relational schema between the two variables in the conditional statement are subjected to a number of limitations imposed on the reasoning process by some cognitive parameters. According to Markovits and Barrouillet (2002), working memory capacity limitations are imposed during both knowledge activation and retrieval and mental model construction and fleshing-out. The limitations on reasoning due to working memory capacity limitations are the third assumption of the model. The process of retrieving information from long-term memory is triggered by elements of knowledge already activated and, thus, present in working memory (Cowan, 2001). The amount of the retrieved knowledge which is maintained active strongly depends on the function of working memory.

Individual differences in the functions ascribed to working memory are consequently present in the reasoning process. The limitations of working memory affect the amount of knowledge to be retrieved, the amount of knowledge to remain activated during the reasoning process, the amount of alternatives to be used during the mental model fleshing-out procedure, and the amount of the mental models to be constructed and evaluated. What Johnson-Laird (1983) called mental footnote to define the search for alternatives, is described as retrieval of knowledge triggered by the information already present and thus activated in the first mental model which is constructed solely based on the values of P and Q variables as given in the conditional premise. Mental footnote is thus a procedure with cognitive cost; a cost that reasoners tend to keep at the lowest possible level (Sperber, Cara, & Girotto, 1995). In order to keep cognitive cost low, reasoners retrieve knowledge from long-term memory in a way that maximizes the relevance of the conditional premise. Maximum relevance is conveyed by retrieving what Markovits and Barrouillet call *complementary* knowledge, that is knowledge which is complementary to the knowledge specified in the original conditional statement (Barrouillet & Lecas, 1998). So, if the original statement is of the type “if p then q”, then its complementary knowledge would be consisted of cases different of p which are related to not q, and thus be of the type “not p, not q”. In the cases where the reasoner does not stop the retrieval and activation process at the complementary hypothesis, a second level of activated knowledge follows. In this level, knowledge which is retrieved and activated modifies the relational representation between p and q, either in the form of *alternative* knowledge, which is of the type “not p, q”, or in the form of *disabling* knowledge, which is of the type “p, not q” and which allows the relation between p and q to be violated.

The role of inhibitory control process, although not extensively studied in the Markovits and Barrouillet model, seems to be crucial both in preventing the reasoner from adopting alternatives which either violate the relation between p and q or which are irrelevant for the relation at hand, and in preventing the reasoner from ending the fleshing-out procedure prematurely, without exhausting all alternative models.

The Complexity of Reasoning Tasks

Reasoning development is directly related to cognitive change, as they are both manifested as the product of the synergy of multiple parameters, often not evident via single test performance. Various methods for assigning an objective assessment of reasoning development have been proposed over the last 30 years or so. Siegler (1981; Brians & Siegler, 1984) had proposed the method of rule assessment according to which each cognitive process or strategy was assumed to be represented by a unique pattern of responses. This method, according to Halford and Andrews (2006), was an important step towards the objective assessment of cognitive processes underlying each task and an important shift from observing behavior to inferring the cognition that underlies the behavior. In the researchers' focus of attention lied, not only *what* individuals did, but *how* they did it. Towards this direction of understanding cognitive change via studying cognitive processes or strategies, another class of methods was developed by Kuhn (1995) and Siegler (1995; Siegler & Crowley, 1991) namely the microgenetic methods. An important finding of these methods is that individuals, at any time, have available multiple cognitive strategies from which they choose the optimum one to apply to a problem situation. The available strategies are to a different extent developed, and therefore, individuals are in an ongoing process of evaluating these strategies. More efficient strategies are strengthened while less efficient ones are abandoned. This shift to more efficient strategies constitutes the manifestation of development and the manifestation of some meta-level executive that manages strategy selection (Kuhn & Franklin, 2006).

Markovits and Barrouillet (2002) view reasoning development through the information processing theories. Specifically, they account for developmental changes in reasoning in terms of quantitative change in the cognitive or working memory capacity (Pascual-Leone, 1970; Case, 1985, 1992) rather than in terms of emergence of a qualitatively new structure. Therefore, they postulate that children are progressively more able to solve increasingly complex reasoning problems as a result of the increase in information processing capacity, i.e. in working memory capacity and the efficiency of the retrieval process, and of the increase of their knowledge through learning. This model for studying reasoning development, proposed by Markovits and Barrouillet, suggests that complexity is a function of the number of processing steps and the quantity of representations, or mental models, to be constructed, maintained, and processed in working memory.

Halford and his colleagues (Halford & Andrews, 2004; Halford, Wilson, & Phillips, 1998) developed the Relational Complexity theory with which they propose that the assessment of children's reasoning should be done based on the complexity of the inferences they make and, consequently, on the cognitive processes they use. According to Relational Complexity theory, the difficulty of a given reasoning argument depends on the relational complexity of the mental model that needs to be constructed. The more complex the model is the higher the computational cost is. Therefore, the developmental patterns of reasoning inferential schemata are defined not as a reflection of additive reasoning complexity, but as a product of the interaction of the computational cost in terms of understanding and control, of the complexity of relations, that is the number of independent variables that can be related in a single cognitive representation (Halford, Wilson, & Phillips, 1998) and, of children's increasing processing capacity and logical metaconcepts. This theory succeeds in resolving some paradoxes in terms of children's and adults' reasoning abilities "by assigning cognitive tasks to equivalence classes, with common properties, and relating tasks in different classes to each other in an orderly way" (Halford & Andrews, 2004, p. 141). When young children's performance on complex tasks is compared to adult performance, this should be done on a common basis.

Cognitive Task Analysis

Cognitive task analysis is strongly related to models on cognitive development. Theories often seek confirmation through research data, or they may even appear as generalizations emerging from data patterns. As a consequence, the cognitive tasks which are used in cognitive developmental research can have an influential role in the emerging theory or in the process of validating a theory. The first researcher who had systematically tried to integrate task-related information into a model on cognitive development was Piaget. He extensively studied the actual process of solving a problem and dealing with the data at hand at real time. His observations were based on very specific task-settings, a procedure that offers the researcher the opportunity for a very detailed insight of the problem solving processes, but, on the other hand, a procedure that restrains the right to generalize the conclusions and propose a well grounded theory. Though Piaget was to a great extent correct in the stages of intellectual development he has proposed, some grey zones exist.

Many experimental designs, which were based on Piaget's original experiments, and which were applied using some variations of the tasks he used, gave different results and led to concluding that the intellectual processes are more specific in terms of content, context, and culture than Piaget had suggested (Case, Okamoto, et al., 1996). Furthermore, a limitation in Piaget's proposed model, which we consider important in terms of task analysis, is the retrospective nature of his task analysis. He first watched the children solve the tasks and he subsequently reported the observed difficulties as these were revealed during the procedure. This post hoc analysis of the collected data was used to describe the so called "epistemic subject" (Beth & Piaget, 1961), a construct which was abstracted by describing the invariant behavior exhibited by the majority of normal participants of the same age (50 to 75%) across different tasks. So, it is obvious that Piaget conducted a task analysis which was mental-process-oriented so that it could serve as a criterion which would describe, and in a sense it would define, the epistemic subject and the intellectual stage it referred to. Therefore, the proposed developmental stages are the distillation of the massive amount of observations which were introduced into more generalized conclusions in an inductive manner, and which were used as a basis for constructing an ordinal scale of intellectual development. Pascual-Leone (1979) refers to this scale as representing the informational complexity of the task as it is considered from the participant's respective. Thus, it could be argued that though Piaget gave a good model which describes the developmental stages and the mechanisms of developmental change based on the evidence extracted from the experiments it is subjected to the specificities and the weaknesses of the experimental design and the post hoc analysis of the tasks he designed.

Despite any methodological or theoretical weaknesses in Piaget's theory it remains a fact that it was influential in many respects. It served as a starting point to the neo-Piagetians some of whom (Pascual-Leone, 1970; Case, 1985; Halford, 1993) have proposed models of developmental change in which the cognitive task analysis was essential in conceptualizing the developmental stages. Though their work is related to Piaget's theory, they have proposed different models which they relied not on general-purpose logical structures as Piaget did, but on concepts, skills, and mental structures that are acquired in a less global fashion, strongly affected by specific experience. According to Case, Okamoto et al. (1996), "what gives development its generality […] is that the complexity of these structures is subject to a common ceiling, a ceiling that can be attributed to the existence of age-linked constraints on children's information-processing capacity and/or working memory". This thesis serves as a bridge connecting the concepts deriving from information processing and decision-making theories with the theories on cognitive tasks analysis. Cognitive task analysis is based on a set of rules, and the apodosis of a qualitative or quantitative attribute retains its objectivity within the limits defined by the predefined rules of analysis. These rules are by nature contained to addressing the tasks per se; not the reasoner. Therefore, all non-task attributes, such as information processing efficiency and working memory capacity, cannot be included in the analysis of the task complexity, even though they affect task performance. Efficiency in information processing and working memory capacity set the limits to each individual's attainment and therefore shape a *subjective* metric of mental workload and play an important role in shaping cognitive development. In a sense, the results from task analysis function in a complementary way with the parameters of processing efficiency and working memory in explaining or even predicting task performance. We will elaborate on that later, after we present the main neo-Piagetian endeavors in proposing models of cognitive development based on task analysis.

Based on Piaget's conceptualization of the existence of a cognitive-developmental variable Pascual-Leone proposes the construct of a central processor or computing space *M*, which is responsible for information transformation and coordination, and which can be assigned to a specific numerical value. The quantitative values of the central processor, *M*, are taken as the quantitative characteristic of each developmental stage and they reflect the number of separate schemes on which the participant can operate simultaneously. Pascual-Leone (1970) notes that "if the existence of this numerical characteristic was proven, and if a recursive function was found which generates the numerical characteristic corresponding to the Piagetian stages, this model could perhaps be used as a rule explaining (or at least formulating more clearly) the transition from one stage to the next". The need for a model for computing the *M* values aiming at connecting theory and experimental data opened the way to assigning quantitative attributes to qualitative characteristics. Pascual-Leone (1970) made a break through by conceptualizing that the central computing space *M* is the "hidden parameter" which explains cognitive development, as this was extensively studied by Piaget, and which increases in a lawful manner during normal development. Each individual is considered to have a maximum capacity, or *structural M* which is different from the *functional M* which constitutes the amount of the *structural M space* used at any particular case. The model proposed by Pascual-Leone was "inductively derived from the cognitive-developmental (mainly Piagetian) data by means of a semantic-pragmatic analysis […] of tasks using symbolic logic" (1970, p. 305) and was successfully linked to Miller's (1956) postulated "magical number seven" since it was suggested that the upper limit of the computing space *M* is seven schemes. Pascual-Leone's model was a major step towards assigning quantitative characteristics to qualitative attributes of the mind. However, this model, like the one proposed by Piaget, were based on posterior observations and analyses; no a priori propositions were set. Furthermore, it is absolutely based on the notion of schemes which is still a vague concept, totally alien to the contemporary notions of information processing. Thus, we consider that the model proposed by Pascual-Leone is based on a set of arbitrary computations and therefore, its credibility could be questioned.

Case (1985) moved a step forward by proposing a model on cognitive task analysis which placed emphasis on studying goal-directed representations and strategies individuals use during problem solving. His *executive control structures* are internal arrangements, or as Case calls them “internal mental blueprints”, which are used in problem solving situations. They include representations of the problem situation, representations of the objectives that fit in such situations, and representations of the strategies they need to be employed to move from the problem situation to the desired situation. According to Case’s theory these executive control structures are shaped on the basis of more general structures, namely the central conceptual structures, which are applicable to a broad spectrum of tasks. When faced with a new task, the reasoner utilizes the most relevant central conceptual structure as a guide for assembling the particular executive control structure that fits the new task (Case, 1985). Task complexity is defined with respect to the structural and conceptual characteristics of the executive control structures which are utilized. These structures undergo developmental changes which are closely related to changes in the processing efficiency and the memory capacity of the system. Specifically, they are moving along four general levels of abstraction (the sensorimotor, the interrelational, the dimensional, and the vectorial) each of which has at least three levels of complexity within it.

Case’s theory initiates a new perspective in task analysis, and he is doing it so in a subtle way, by indirectly introducing the parameters of processing efficiency and working memory in the cognitive task analysis. Specifically, he suggests that a complex task calls upon more complex structures which, in turn, are shaped on the basis of processing efficiency and working memory development. It should be noted that contemporary research interest in cognitive task analysis is drawn on the mental processes which take place during problem solving. The main goals is to understand and map the ongoing procedure of information use and information production, identify the underlying cognitive processes leading to particular error types, and be aware of the options that were faced and the decisions that were made. These are core representational processes in Case’s task analysis. Nevertheless, his model was not empirically tested. His task analyses were not tested for their validity in reference to the performance on the tasks, so his model could not be used as a predictive for the complexity of other tasks.

Halford and his colleagues (Halford, Wilson, & Phillips, 1998) have proposed a theoretical approach for studying task complexity based on the complexity of the embedded relations. They argue that the complexity of the relations that a reasoner has to process is subject to the limitations of the processing capacity. They also claim that, unlike the complexity of the relations, the amount of the information bits needed to be processed is not subject to processing capacity limitations. The Relational Complexity theory, proposed by Halford and his colleagues (Halford et al., 1998; Birney, Halford, & Andrews, 2006), quantifies the characteristics of the processes which are activated during task completion on the basis of two axioms. The first one defines the complexity of a cognitive process as "the number of interacting cognitive variables that must be represented in parallel to implement that process" (Halford et al., 1998, p. 805). The second one defines the processing complexity of a task as "the number of interacting cognitive variables that must be represented in parallel to perform the most complex process involved in the task, using the least demanding strategy available to humans for that task" (Halford et al., 1998, p. 805). According to this theory there are unary relations, which have one argument (e.g. A is a boy), binary relations, which have two arguments (e.g. A is older than B), ternary relations, which have three arguments (e.g. A is older than B, and A is younger that C), and so on. What determines the complexity of a relation is the number of the arguments involved in it used to instantiate the relation. Since the complexity of the relations that a reasoner has to process is subject to the limitations of the processing capacity, the Relational Complexity theory (Birney et al., 2006) proposes two processes through which individuals manage to reduce the cognitive demands of the tasks in order to harmonize them with their processing capacity. The proposed processes are *conceptual chunking*, that is recoding the relation into a lower dimensional concept, and *segmentation* that is decomposing the task into a series of lower dimensional processes. Therefore, the complexity of a task is defined by the complexity of the most complex process which results after applying the conceptual chunking and the segmentation.

As research on task analysis gets more refined and as it moves towards the direction of merging concepts and tactics from different psychological approaches, such as the cognitive and the psychometric ones, the concepts of *task complexity*, *task difficulty*, and *task performance* are used in less confounding ways. Until very recently the terms *task complexity* and *task difficulty* were used as different names of the same concept. Moreover, *task performance* was viewed as a clear reflection of the complexity of the task. Some good definitions of these terms are given by Halford, Wilson, and Phillips (1998), and Lohman (2002). Specifically, Halford et al. (1998) suggest that task complexity refers to the complexity of the relations involved in a task, while Lohman (2002) suggests that the term task complexity reflects the difficulty in the activated processes in terms of cognitive resources which need to be used, and the requirement in metarepresentational resources. Commons, Trudeau, Stein, Richards and Krause (1998) disclaim the postulation of the traditional information theory on the identification of task complexity with the way information is coded as bits that increase quantitatively. They suggest that task complexity is strongly related to the notion of mental power needed to solve a cognitive task and, therefore, a thorough task complexity analysis can illuminate the sources of individual differences.

On the other hand, task difficulty reflects the number of information units needed to be processed (Halford et al., 1998), or the number of simple processes running in tandem or in succession (Lohman, 2002). Of course, this distinction is only theoretical since, in most cases, the two parameters, i.e. the complexity and the difficulty of a task, are confounded in a way that isolating them and studying their relation with processing capacity is not achievable. *Task performance*, though definitely related to the concepts of task complexity and task difficulty, can by no means be identified to either of them since it reflects individual differences which are not necessarily indicative of the way individuals solve tasks and which exist irrespective to the task complexity and difficulty. The task's cognitive characteristics are facilitating the emergence of individual differences and the traceability of developmental profiles, but are not identified with task performance. Task complexity and task difficulty can be objectively defined, prior to testing, based on a set of rules and following some task analysis techniques. Unlike that, individual differences, as they are revealed in the observed variance in task performance, cannot be defined unless after the end of the testing procedure.

The decomposition of the observed variance in test performance into its constituent parts, namely the construct-relevant variance and the variance due to individual differences per se, would illuminate the real dimensions of the test difficulty sources and would allow researchers to develop cognitive ability tests grounded in information-processing psychology and composed from items with predictable cognitive characteristics (Lohman, 2002). Predictability in terms of task complexity and task difficulty is possible since these characteristics are independent of external factors, unlike task performance, and therefore they are invariant. Invariance in the cognitive characteristics of the task is secured by following the task analysis rules austerely. One of these rules refers to analyzing task complexity and difficulty based on the pattern of goal setting, and actions towards goal attainment an expert would follow to complete the task. Cognitive task analysis aims at tapping the knowledge (schemas, mental models, representations, and strategies) that differentiates experts from novices (Flach, 2000). Experts use information to guide action by setting goals and they use the outcome of their action to create new information. Most of the contemporary theoretical analyses of task demands are based on the experts' actions suggesting that the minimum number of processes will be activated and the minimum number of steps will be taken. This rule allows researchers to conduct analyses prior to testing and have their theory validated by the test results.

At the beginning of the 1970s, Annett, Duncan, Stammers and Gray (1971) developed an approach, namely the Hierarchical Task Analysis, whose emphasis was not the recording of overt behavior per se, but the systematic decomposition of goals. Its basic assumption was that behavior is strongly goal directed and that goals are hierarchically structured in such a way that the attainment of primary goals is depended on the realization of sub-goals, which may be further analyzed into more specific goals. Goal setting is related to understanding the problem and decomposing it into goals and sub-goals through the process of planning and decision making. Goal attainment is related to the sequence of mental and physical operations an individual has to apply as a result of the goal setting procedure.

The study of the hierarchical complexity of cognitive tasks is a research area originated in the Hierarchical Task Analysis theory which regards hierarchical complexity as a mathematical concept defined by mathematical principles on how information is hierarchically organized. The true value of a concept's complexity exists irrespective of the content and of the participant's performance, and is constructed entirely from the observer's perspective (Commons et al., 1998). One of the most promising models of hierarchical complexity of cognitive tasks is proposed by Commons and his colleagues (Commons, Richards & Armon, 1984; Commons et al., 1998), namely the General Model of Hierarchical Complexity. This model aims at providing some answers to the questions raised in regards to task analysis in general and to cognitive task analysis in specific. Its main assumption is that development is an ongoing process which unfolds in stage wise fashion. Unlike Piaget's theory where the notion of stage in is tangent with the trace of patterns of behavioral change and with the classification of instances of thinking exhibited while working on the tasks, the General Model of Hierarchical Complexity defines developmental stages on the basis of the hierarchical complexity of tasks. Specifically, task analysis results in a sequential ordering of tasks which form hierarchies that become increasingly complex. These hierarchies of increasing complexity are of key importance to specifying developmental change and therefore developmental stages. So, the difference with the Piagetian approach in regards to how a stage is defined is apparent. Piaget seeks for the answer in the overt behavioral patterns while the Model of Hierarchical Complexity seeks for the answer in the hinder complexity patterns of the cognitive tasks and their hierarchical profile and then on the performance on these tasks. The task is separated from the performance. The participant's performance on a task of a given complexity represents the stage of developmental complexity. Furthermore, the Piagetian approach in analyzing cognitive tasks has a perspective character. Piaget's approach was participant oriented, that is, it strongly relied to the performance of the participant and therefore it had a post hoc character. Common's analysis is done from the observer's perspective, that is, analysis rules are applied and a level of complexity is assigned prior to the testing and therefore it has an autonomous character.

According to the General Model of Hierarchical Complexity, hierarchical complexity "refers to the number of non-repeating recursions that the coordinating actions must perform on a set of primary elements" (Commons et al., 1998, p. 240) while actions at a higher order of hierarchical complexity are defined in terms of the actions at the next lower order of hierarchical complexity. Moreover actions at a higher order hierarchical complexity organize and transform actions at the lower orders of hierarchical complexity into new organizations which are more complex than the primary elements and more dynamically useful. So, actions are set at the centre of the hierarchical task analysis and tasks can be analyzed in terms of the actions the participant has to make in order to successfully complete the task. An ideal task analysis would reveal the ideal number and sequence of actions needed for the completion of the task. This set of ideal action defines what is known as *task demand*. Task demand is strongly associated with the notion of mental power allocated during the process of task completion, and, therefore, it is strongly related to the order of complexity of the task. Task demand is also related, to a lesser degree, to the notion of task difficulty which is expressed as a function of two parameters, namely the number of information bits to be processed in a serial fashion and the number of actions to be taken. Admittedly, the acceptance of this definition opens the way for a more precise approach to task analysis, by allowing for the use of two directions in analyzing cognitive tasks. These directions function in a complementary way and their combination provides a more objective view of the order of complexity of a given task.

The first direction of analysis is the nonhierarchical (Commons et al., 1998) which is defined by the amount of information bits need to be processed during the task solving. Nonhierarchical demands, such as rote work, unfamiliarity with some of the elements of the task (such as unknown words), and lack of available representations can make the task difficulty or can add to its *horizontal complexity*, the complexity as it is defined by the theory of classical information. On the other hand, the second direction of analysis deals with the hierarchical complexity and specifically with the number of non-repeating recursions, that is, the number of non-repeating processes by which the output of the lower order actions is used as an input of the higher order actions. Actions at a higher order of hierarchical complexity are defined in terms of actions at the next lower order of hierarchical complexity. Moreover, they coordinate the actions of the next lower order by organizing and transforming the lower-order actions and by producing organizations of lower-order actions that are new and not arbitrary, and cannot be accomplished by those lower-order actions alone. Commons et al. (1998) suggest that a task can be assigned to a certain complexity level by analyzing its demands and by breaking them down into their constituent parts. The order of complexity of the task is then assigned by adding one unit to the complexity of its highest sub-task demand. Sub-tasks are the actions needed to be taken during the process of task completion. Further, they theorize that hierarchical complexity is a linear, ordinal scale which refers to the performance on a single sequence of tasks within a single domain.

The model of hierarchical complexity analysis is closely related to the notion of stage which, in turn, is conceptualized in terms of qualitative differences that could be interpreted as discreteness or *gappiness* between the stages. Stages define the developmental pattern and the observed discontinuity in the pattern is mostly relevant to the measurement profile which takes place. In the case of measurement density it is more likely that a continuous developmental pattern will come up, or it is possible that periods of no change will be revealed. But, in the case of measurements taking place with long intervals then it is likely that discontinuity may arise as characteristic of the developmental pattern. Lohman (2002) suggests that development is continuous and therefore when few tasks are used in a test, then they will unavoidably lead to stage formation. On the other hand, when many tasks of varying complexity are used, then development will be reflected in a pattern of continuous change.

Summary

Human intelligence has been extensively studied over the course of history. Psychologists have taken some important steps over the course of the past century in understanding individual differences in mental ability and its development. Intelligence has been studied under the psychometric, the cognitive and the developmental approaches, each of which has contributed significantly to shedding light at its multiple facets. Recent research interest has focused on the relation between general intelligence and the cognitive processes, namely the speed and control of processing, the simple and executive functions of working memory, and the inductive and deductive reasoning abilities, providing a wealth of cognitive and developmental data. Yet, most of the studies have focused on examining the relation of one or very few cognitive processes with intelligence, while many have suffered from a confounding of individual differences and age-related changes. Very few longitudinal studies have been conducted making the theoretical gap even bigger. Additionally, it is suggested that the discrepancy in research findings should be attributed to the different tests used and the confounding of methodological and statistical considerations. Cognitive task analysis has been lately proposed as a means of better understanding the cognitive underpinnings of intelligence and designing tests that will provide researchers with more reliable data.

CHAPTER 3

RESEARCH DESIGN AND METHODOLOGY

Introduction

Longitudinal data are very informative since they allow the researcher to observe developmental patterns within individuals. However, time constraints often discourage researchers from designing longitudinal studies. As an alternative, they turn to cross-sectional studies which can, to a certain degree, uncover developmental trends. Cross-sectional studies, however, confound individual differences with developmental differences. Our aim was to have pure developmental data which would cover the age span of 6-to-11 years. Taking into account the time limitations and the need to address our research questions we designed a cohort sequential study which combined cross-sectional and longitudinal evidence. Six cohorts were selected, one for each of the six primary school grades.

Problem and Purpose Overview

The discrepancies reported in the literature review between the theories proposed to explain the cognitive and developmental aspects of the processes which are considered to be important parameters of general intelligence, call for a different approach. Moreover, the study of the dynamic interplay between processing efficiency, working memory, information integration processes and inductive and deductive reasoning is needed to fill a gap in the theory of general intelligence and reasoning ability. This cohort sequential study was designed to shed light on the multidimensionality of the web of cognitive processes and to uncover the interplay of all mental processes under the cognitive, the psychometric, and the developmental perspective.

Two testing waves were designed, separated by a one-year interval. All participants from the first testing wave were included in the second testing wave (except those who were attending Year 6 during the first testing wave and who left the school at the next academic year) and these participants formed the longitudinal study group. The second testing wave included almost three times more participants than the first testing wave.

Participants

At the first testing wave a total of 140 participants were tested, all of them coming from middle class families living in Nicosia, Cyprus, and attending a centrally located elementary school. These participants were about evenly distributed across the six primary school grades and gender. Specifically, from first through sixth grade, there were 23 (11 female, 12 male; mean age 80.3 months, SD=3.7), 24 (12 female, 12 male; mean age 92.6 months, SD = 3.5), 22 (12 female, 10 male; mean age 106.2 months, SD = 4.9), 21 (11 female, 10 male; mean age 117.9 months, SD = 3.4), 25 (13 female, 12 male; mean age 128.3 months, SD = 3.2), and 25 (13 female, 12 male; mean age 140.4 months, SD = 3.7) participants, respectively.

The second testing wave included 395 participants, all of them attending the same elementary school. These participants were about evenly distributed across the six primary school grades and gender. Specifically, from first through sixth grade, there were 62 (33 female, 29 male; mean age 80.2 months, SD=2.9), 62 (29 female, 33 male; mean age 92.4 months, SD = 4.0), 75 (38 female, 37 male; mean age 105.1 months, SD = 3.6), 68 (35 female, 33 male; mean age 116.4 months, SD = 4.7), 54 (25 female, 29 male; mean age 128.9 months, SD = 3.9) and 74 (36 female, 38 male; mean age 140.5 months, SD = 3.6) participants, respectively. From the total of the 395 participants in this testing wave 111 participants were included in the longitudinal group. Specifically, from second through sixth grade, there were 23 (11 female, 12 male; mean age 91.9 months, SD=3.7), 22 (12 female, 10 male; mean age 104.6 months, SD = 3.7), 20 (10 female, 10 male; mean age 118.6 months, SD = 4.9), 21 (11 female, 10 male; mean age 129.9 months, SD = 3.4), and 25 (13 female, 12 male; mean age 140.8 months, SD = 3.8) participants, respectively.

Data Collection and Instrumentation

Data Collection Methodology

Both testing waves took place at the school’s premises. The data collection methodology was identical at the two testing waves. The tests used in the two testing waves were the same in as far as their structure is concerned. They differed in only the number of the tasks included in the reasoning battery. Specifically, because of time limitations, the tests used at the second wave were only the one third of the tests used in the first testing wave. That is, tests of the second wave were selected among those used at the first wave, based on the calibration of their complexity, as indicated by the Rasch Analysis (to be further discussed in the next chapter). The selected items addressing each specific aspect of reasoning ability were evenly distributed along the Rasch hierarchy complexity so that items of all complexity levels were included in the second testing wave.

Each testing wave was conducted in two phases. The Reasoning Ability test was administered at the first phase and the Processing Efficiency, the Information Integration, and the Working Memory tests were administered at the second phase. Since all tests were divided in subtests, the presentation order bias was counterbalanced across participants by systematic reshuffling the subtests' order. The computerized tests, that is all the tests but the Reasoning Ability test, were administered in the school computer lab. This was a familiar setting for the participants. Groups involving a maximum of 12 participants were examined. The reasoning ability test took place in the participants' classrooms, where all students were tested simultaneously.

Participants went through a brief introductory session during which the practical requirements and the technical requirements of the tests (e.g. logging in, personal code entering, assigned keyboard key function), were explained. In addition, it was made emphatically clear that speed and accuracy of response were the primary determinants of success for the computerized tests, a remark which was steadily repeated to every group and before every subsequent test, as the testing was progressing.

Processing Efficiency, Information Integration, and Working Memory Tests

Prior to every computerized test, its special requirements were explicated and an example was demonstrated on the whiteboard. Participants could ask the experimenter to clarify what may have remained vague. Every test began with a practice session which varied from 2 to 5 trials. After this session, a statement appeared on the screen saying that the actual test was about to begin. Participants were asked to wait after completing each test until everybody was ready for the next test. For all the participants who were 6 and 7 years old, the experimenter did all the necessary procedure, that is logging in and personal code entering, prior to the actual beginning of the test. In the case of executive working memory, the testing time for every participant varied according to her degree of successful trials, as it will be explained below. So, the experimenter explained to the participants that the test had 7 levels and that moving on from one level to the other was a function of their success on the trials.

Reasoning Ability Tests

The inductive and deductive reasoning tasks were presented in a paper-and-pencil form under untimed conditions. Unspeeded reasoning measures contain more mental speed variance than reasoning measures under timed conditions (Wilhelm & Schulze, 2002). The relationship between simple mental speed tasks, as the ones used in our battery, and unspeeded reasoning tasks is a better estimate of the true correlation between both abilities because it removes the biasing influence present in time restricted measurement of reasoning ability and it focuses on the functions ascribed to working memory and inferential processes per se. In the case of the 8-, 9-, 10- and 11-year-olds, the experimenter read the instructions for every task and gave an example on the whiteboard prior to the testing. Following that, the participants proceeded to complete the test on their own without any further guidance from the experimenter. Since the majority of the tasks had the form of a multiple choice, the participants were asked to clearly mark their answers. In the case of the 6 and 7 year-olds the reasoning tasks were completed in a step-by-step manner with the experimenter halting the test after each task was completed, to explain the next one and to allow time for demonstrating an example.

Processing Efficiency Tasks

Speed of Processing

A simple choice reaction time task was used to address speed of processing. Specifically, a computerized version of a part of the Simon effect task was used that does not involve any kind of conflict management between stimuli and responses. Children were instructed to press the M key (which is on the far right end of the keyboard) when the target stimulus (a number digit) appeared on the right half of the screen and the Z key (which is on the far left end of the keyboard) when the stimulus appeared on the left half. Reaction times between stimulus and response onset were recorded. Twenty trials were presented for each condition and their average was automatically calculated. Thus, there were two measures of speed of processing.

A filter set at 300 and 1000 ms was used to exclude unreasonably fast or slow responses, respectively. Wrong responses were also automatically excluded. The same exclusion criteria were used for the speeded performance tasks to be described below. Moreover, the filter for unreasonably slow responses for the perceptual and the conceptual control tasks to be described below was set at 5000 ms.

Perceptual Discrimination

To examine perceptual discrimination, two pictures, one small and one big, were presented simultaneously on the screen, one on the left and the other on the right half of the screen (Figure 1). The position of the two pictures alternated randomly between the two

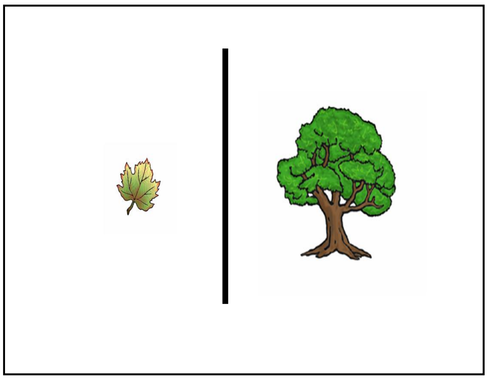


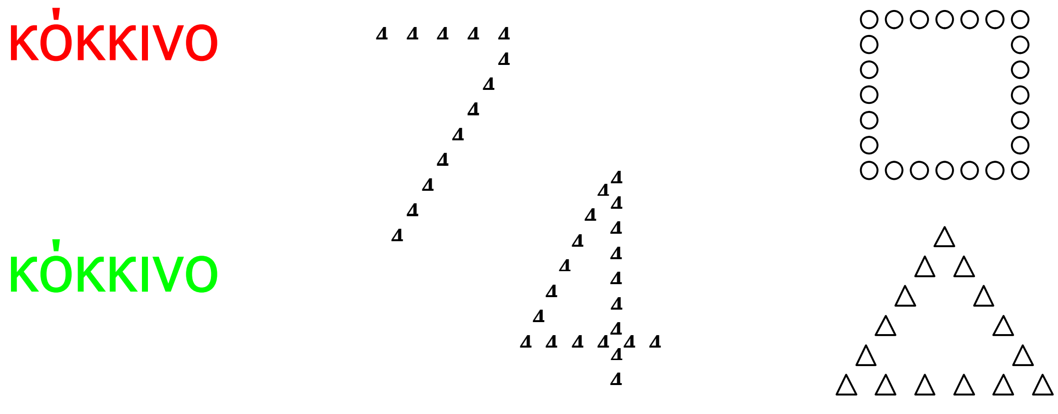
Figure 1. Examples of tasks addressed to perceptual discrimination.

sides of the screen and the participants were asked to choose the bigger of the two by pressing the M or the Z key, as described above. The objects in each pair of pictures were related physically (e.g., a “leaf” and a “tree”, see Figure 1), functionally (e.g., a “hammer” and a “nail”), and conceptually (e.g., an “apple” and a “cherry”). Thus, there were three measures of perceptual discrimination, each involving 8 trials.

Perceptual Control

A series of Stroop-like tasks were used to address perceptual control. Specifically, there were tasks using verbal, numerical, and figural stimuli. The verbal tasks were similar to the standard Stroop (1935) task, as shown in Figure 2. That is, three Greek words, which have the same number of letters—κόκκινο (red), πράσινο (green), κίτρινο (yellow)—were used and participants were tested under two combinations of meaning and ink-color, that is, word reading-compatible color and color naming-incompatible word, which is considered to be the proper test for perceptual control. Participants were instructed to use the R, the G, and the Y keys for red, green, and yellow, respectively. To facilitate responding, a red, a green, and a yellow sticker were placed on the respective keys.

The number and the figural tasks were organized according to Navon’s paradigm (1977). Specifically, the number task involved the digits 4, 7, and 9, composed either of the same digit (compatible condition) or a different digit (incompatible condition), as shown in Figure 2. That is, in the compatible condition, the large digit (e.g., 7) was composed of the same “small” digit (i.e., 7). In the incompatible condition, the large digit (e.g., 7) was composed of one of the other digits (e.g., 4). The participants were tested under two combinations of the dimension to be attended to and compatibility, that is, large-compatible and small-incompatible. Number keys on the keyboard were specified as response keys for the numbers used.



A **B** **C**

Figure 2. Examples of Stroop-like tasks addressed to verbal, numerical and figural information.

The figural system was addressed through a task battery similar to the number battery. That is, three geometrical figures (circle, triangle, and square) were used to produce the two combinations of the dimension to be attended to and compatibility, as shown in Figure 2. The participants were instructed to use the S, the C, and the F keys for "square", "circle", "triangle", respectively. In order to facilitate participants, stickers showing a square, a circle, and a triangle were placed on the respective keys. Thus, there were three measures of perceptual control, one for each symbolic medium. Each measure involved 9 trials.

According to Stroop (1935) the longer reaction time of the incompatible condition results from the inference of the dominant aspect of the stimuli (the tendency to read the word or see the big digit or shape) with the weaker but goal-relevant aspect (naming the ink-color, recognizing the small digit or shape). Moreover, in his serial model, Navon (1997) argues that perception proceeds from a global to a local analysis of scenes and that the global features of an object would have to interfere with the identification of local features, if the two are in conflict. Therefore, the incompatible conditions as described above address perceptual control. Reaction times on these incompatible conditions were taken as the perceptual control indicators.

Conceptual Control

The tasks addressed to conceptual control were similar to the perceptual discrimination tasks. That is, pairs of objects, one small and one big, were presented on the left and the right half of the screen in a way that the size of the two pictures would not differ (Figure 3).

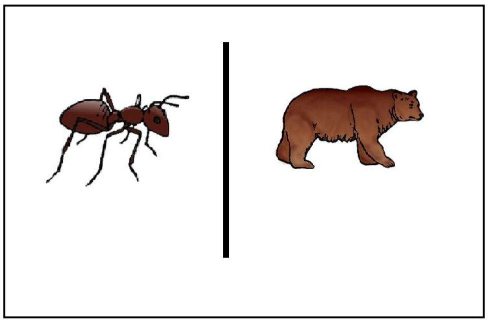


Figure 3. Example of tasks addressed to conceptual control.

The participant's task was to choose the object which was bigger in reality. Therefore, the participant would have to control the interference coming from the object that appeared bigger on screen, but it was smaller in reality, since the picture of the smaller object was enlarged so that the two objects would be presented as equal in size. These tasks are similar to those used by Paivio (1975) to examine control processes when manipulating mental images. The M and the Z keys were used as response keys for the two sides of the screen. The pictures in each pair were related physically (e.g., a "sail" and a "boat"), functionally (e.g., a "knob" and a "door"), and conceptually (e.g., an "ant" and a "bear", see Figure 3). Thus, there were three measures of conceptual control, each involving 8 trials.

Cronbach's alpha for the set of 11 measures (two for speed, three for perceptual discrimination, three for perceptual control, and three for conceptual control) described above was very high (.89 and .90, for the first and the second testing wave, respectively). Cronbach's alpha varied between .87 and .90 for the first testing wave, and .88 and .90 for the second testing wave, if any one of these 11 measures was deleted, indicating that all of these measures were very reliable indicators of processing efficiency.

Working Memory, Information Integration, and Reasoning Tasks

Working Memory Tasks

Four working memory tasks addressed the working memory capacity as a simple short-term storage of visuo-spatial information and the working memory capacity under the activation of the executive control processes when numerical information is been processed.

Short-term Memory. Short-term memory tasks addressed memory that involves recall of information for a relatively short time. In the first of the tasks addressed to visuo-spatial memory, a total of eight arrangements of geometrical figures of varying complexity were presented to the participants. Specifically, of this total, two arrangements involved two figures, two arrangements involved three figures, and the other four arrangements involved four, five, six and seven figures, respectively. Each of the arrangements was presented for as many seconds as the number of figures in it. Four alternative arrangements, each one corresponding to one of the numbers 1 to 4, were presented immediately after the presentation of the target arrangement. The participant's task was to identify the target arrangement among four alternative arrangements, presented immediately after the presentation of the target arrangement.

In the second task, the component figures were superimposed on each other. Specifically, triangles, squares, rectangles, hexagons, circles, open angles, and arcs, were used to form configurations of increasing complexity. A total of 15 stimulus arrangements were presented, organized in five levels of difficulty. Specifically, task difficulty varied in relation to the number of component figures superimposed on each other to form the target configuration. Thus, there were five difficulty levels, each including three tasks. The participant's task was to identify the stimulus arrangement among five alternatives presented immediately after the presentation of the stimulus arrangement. Due to time limitations only the second task was used in the second testing wave.

Executive Memory. These tasks were patterned on Case's (1985) paradigm addressed to working memory. Both tasks involved seven levels of difficulty. Each level was defined by the number of items to be stored in memory, so that the participant would be able to make a simple mathematical comparison. In the first task a set of numbers digits, differently colored, were presented in succession for 2 seconds each. At the end of the presentation of each set, a target digit was presented and the participant's task was to specify if this target digit was bigger than the same color digit included in the set. Four trials were given for each level of difficulty. Participants ought to succeed in at least two of the four trials in order to move on to the next level. The second task was identical to the first in all respects but the presentation of the numerical information involved in each trial. That is, instead of number digits, the numbers were represented by dots of equal size. Participants were instructed to keep in memory both the numerical information and the color of the items presented in each trial.

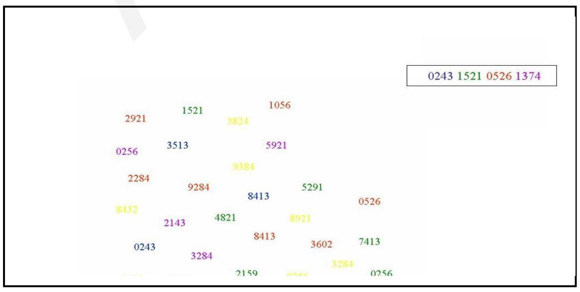
Participants were scored for their performance on each of these four tasks. Specifically, the score given to each task was equal to the highest difficulty level attained. Following Case (1985), participants were credited with a level if they succeeded on half or more of the items addressed to this level. The maximum score was 5 for the short-term memory tasks and 7 for the executive memory tasks.

Cronbach's alpha for the four working memory tasks was satisfactory (.57 and .55 for the first and the second testing wave, respectively), taking into account their small number. Cronbach's alpha varied between .48 and .52, if any one of these 4 measures was deleted from the first testing wave, indicating that all of these measures were satisfactory indicators of working memory. In the case of the second testing wave, Cronbach's alpha varied between .25 and .62, if any one of the 3 measures was deleted from the second testing wave.

Information Integration Tasks

The integration of information was measured by using an array of computerized tasks that involved three types of information; verbal, quantitative, and figurative. In this task a target stimulus was presented in the top right corner of the screen as shown in Figure 4. The components of the target stimulus (i.e., syllables for words, numbers for the number digits, and shapes for the pictures of objects), together with other irrelevant but similar components, were scrambled on the rest of the screen.

Participants were asked to decide if all of the components of the target stimulus were present on the screen (by pressing the respective key standing for "yes" or "no"). The complexity of the items varied in relation to the number of components involved in the target stimulus and the number of redundant information on screen. Obviously, in order to succeed on this task participants would have to be able to keep the necessary information in working memory, at least in part, formulate and execute a search plan for identifying components, control interference from irrelevant components, integrate the results of research into an integrated representation which could be mapped onto and compared with the target stimulus. Thus, there were three measures of information integration, one for each symbol system. A filter for unreasonably slow responses for these tasks was set at 30000ms.



Target-stimulus

Figure 4. Example of tasks addressed to information integration.
Note.
Participants must specify if all components of the target-stimulus are present on the screen.

Cronbach's alpha for the three information integration tasks was satisfactory (.63). Cronbach's alpha varied between .40 and .63, if any one of these 3 measures was deleted, indicating that they were satisfactory indicators of information integration. Due to time limitations only the numerical variant of the test was included in the second testing wave, so reliability coefficient cannot be reported.

Reasoning Tasks

A long array of tasks addressed the reasoning ability based on the assumption that the mental processes which are activated during the inference procedure are differentiated according to the type of the premises, namely their structure, their content and the meaning they convey. As a consequence, inductive and deductive reasoning ability was addressed by a number of tasks expressed in verbal, quantitative, and visual-spatial context. The whole battery of reasoning tasks used in both testing waves is presented in Appendix A. It should be noted that during the first testing wave a total of 70 reasoning items (40 items addressing inductive and 30 items addressing deductive reasoning) were used. Due to time limitations, 33 of these items (21 items addressing inductive and 12 items addressing deductive reasoning) were used at the second testing wave. The selection of the second wave items was based on the item estimates obtained from the Rasch scaling of the items. At least one easy, one of medium difficulty and one difficult item was selected for each subtest of inductive and deductive reasoning tests.

Inductive reasoning was addressed by analogies and syllogisms. Analogical thinking is the most precise expression of inductive reasoning. It looks for, and codifies, structural similarities between the source and the target situation, it extracts and applies rules, and it leads to generalizations. Syllogistic thinking refers to dealing with logical arguments which are composed of a group of premises and a plausible conclusion. It presupposes the use of an inference rule in formulating or judging a conclusion based on the premises which could in fact be some pieces of information or some subjective observations. Formulating a conclusion in inductive reasoning, can be more or less valid, based on the degree of reliability of the premises.

Deductive reasoning is the ability to reach valid conclusion by applying an inference rule on a set of premises. Verbal, quantitative and spatial syllogisms were used to address deductive reasoning ability. In designing the tasks, we made sure to control for the bias of previous knowledge (Evans, Newstead & Byrne, 1993) as much as possible by using imaginary context in the verbal syllogisms.

Inductive Reasoning. Seven verbal syllogism tasks were included. Specifically, a set of premises concerning three persons were stated. This was followed by five tasks, each one having an additional set of two premises. The participants were asked to take a stance against the validity of a proposition based on the previously suggested set of premises. The alternatives were a definite agreement, a definite disagreement, and one implying that no conclusion could be reached with certainty. Following these five tasks, two questions which referred to generalizations based on the initial premises, were posed. Again, the participants had to choose among three alternatives similar to the ones described above.

Seven word analogies addressed inductive reasoning in the verbal context. These analogies were of the form a:b::c:d, where word “d” was missing in three analogies, word “c” was missing in two analogies, and word “b” was missing in the other two analogies. The participants were asked to choose the best fitting word among four given alternatives. Difficulty was controlled in reference to the familiarity and abstractness of the relations involved.

Seven tasks addressed inductive reasoning in mathematical context. Four of them were based on a graphical display of even and odd numbers. Specifically, the numerical representation of the numbers 1 to 7 was given, laid out in horizontal sequence. In the space directly beneath each, the corresponding quantitative representation, expressed in small coupled circles, was drawn. The digits and the circles were color coded as white for odd quantities and as black for even quantities. This visual coding was also explicitly described in premises, as was the fact that the odd quantities have an uncoupled circle in their visual representation. The above information was expressed in the general premises. Following these general premises a set of four other premises were given, each of which was accompanied by a question. Participants were asked to choose one of the three alternative answers which denoted definite agreement, definite disagreement and uncertainty.

Three more mathematical syllogisms addressed inductive reasoning, containing information on prime numbers. These tasks were based on the theorem that each even number can be expressed as a sum of prime numbers. Each different task was based on the given premises along with an extra one, specifying added information. Participants were asked to decide whether a given conclusion was true, false or with no true value (not always true and not always false).

Six mathematical analogies were used to measure the ability to recognize a mathematical rule that has been applied to three different cases and then apply that rule to a fourth case. Numbers in each mathematical analogy task were presented in two columns.

Participants were told that the four numbers on the left column, which were painted white, were transformed into the black painted numbers on the right column. Each pair of numbers was laid on the same horizontal line. The task was to apply the same rule onto the fourth white number and transform it into a black number. The six mathematical analogies were designed based on both mere multiplicative relations, such as 2χ, 3χ, χ^3, and combinations of multiplicative and additive relations such as $2\chi + 1$, $\frac{\chi}{2} - 1$, $\chi^2 - 1$.

Six tasks addressed the ability to extract a general rule based on information given in a visual-spatial context and apply that rule on a new situation. All six tasks had the same structure but the level of difficulty varied. Small black and white circles were ordered in an $n \times n$ orthogonal mesh with boundaries defined by a prescribed square. This was a garden diagram with the square indicating the fence and the circles standing for stones. Three worms entered the garden, moved around, and got out. The course of the two worms was drawn. Participants were told that the worms moved based on a rule that had to do with the color of the stones and they were asked to carefully watch the two worms' given course and, based on the same rule, draw the course the third worm would follow. Complexity varied as a function of the size of the matrix (there were two 5x5, two 7x7, and two 11x11 matrices) and the number of turns in the matrix.

Seven a:b::c:d Raven-like matrices addressed spatial analogical reasoning and specifically, the ability to identify a transformation rule a shape has undergone, and apply that rule on a different shape. All shapes were constructed by combining shapes (square, circle, and equilateral triangle) using two colors, black and white. Complexity varied as a function of the dimensions involved (color, shape, and transformation). The participants were asked to identify the transformation rule in the relation between the components of the a:b pair and apply it on the c component of the second pair by choosing the right answer from a given set of four alternative shapes.

Deductive Reasoning. Sixteen arguments were designed to assess the ability to judge the true value of a conclusion that is based on a set of two premises. The first premise, a conditional one, stated a general rule, while the second one referred to a specific situation. A conclusion was given and the participants had to decide whether the conclusion suggested from the two premises was true, wrong or if the information given did not allow for a definite answer.

The first eight arguments were based on one scenario and the other eight arguments were based on a different one. The first scenario was about an imaginative group of aliens, the Paffs, who live on three different planets (the red, the blue and the purple planet), and who have three different head shapes (square, circular and triangular heads). The Paffs' names were letters from the Greek alphabet ("Alpha", "Beta", "Phi", etc). The second scenario was about another imaginative group of aliens, the Zanns, who live on two different planets (the green and the yellow planet), and who have two different head shapes (square heads and triangular heads). The Zanns' names were numbers ("One", "Two", "Eight", etc). The first scenario allowed for three different alternatives on the head shape and the planet color, while in the second scenario the alternatives were binary. This setting allowed for the study of the participants' responses when facing a binary and a non-binary situation and how this affects their conclusions in arguments like "Affirming the Consequence" and "Denying the Antecedent". So, based on the information given in the second scenario, the arguments, as designed in this test, always lead to a definite conclusion, since there are only two alternatives. This, of course, is not the case with the first scenario. Both groups of tasks examined the same pattern of arguments, based on "Modus Ponens", "Modus Tolens", "Affirming the Consequence" and "Denying the Antecedent".

Seven tasks addressed deductive reasoning involving mathematical relations. The participants had to find the missing digits of a number (a three-digit number at the four tasks and a four-digit number at the three tasks) based on a set of information. The premises given were sentences containing one or more logical connectives, such as negation, conjunction, disjunction, conditional, and biconditional. Difficulty was controlled in reference to the number of digits to be specified (four problems involved three digits and three problems involved four digits), the number of propositions involved (three 3-digit problems involved five propositions and one involved six propositions; of the 4-digit problems one involved seven, one involved eight, and one involved nine propositions), and the logical relations involved in the propositions.

Finally, deductive reasoning based on spatial information, was addressed with seven tasks. The structure of these tasks was similar to the structure of the tasks above involving mathematical relations. That is, participants were asked to specify the position of a number of animals or persons sitting next to each other based on the information of a number of propositions constraining each other in the fashion of the mathematical reasoning tasks described above. Difficulty was controlled in reference to the number of the propositions that were given and the logical connectives that were used.

Cronbach's alpha for the set of 9 measures described above (i.e., six inductive and three deductive reasoning measures) was very high (.81 and .80 for the first and the second testing wave, respectively). Cronbach's alpha varied between .79 and .80 for the first testing wave, and .76 and .81 for the second testing wave, if any one of these 9 measures was deleted, indicating that all of these measures were very reliable indicators of reasoning. The reliability of each of the two scales was also very high (i.e., .78 and .70 for inductive and .76 and .70 for deductive reasoning, for the two testing waves, respectively).

Two composite scores were formed based on the nine observed variables used in the reasoning test. Specifically, the score for inductive reasoning was the mean score of the six inductive reasoning tests and the score for deductive reasoning was the mean score of the three deductive reasoning tests.

Data Analysis

To test the hypothesis about the structural relations between the various processes addressed by our study, a series of structural equation models were evaluated using Bentler's EQS (1995). To specify the pattern of development of the various processes a series of ANOVAs with repeated measures were run. Finally, the Rasch Model (Rasch, 1997) was applied on the reasoning data to obtain an estimate of the relative reasoning abilities of the participants, independently of the specificities of the items used in the measurement, and to calibrate the reasoning items' complexity without regard to the participants' abilities or any other characteristic.

Summary

This study was designed to provide answers to complex cognitive and developmental questions addressing the development and interaction between mental processes during the school age period. The design of the study ensures that both individual differences and developmental parameters will be clearly mapped. Processing efficiency (that is, speed and control of processing), information integration and working memory capacity were addressed by a big array of electronically administered tests. Response time and accuracy were automatically recorded. These data along with the data from the reasoning ability tests comprised each participant's cognitive profile. All analyses were applied to the data from the two testing waves in order to test the stability of the proposed models. The data from the longitudinal study was analyzed separately in order to give answers from the longitudinal perspective.

CHAPTER 4

RESULTS

Introduction

To specify the structural organization of the cognitive processes and their dynamic interplay during the age span of 6 to 11 years a series of elementary cognitive tests and reasoning ability tests were administered in two testing waves with a one-year interval. Analyses were conducted based on the data collected from both testing waves, for better validating the results and the constructed models, and for adding the information from the longitudinal perspective in the proposed models. Thus, first, the architecture of intelligence, the organization and the interrelationships of the cognitive processes will be specified based on structural equation modeling. All models constructed will be tested on both testing waves' data. Based on the longitudinal data (the data collected from the participants who received the tests in both testing waves) the organization and the dynamic interrelationships of the cognitive processes will be studied from another perspective which places time as a contributing factor of change. The cross-sectional design of the study allows for a thorough analysis of the developmental profile of each cognitive process. Moreover, the role and the effect of the processing efficiency parameters on the development of the more complicated and mental consuming processes, such as the executive functions of working memory and the inductive and deductive reasoning, is examined.

The reasoning ability and its close relation with the quality of the information processing and the working memory functions is further studied by tracing the developmental stages in inductive and deductive reasoning and by mapping out the cognitive profile of the individuals who are accommodated at each reasoning stage. In so doing, the reasoning data is analyzed by applying the Rasch model. The resulting calibration on the same interval scale of the items according to their difficulty and of the participants according to their performance facilitates a further analysis on the cognitive demands of the reasoning tasks which address each developmental stage.

Finally, a theoretically based, and practically evaluated, suggestion of a formula which addresses the complexity of reasoning tasks will be presented. The complexity of the tasks will be also related to their cognitive demands in terms of activated cognitive resources. To this end, the profile of the individuals who succeed and the individuals who fail at each stage will be examined.

Analysis of Data

To test the hypothesis about the composition of the various cognitive processes and their structural relations, confirmatory factor analysis and structural equation modeling were used. All structural equation models were tested for their stability across time by using the data from both testing waves.

The Architecture of Intelligence and the Organization of Cognitive Processes

Confirmatory factor analysis was used to corroborate that the tasks that were used in the processing efficiency, the working memory, and the reasoning tests were indeed measuring the cognitive abilities they were designed to measure. The multiple indicators that were used to measure each hypothetical construct were allowed to load on the latent factor which stood for the specific hypothetical construct. In the case of the processing efficiency tests (speed of processing and inhibitory control) all indicators were mean RTs calculated as geometric means resulting from the correct responses on the multiple trials included in each task. The use of the geometric mean as a measure of central tendency is less susceptible to outlying scores than arithmetic mean is (Alf & Grossberg, 1979). All erroneous responses were not included in the computation of the mean RT and therefore they were excluded from the formulation of the indicators. Thus, for example, in the case of the sheer processing speed task there were 20 trials for the right hand and 20 trials for the left hand. Two indicators were formulated, the right and the left hand speed, each based on a maximum of 20 RTs. All tasks used in the processing efficiency, the working memory and the reasoning ability tests were used as indicators for the latent factors.

Thus, the following eight latent factors were specified with reference to 23 indicators. Specifically, sheer speed of processing (SP) was specified with reference to two indicators (left and right hand speed), perceptual discrimination (PD) was specified with reference to three indicators (part-whole relation, conceptual proximity, and physical similarity), perceptual control (PC) was specified with reference to three indicators (word, digit, and figure stimuli), and conceptual control (CC) was specified with reference to three indicators (part-whole relation, conceptual proximity, and physical similarity). Working memory (WM) as short-term storage and retrieval of information and as executive functioning was specified with reference to three indicators (complex configuration which demanded simple short-term storage, and number symbols and dice-like representations of number quantities which activated the executive functioning of working memory).

Information integration (II) was specified with reference to three indicators (words, numbers, and figures). Finally, inductive (Ind) and deductive (Ded) reasoning were specified with reference to three indicators (verbal, mathematical, spatial) each.

The use of three indicators for the identification of most hypothetical constructs enhances construct validity since the different indicators may appraise a different facet of the hypothetical construct. Moreover, the use of multiple indicators reduces the effects of measurement error on any observed variable (Kline, 1998), and therefore, increases the test's reliability. Cronbach's alpha, which reflects the magnitude of reliability and is, therefore, a very useful index of the measurement error present in the items, was calculated for each sub-test in each testing wave. Hence, Cronbach's alphas for the two testing waves were .893 and .899 for the processing efficiency test, .672 and .582 for the working memory test, and .857 and .819 for the reasoning ability test, for the first and the second wave respectively (see Table B1a and Table B1b in Appendix B for a detailed presentation of the reliability coefficient for each item, as well as the Cronbach's alpha for each test, namely the Speeded Measures, the Working Memory and Information Integration, and the Reasoning test). Therefore, the scales used for processing efficiency and reasoning constructs were excellent and the working memory scales were acceptable in terms of reliability. Moreover, the set of indicators which were presumed to measure each hypothetical construct showed convergent validity, since their intercorrelations were moderate to high (see Table B2a and Table B2b in Appendix B). Moreover, the correlations of the hypothetical constructs were not extremely high (see Table B3a and Table B3b in Appendix B), which serves as a strong indicator of discriminant validity.

The Hierarchical Model

The confirmatory factor model tested is shown in Figure 5[1] . The model fit for this model was excellent (χ^2 (210) = 241.222, p = .069, χ^2/df= 1.149, CFI = .972, RMSEA = .042). More specialized cognitive processes lie at the lower level of the hierarchy reflected by the eight first order factors. The shared variance between groups of elementary cognitive processes is responsible for the inclusion of the first order factors in a set of second order factors. Specifically, sheer speed of processing, perceptual discrimination, perceptual control, and conceptual control were regressed on a second order factor representing processing efficiency (PE). The working memory and information integration factors were regressed on the information storage, retrieval, and integration factor (SRI).

[1] Asterisks in all models presented hereafter denote significance at the .05 level. All coefficients presented in the models are taken from the standardized solutions.

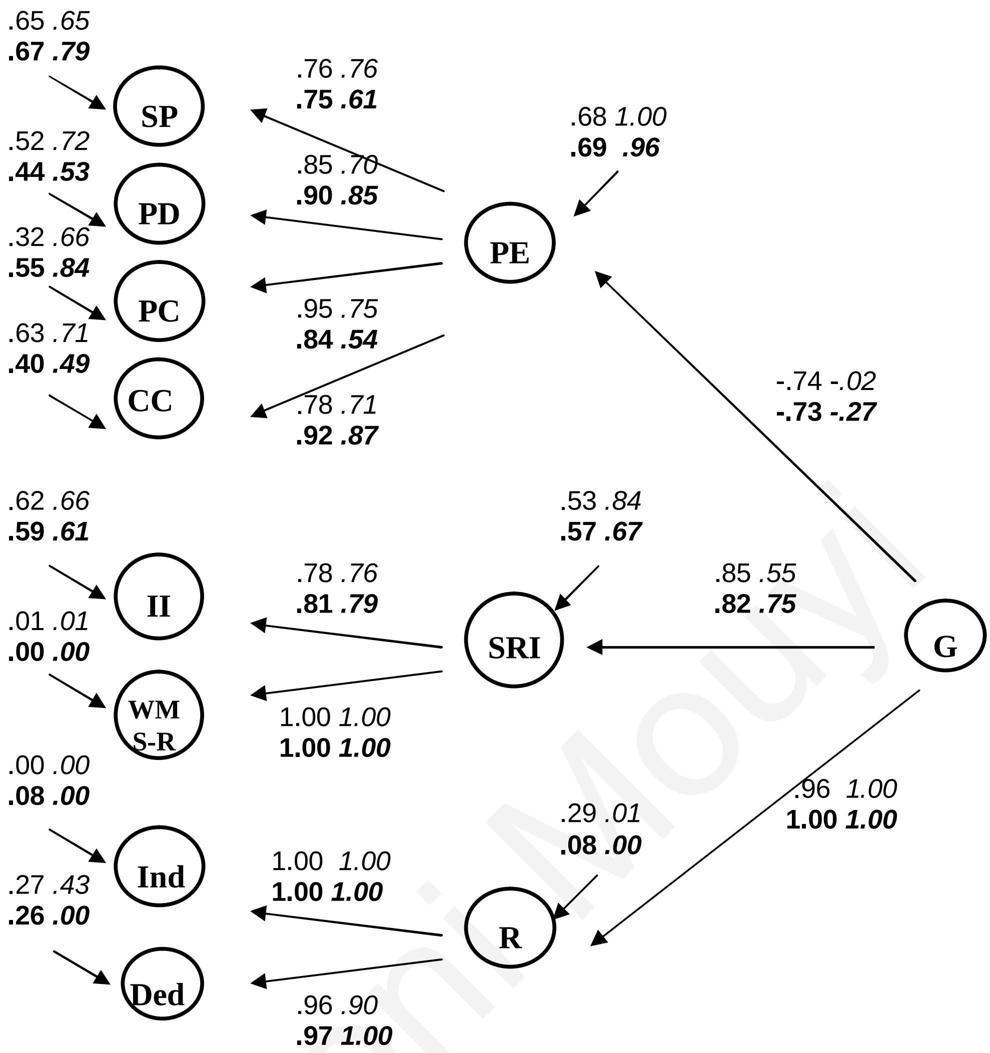


Figure 5. The three-level hierarchical model of the structure of intelligence.

Notes.

Numbers in bold refer to the second testing wave. Numbers in italics refer to the results after partialling out the effect of age.

SP: speed of processing, PD: perceptual discrimination, PC: perceptual control, CC: conceptual control, II: information integration, WM S-R: working memory as information storage and retrieval, Ind: inductive reasoning, Ded: deductive reasoning, PE: processing efficiency, SRI: storage-retrieval-integration, R: reasoning ability, G: general intelligence factor.

Finally, inductive and deductive reasoning were regressed on the reasoning factor (R). Finally, the three second order factors were regressed on a third order factor, which we consider as the factor of general intelligence (G) reflecting whatever is common between all processes (Jensen, 1998).

The same structure of the cognitive abilities emerges from both waves' data. The model fit for the second wave data (the parameter estimates are given in bold letters on Figure 5) was excellent (χ^2 (181) = 316.880, p = .000, χ^2/df= 1.750, CFI = .964, RMSEA = .047), adding to both the validity and the reliability of the constructed model. The fit indices for both models are excellent suggesting a high degree of discriminant validity which is translated into the existence of hypothetical constructs significantly different from one another. Moreover, the obtained parameter estimates from both testing waves suggest reasonable overall convergent validity, especially for the first order factors of sheer speed and perceptual discrimination (both of which are measures of speed of processing) and the perceptual and conceptual control factors (both of which are measures of inhibitory control).

A closer look at the parameter estimates is much informative in as far as the intra-structure of the more general factors and the intensity of the relations which define each second order factor. The processing efficiency of the cognitive system is defined by the specific attributes of the speed of processing and the ability of the cognitive system to control its own impulsive reactions. Speed of processing, perceptual discrimination, perceptual control and conceptual control were regressed on the processing efficiency factor. The obtained factor loadings were high, and thus reflecting a relatively small proportion of unexplained variance for the first order factors. Specifically, the general factor of processing efficiency explained 58% (56%)[2] of the variance in speed of processing, 73% (81%) of the variance in perceptual discrimination, 90% (70%) of the variance in perceptual control, and 60% (84%) of the variance in conceptual control. It is evident that the ability for perceptual control is the most robust aspect in as far the processing efficiency is concerned, suggesting that it is of vital importance in the course of information processing.

The general ability of information storage, retrieval, and integration has direct effects on the information integration factor and on the working memory factor which accommodates simple storage and executive control functions. The differentiation between the processes that underlie the two first order factors that were regressed on the information storage, retrieval, and integration factor is confirmed by the obtained factor loadings. Obviously, the system is activated in a different way according to the specificities of the task and the nature of the information that is being processed. The proportion of the variance of the information integration factor explained by the general factor of information storage, retrieval, and integration is 61% (65%), while the variance in working memory is completely explained by this general factor. This suggests that information integration is not a purely memory process but it incorporates other processes uniquely attributed to it such as planning, decision making, checking, updating and adjusting.

[2] Percentages in parentheses refer to the model obtained from the second testing wave data.

The two first order factors standing for deductive and inductive reasoning were regressed on a second order factor, namely the reasoning ability factor. Both factor loadings were extremely high, probably suggesting that the two types of reasoning are not easily discriminated from each other in regards to the underlying inferential mechanisms. Though different in procedure – since they do have different starting points and they lead to different kinds of conclusions – deduction and induction both deal with premises, apply mental rules some of which are already installed in the system, and construct mental models as a means to test alternatives and reach for a conclusion. The proportion of the variance in deductive reasoning accounted for by the general reasoning factor is 93% (in both data waves) while the respective proportion for inductive reasoning, again in both data waves, is 100%.

All three second order factors were regressed on the third order factor which stands for the general intelligence. The effect of this on reasoning was extremely high accounting for 92% (100%) of its variance. For the working memory the variance explained by the general intelligence factor is 72% (68%) and for the processing efficiency the proportion of the explained variance reached 53% (54%). It could be argued that the reasoning ability is an almost perfect reflection of the general intelligence factor, and thus it could be used as a means of measuring the general intelligence. Moreover, these findings suggest that there are processes attributed to working memory which are not included in what is conceived as general intelligence. Presumably, these are processes that are closely based on mnemonic strategies knowledge and application and on any kind of knowledge that is acquired via educational and cultural means. Furthermore, these findings suggest that general intelligence has a moderate relation with the processing efficiency parameters meaning that these parameters have half of their variance explained by their biological substrate.

In order to examine whether the suggested structure is subjected to age related differences and is thus a product of developmental changes, the same model was re-run after partialling out the effect of age, by regressing all indicators on the age of the participants at the time of the testing. The suggested model fitted the data from both waves perfectly (χ^2 (209) = 236.770, p = .091, χ^2/df= 1.133, CFI = .978, RMSEA = .040, and χ^2 (166) = 229.240, p = .001, χ^2/df= 1.381, CFI = .980, RMSEA = .036, respectively).[3] The

[3] The p value of the χ^2 statistic for the second wave data is less than .05 when this value should be higher than .05 in order for the null hypothesis of no difference between the obtained model and the real data, not to be rejected. Despite this, in the case of large samples (as is the case with the second wave where approximately 400 participants were tested) this is not a problem since the χ^2/df ratio of less than 2 is considered a satisfactory criterion for the model fit.

parameter estimates for these two models are given in italics on the Figure 5 (the parameters obtained from the second wave data are in bold italic characters on the same figure).

After partialling out the effect of age, all loadings of the indicators on the first order factors were decreased. The most drastic drops were observed in the loadings of the indicators of the deductive and inductive reasoning factors, although they remained significant. This drastic drop indicates that reasoning ability covaries extensively with age and therefore radical changes occur in reasoning performance in the age span studied here. These changes that come as a byproduct of age maturation are basically in the sphere of knowledge acquisition, of learning how to get access to categorically organized information, and of the accumulated repertoire of alternatives to pragmatic, semantic, and hypothetical schemas. The key role age has in the development of reasoning is best uncovered by the analyses to be discussed below that focus on age-specific transformations. A noticeable decrease was observed in the loadings of the speed and control indicators on their respective first order factors suggesting that the development of the processes of speed of information processing and inhibitory control is in a great extent depended to age-related, most probably organismic, changes. The least impressive decrease was observed in the loadings of the indicators of working memory and information integration. The moderate level of these decreases is probably suggesting that working memory and information integration are affected by age-related differences in a more subtle way than the reasoning and the processing efficiency abilities. Specifically, it seems that information storage and retrieval, and information integration are partly affected by the biological changes which are manifested in the speed and control of processing and partly affected by changes in the representational capacity that occur in the course of maturation. The regression coefficients obtained in the first level of the hierarchical model clearly reflect intra-variance, that is, variance accounted by the specific abilities and hence, they reflect the manifested individual differences, their nature, and the degree of their covariance with age.

At the second level of the hierarchical model controlling for the effect of age resulted in just a slight decrease of the correlations between the first and the second order factors indicating that the presumed interrelations between the hypothetical constructs are accurate. The structure and the intensity of the relations of the more specific cognitive abilities with the more general processes are proved to be invariant at least for the age span from early childhood through preadolescence. The hierarchical model strongly suggests that the interrelations of the more general processes of processing efficiency, working memory and integration, and reasoning with the more specific abilities are both robust and steady. At this level, the obtained factor loadings do not reflect individual differences in performance. Rather, they reflect the reliability of the cognitive processes web irrespectively of any age-related differences. Speed of processing, perceptual discrimination, perceptual control, and conceptual control are highly correlated to the processing efficiency factor. Working memory is perfectly correlated to the factor of information storage, retrieval, and integration while information integration remains highly correlated with this factor. The perfect correlation of inductive and deductive reasoning with the general reasoning ability remains unaffected from the age-related changes. The structure and the intensity of the web interweaved by both the more specific and the more general cognitive processes is statistically confirmed and it is present from the early stages of childhood till the entrance to adolescence.

Finally, at the apex of the hierarchical model, the correlations between the second order factors with the general intelligence factor reveal a pattern of possible developmental changes. Specifically, the reasoning ability factor demonstrates an impressive stability in as far as its correlation with the *g* factor, while the correlation of working memory with the *g* factor is somewhat decreased. What is very remarkable is the drastic drop of the correlation between the processing efficiency and the *g* factor. Generally speaking, this pattern of correlations between the second order factors with the general intelligence factor, before and after partialling out the effect of age, strongly suggests that the ability to reason is the cornerstone in the architecture of mind and of what constitutes intelligence. Working memory is an important part of the mind structure, while the processing efficiency is strongly subjected to the changes due to maturation. Moreover, this pattern of correlations indicates that some mechanisms maintain a reasonably stable relation with general intelligence by remaining invariant to age-related changes. Seen from a closer look, the hierarchical model suggests that basic inferential rules and mental model construction principles are established in the system early in life, making reasoning a vital part of general intelligence.

Comparatively stable, yet less strong, is the relation of the functions ascribed to working memory with the general intelligence factor. Information storage, retrieval, and integration mechanisms are presumably not intensively subjected to age-related differences. The magnitude of the factor loadings decrease when the age-related variance is controlled indicating that the relation of the cognitive construct of information storage, retrieval, and integration with the general intelligence factor is only partially manipulated by changes due to maturation. To a great extent, this relation is developed based on the functions ascribed to information storage, retrieval, and integration as such in a reasonably invariant manner. The manifested increase in working memory capacity (as we will demonstrate below) is most likely a side effect of the radical changes that occur in the parameters of processing efficiency. The drastic drop of the regression coefficients of processing efficiency with the *g* factor is strong evidence that processing efficiency and age covary in a way that the underlying mechanisms of speed and control of processing are developing with maturation and are gradually becoming a significant part of *g*. As time goes by the system becomes progressively more efficient in managing the input information and subsequently, the storage, retrieval, and integration mechanisms are improved. The information is processed in a more “dexterous” manner drawing less on the cognitive resources of the system.

The hierarchical model which resulted from both testing waves strongly suggests that the mind is hierarchically organized. More specialized abilities lie at the lower level of the hierarchy and are represented by the clearly distinct first order factors. Their functional role is to act like information receptors and information processors. Each specialized system acts in a relevant functional autonomy, but it is constrained by the limitations imposed on it by the condition of the higher factors. It is clear that higher order and more general systems do have strong direct effects on the hierarchically lower factors and at the same time are subjected to their possible drawbacks.

The pattern of factor loadings as they are presented in the hierarchical model before and after partialling out the effect of age confirms that the proposed three-stratum architecture of intelligence is not only statistically plausible but it is cognitively reasonable and informative as to the real existence of functionally discernible levels of organization of the mind. Specifically, the first level of the hierarchy represents the observed deviance in the various specific cognitive functions as a result of individual differences in performance. At this level, specificity of the cognitive functions is defined in terms of the process and the content of the information. The second level of the hierarchical model represents the structure and the strength of the interrelations of the more general functions. The cognitive processes’ web is shown to be austerely defined and invariant over time. Finally, at the third level of the hierarchy the model uncovers the structure of general intelligence in terms of processing efficiency, information storage, retrieval and integration, and reasoning. This structure is to a degree subjected to age-related differences. Limitations imposed on the system, due to shortcomings in the speed and control of information processing, are reflected on the relation of the processing efficiency factor with the *g* factor. As a result of the processing efficiency limitations a moderate effect on the relation of information storage, retrieval and integration with the *g* factor is observed. Biological and representational changes that occur during early and middle childhood are obviously affecting information processing in an extensive degree and information storage, retrieval and integration in a more subtle way. On the contrary, the nature of the relation of the inferential mechanisms that underlie reasoning ability with the *g* factor is not affected by age-related changes. The reasoning processes, namely rule application and mental model construction, have a perfect correlation with the *g* factor which constitutes reasoning the best predictor of general intelligence.

The Simplex Model

The cognitive processes are hierarchically organized in such a way that more simple processes lie at the core of more complex process in a cascade fashion. Measures of the various cognitive processes were designed based on this encapsulation assumption, and the suggested hierarchy is first theoretically and then statistically supported. Theoretical considerations on the way the various cognitive processes are organized and on the mental demands the various tasks impose on the system were the principles on which the task design was based. First, based on Jensen's work (1998) we consider speed of processing as being the simplest process which affects the condition of all other processes. Our attempt to measure speed was based on the Simon-like tasks which were designed taking under account the need for hierarchical complexity. As a result, speed of processing was measured in two ways which illuminated this ability from two different perspectives. Specifically, as confirmatory factor analysis showed, the tasks addressed sheer speed of processing (measured with the Simon-like tasks under the compatibility condition) and perceptual discrimination (measured with similar tasks differing only in the amount of information they conveyed, making this measurement more demanding in cognitive terms than the previous one). Drawing on the ability of perceptual discrimination, a set of Stroop-like tasks were designed as measures of the ability to perceptually discriminate between two types of information integrated in a stimulus, and to control the tendency to let the perceptually dominating, but non-relevant information to interfere with the processing of the relevant information. Thus, perceptual control is a more hierarchically complex process that involves the functioning of sheer speed of processing and of perceptual discrimination. Taking a step further, a set of tasks was designed to measure the ability of controlling the interference, and consequently the dominance, of the perceptual impression the stimuli make, and process the conceptual information existed in the stimuli. Conceptual control builds on the resources of speed of processing, perceptual discrimination, and perceptual control. All of these processes reside on the same level of primary processing of information which sets the stage for a more demanding and more advanced processing to follow.

All of the processes that are assumed to reside on the level of primary processing are included in the functions ascribed to information storage, retrieval and integration along with the process of retaining the information in a state where it can be intentionally retrieved. The tasks which were designed to address working memory also satisfied the need for hierarchical complexity, since part of them called on simple storage and retrieval processes, and the rest called on the executive functions of working memory as well as storage and retrieval. The next array of tasks, which addressed information integration, were designed based on the assumption that working memory was highly activated when dealing with these tasks as well as the mechanism of making a plan of how to deal with a set of information units under time constraints. Finally, reasoning ability is presumed to incorporate all processes integrated in information integration along with the inferential processes which are, by themselves, a complicated process aiming to make valid arguments and draw the right conclusions. Working memory, information integration and reasoning, reside on a higher level of representational and operational processes whose executive functions are strongly depended on the processes residing on the lower level of primary processing of information. This level of representational processes could be, at least partly, identified with the processes attributed to the hypercognitive system, as this is well defined in Demetriou's theory (Demetriou et al., 2002).

Before moving to the next level of analysis at which the variance of each cognitive process will be decomposed into its components involved in the processes lying lower than it in the hierarchy, the assumed hierarchical organization of the processes lying at each level and the hierarchical relation of the two levels will be examined. The simplest test of the hierarchical calibration of the processes would be a simplex model where each factor in the hierarchy is regressed on the factor residing one level lower than it (Gustafsson & Carlstedt, 2006). Identifying the best hierarchical structure presupposes that a number of possible, theoretically grounded, models are tested so that the best fitting model that is theoretically meaningful and sound is chosen. Two constraints were imposed on these models. The first, a theoretical one, referred to the existence of two levels of processing, namely the primary information processing and the representational and operational processing. In the level of primary information processing reside the factors of speed and control of processing, while in the level of representational and operational processing

Table 1. Alternative simplex models with fit indices.

Suggested Structure	X^2	**p**	**CFI**	**RMSEA**
SP-PD-PC-CC-**WM-II-R**	178,713	.03	0,965	0,053
SP-PD-CC-PC-**WM-II-R**	169,397	.09	0,975	0,044
PD-SP-PC-CC-**WM-II-R**	196,259	.00	0,946	0,065
PD-SP-CC-PC-**WM-II-R**	171,365	.07	0,973	0,046
PC-CC-SP-PD-**WM-II-R**	197,588	.00	0,943	0,067
PC-CC-PD-SP-**WM-II-R**	195,604	.00	0,945	0,066
CC-PC-SP-PD-**WM-II-R**	194,764	.00	0,947	0,064
CC-PC-PD-SP-**WM-II-R**	179,049	.03	0,964	0,053
SP-PD-PC-CC-WM-R-II	175,770	.05	0,968	0,050
SP-PD-PC-CC-II-WM-R	177,739	.04	0,966	0,052
SP-PD-PC-CC-II-R-WM	180,694	.03	0,963	0,054
SP-PD-PC-CC-R-WM-II	202,480	.00	0,939	0,069
SP-PD-PC-CC-R-II-WM	181,022	.03	0,962	0,054

reside the factors of working memory, information integration and reasoning. This constraint was posed in order to ensure that the hierarchy of the processes would not be violated. The second constraint, a statistical one, was based on the evaluation of the complexity of processes that belong in the same sub-level of processes. Specifically, based on the mean reaction times for the two speed factors, namely sheer speed and perceptual discrimination, it was concluded that the latter is a more complex process than the former. Accordingly, it was concluded that conceptual control was a more complex process than the perceptual control. Therefore, the processes belonging in each sub-level were limited in following an inner hierarchy imposed by the reaction time study.

The fit of all models tested is summarized in Table 1. In the first group of models the processing efficiency factors were interchanged and the processes at the representational level retained a certain hierarchy. Working memory was considered the less complex process of the three while the reasoning was considered the most complex one. In this group of models reordering of the processes was done on the assumption that the processes belonging at each sub-level should lie next to each other in the hierarchy. In the second group of models the representational level processes were reordered while the parameters at the processing efficiency level retained a certain hierarchy. Based on the mean reaction times of each test, speed of processing was considered the less complex process of the four while the conceptual control was considered the most complex one. In both of these groups the two levels of processes retained their relational hierarchy, that is, the representational processes were considered as lying at the higher level of the hierarchy. All models have the same df (146), enabling one to easily compare the chi square statistics. As it can be seen in Table 1, all alternative models have CFIs ranging from .939 to .975.

Based on the fit indices of the first group of models where the two speed factors are placed at the lower level of the hierarchy, three out of the four models that are presented are statistically robust (CFIs circa .97) suggesting that speed of processing is the most simple function of the system. The fit indices of the models presented in the second group of alternative models, which are based on the assumption that control processes are the most fundamental ones, clearly suggest that the control processes cannot be considered as the basis of the cognitive processes' hierarchy. Control of processing is effected on the basis of the speed of processing. Non-relevant information is efficiently controlled, and hence the system is better protected, when the incoming information is processed at a pace which allows the *scanning* of as much bits of information as possible. The findings from the first two groups of alternative models indicate that speed of processing lies at the lower end of the hierarchy followed by the control of processing which is more complex and demanding than the sheer speed of processing.

The last group of alternative models deals with the assumption that at the processing efficiency level lie the speed and control processes in a fixed manner (SP-PD-PC-CC) and that the processes in the representational level are allowed to be placed in any position of the hierarchy within the constraints of their level. The fit indices of most of the models in this group are satisfactory. These findings suggest that representational processes which lie at the highest level, in terms of complexity, are not hierarchically organized within the level. They function in such a way that their dynamic interplay within the representational level, and with the other processes, is not defined by any inner hierarchy. Nevertheless, it is suggested by the design of the present study, that the processes are hierarchically organized in such a way that each higher process draws upon the cognitive resources of the process lying lower than it in the hierarchy. The framework of this study suggests that, at the representational level, the reasoning processes are the most complex of all processes studied and that the information integration process entails the executive functions of working memory, in addition to the processes attributed to it per se. Therefore, the proposed structure of the simplex model lies in the first group of alternative models, where control is regressed on speed and the representational processes are regressed on control. In this group of models the representational level processes are functionally organized in a hierarchy that allows for the reasoning ability to be regressed on information integration and this ability, in turn, to be regressed on working memory capacity.

The three statistically robust alternative models in the first group (the first, the second, and the forth one) need to be further compared on a theoretical basis, since their chi square statistic and their CFIs are satisfactory. An important criterion should be the framework set by the aim of the study and therefore by its design. Specifically, the processes residing within each of the two processing efficiency sub-levels cannot be ordered in a non-hierarchical structure. Their hierarchical structure is primarily defined by the complexity of their inner structure. Specifically, perceptual discrimination entails sheer speed of processing and the processing of information is based on their perceptual characteristics without any demand on control processes. Perceptual discrimination should be regressed on sheer speed of processing. Conceptual control entails all control processes embedded in perceptual control and the controlling of information based on its conceptual constraints. Therefore, conceptual control is regressed on perceptual control. As a consequence, based on these restrictions imposed by the design of the study and the complexity of the processes' inner structure and confirmed by the statistical criteria, it is suggested that the first alternative model reflects the hierarchical structure of the cognitive processes.

Figure 6 presents the proposed simplex fashion model. The fit of the model was very good (χ^2 (146) = 178.713, p = .03, χ^2/df= 1.224, CFI = .965, RMSEA = .053 (90% confidence interval for RMSEA = .016 - .077). In order to test the stability of the proposed structure over time, the same model was re-run after partialling out the effect of age. The fit of the model was very good (χ^2 (146) = 170.975, p = .08, χ^2/df= 1.171, CFI = .976, RMSEA = .046, 90% confidence interval for RMSEA = .000 - .072) indicating that the proposed simplex structure of the cognitive processes is stable during childhood.

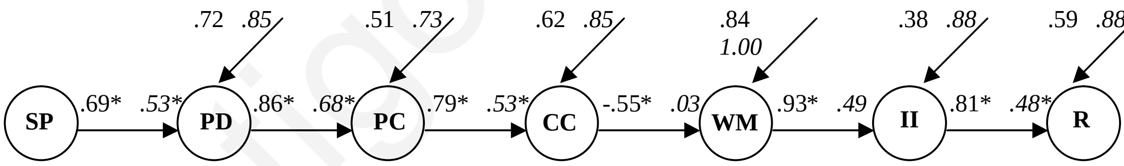


Figure 6. The simplex model of the hierarchical relations between factors.
Notes.
Numbers in italics refer to the results after partialling out the effect of age.
SP: speed of processing, PD: perceptual discrimination, PC: perceptual control, CC: conceptual control, WM: working memory capacity, and R: reasoning.

The simplex hierarchical structure of the cognitive processes suggests that speed of processing is the basic source of individual differences in the control and the representational processes. The processes are involved in a dynamic interplay where they are affected by the condition of the simpler processes and they, in turn, affect the functioning of more complex processes. The proposed simplex model confirms the existence of two broad levels of processes, namely the encoding and selection level and the representational level. Their cut off point, the regression of working memory capacity on conceptual control, is indicative of their distinctiveness. Specifically, the relation of these two processes, which constitutes the link between the two levels, is the weakest relation observed in the model and, moreover, when the effect of age is partialled out, the most drastic drop of the regression coefficients is observed in this relation. This pattern of relations strongly suggests that these processes are organized in two distinct levels and that within each level there are strong relations between processes residing at this level.

The strongest relations are observed between the processes residing in the representational level. Specifically, 66% of the variance in reasoning ability is accounted for by information integration, meaning that inferential processes draw on the ability of planning and integrating information. In turn, individual differences in information integration can, to a very large extent (86%), be attributed to differences in working memory capacity. In the encoding and selection level, the regression coefficients indicate strong relation between the processes, and therefore an important amount of the individual differences in one process can be explained by the variance in the next lower process. Specifically, 62% of the variance in conceptual control is explained by the perceptual control variance, while 74% of the variance in perceptual control is attributed to the individual differences in the perceptual discrimination process. Finally, sheer speed of processing explains 48% of the variance observed in perceptual discrimination.

Attention is drawn to the developmental aspects of the model. Specifically, when the effect of age was removed from the relations of the processes, there was a large decrease of the regression coefficients of the representational processes and a small decrease of the regression coefficients of the encoding and selection factors. These findings indicate that the structure of the relations of the processing efficiency factors is stable throughout childhood, indicating that their change is most probably driven by the same underlying force. As far as the representational factors are concerned, age is an important factor indicating the role of age-related experience in the construction and use of the strategies and processes involved at the representational level.

The Cascade Model

The hierarchical organization of the processes as it is verified by the simplex model is used in the proposed cascade model (Figure 7). This model is an attempt to clarify the dynamic functional relations between the two levels of processes, namely the encoding and selection level and the representational level, by approaching this relation in a refined manner assuming fine differences in the demands of different components of processes.

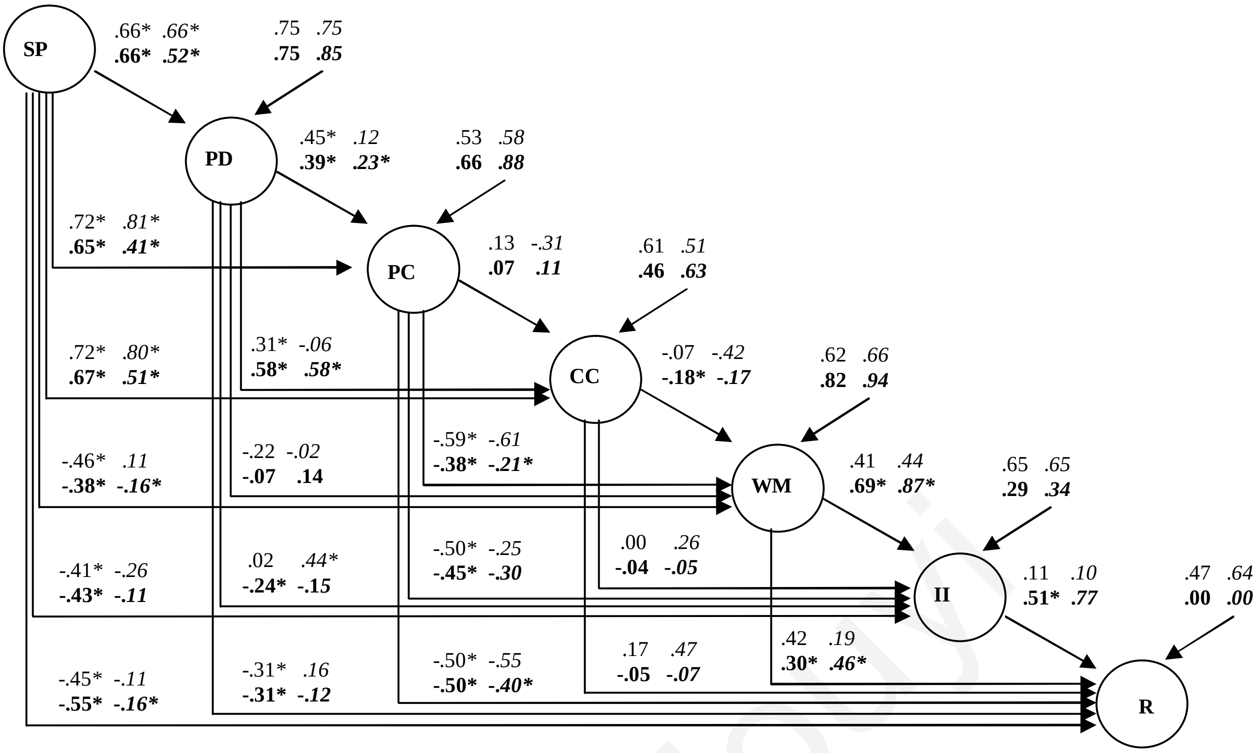


Figure 7. The model of the structural relations between processes.
Notes.
Numbers in bold refer to the second testing wave. Numbers in italics refer to the results after partialling out the effect of age.
Model fit for first and second wave: χ^2 (130) = 110.889, p = .89, χ^2/df= 0.853, CFI = 1.000, RMSEA = .000 (90% confidence interval for RMSEA = .000 - .027) and χ^2 (99) = 177.967, p = .000, χ^2/df= 1.798, CFI = .977, RMSEA = .048 (90% confidence interval for RMSEA = .037 - .059), respectively.
Model fit for first and second wave after partialling out the effect of age: χ^2 (130) = 117.337, p = .78, χ^2/df= 0.902, CFI = 1.000, RMSEA = .000 (90% confidence interval for RMSEA = .000 - .038) and χ^2 (99) = 144.560, p = .002, χ^2/df= 1.460, CFI = .984, RMSEA = .039 (90% confidence interval for RMSEA = .024 - .053), respectively.

The structure of the relations of the cognitive processes which was examined is expressed with the help of the following equations:

Perceptual Discrimination =	Speed + *perceptual discrimination processes*;	(1)
Perceptual Control =	Speed + PD + *control of perceptual attributes interference*;	(2)
Conceptual Control =	Speed + PD + PC + *control of interference from perceptual attributes to knowledge in long-term memory*;	(3)
Working Memory =	Speed + PD + PC + CC + *storage and retrieval processes*;	(4)
Information Integration =	Speed + PD + PC + CC + WM + *planning and integration processes*;	(5)
Reasoning =	Speed + PD + PC + CC + WM + InfI + *inferential processes*;	(6)

Each factor was regressed on speed of processing and on the residuals of all the factors residing lower than it in the hierarchy. With this manipulation the sources of variance of each factor are descriptively identified. The model fit for both testing waves was excellent (see Figure 7).

Sheer Speed of Processing. The cascade model was built on the assumption that speed of information processing is functionally included in every cognitive process. As expected, sheer speed of processing was highly correlated (correlations ranging from .65 to .72 in both testing waves) with all the first level processing efficiency factors standing for speed and control. What is worth noticing is that the correlation between the factor of sheer speed of processing with the other factor standing for speed, namely the perceptual discrimination, was .66 which means that more than half of the perceptual discrimination variance cannot be explained by sheer speed of processing. This finding suggests two things. First, that the test designed for measuring the ability of perceptual discrimination was indeed a test for speed of processing but it was hierarchically differentiated from the measures of sheer speed of processing. The picture stimuli used in that test conveyed an amount of information which was being processed by the system, though this processing was irrelevant to the aim of the task per se, and, it subsequently had an effect on the measures of reaction time. The clear distinctiveness of the two speed tests contributed at a finest measuring of speed and thus approaching with more reliable means the individual differences in the speed of processing. Second, it suggests that another test for measuring speed of processing under a different condition is needed, so that it will serve as an "interface" between the measures of sheer speed and perceptual discrimination and thus provide a more refined picture of the general ability of speed and how it affects the functioning of the other processes.[4] The sheer speed factor was significantly correlated with the working memory factor -.46 (-.38) indicating that the function of working memory is to a significant extent affected by the speed with which the incoming information is processed. More speeded processing contributes to a somewhat lessened cognitive load on the working memory and therefore to a more efficient storage and retrieval of information. The same pattern of correlations was observed between sheer speed and information integration -.41 (-.43) indicating the important role of speed in the process of setting and implementing a search plan based on the perceptual characteristics

[4] One such test could be the measures taken from the Stroop-like test for measuring perceptual control. Specifically, these are the RTs recorded during the trials where the relevant aspect of the information was the dominating one and was compatible with the non-dominating information.

of a set of stimuli which are closely related in terms of perceptual characteristics. Finally, speed of processing plays an important role in the inferential process with correlations reaching -.45 (-.55). In other words, speed of processing accounts for 20% - 30% of the variance in reasoning performance. This finding sheds light on the relation of logical reasoning with speed of processing in an unbiased way. Research on inductive and deductive reasoning has not always objectively approached this relation since it is usually based on measures of speeded reasoning tasks which unavoidably contaminate the results and provide an inflated correlation between speed of processing and reasoning. The use of non-speeded reasoning tasks ensures that the obtained correlation is not inflated and thus, the correlation of sheer speed with reasoning as was obtained in our study is approximately -.50.

Perceptual Discrimination. The residual of the perceptual discrimination factor which resulted after regressing perceptual discrimination on sheer speed was used as an indicator in the regression equations of all higher processes. This residual factor was significantly correlated with the factors standing for inhibitory control. Specifically, its correlation with perceptual control was .45 (.39) and with conceptual control .31 (.58). These numbers reflect the distilled correlation of the inhibitory control factors with the ability of perceptual discrimination freed from any effects caused by sheer speed of processing. The ability to discriminate stimuli based on their perceptual characteristics can explain 20% (15%) of the variance observed in the process of perceptual control whereas the respective proportion of the explained variance observed in conceptual control is 10% (34%). These proportions suggest that a significant part of the individual differences in the performance in inhibitory control tasks is attributed to the specific ability of perceptual discrimination. It should be noted that although the relation of perceptual discrimination with perceptual control was both high and significant, this was not the case with its relation with conceptual control. Our findings support the idea that the system is unavoidably processing the perceptual characteristics of the stimuli even if its target is to make a decision based on the conceptual characteristics.

The obtained correlations of perceptual discrimination with working memory and information integration reveal no relation with either of these processes which can be attributed to the functioning of working memory and information integration. While vast amounts of information reach the cognitive system every minute via the various receptors, only part of it is being processed in the working memory. This process, does not call on the perceptual discrimination function as such. Rather, it calls on the sheer speed of processing and on the control processes, as it will be shown below, in order to ensure that no important information is lost and that no unnecessary processing will take place and cause the overloading of working memory. Thus, perceptual discrimination does not serve the needs of working memory. Similarly, information integration (as it was defined and measured in the present study) draws on sheer speed and perceptual control rather than on perceptual discrimination per se. Under the specificities of the test used, the application of the search plan was not drawing on the resources of perceptual discrimination since the stimuli were identical with the target stimulus in the perceptual dimension.

Unlike the absence of any relation of perceptual discrimination with the other two functions residing in the representational level, perceptual discrimination accounts for almost 10% of the variance in reasoning performance. This finding suggests that when faced with a set of premises the reasoner draws on both speed processes, the sheer speed and the perceptual discrimination, in order to activate the necessary and sufficient alternatives and either use them in mental model construction or use them as a confirmation or a counterexample (in an inductive manner) of a mental rule. Sometimes the available alternatives have to be constrained in order to avoid overload of the system or interference of non-relevant information. The process of perceptual discrimination along with the process of perceptual control, as we will demonstrate below, are activated in order to secure that the alternatives retrieved from memory are the ones needed. Moreover, in the course of maturation, the type and the number of the alternatives used are defined not only by the meaning of the premises but by their syntax as well. Syntactic features are easily traced once freed from the meaning they convey and therefore the role of perceptual discrimination becomes more important in the reasoning process.

Control of Processing. Although perceptual control and conceptual control are the two factors accounting for the variance of the tasks designed to measure the ability to control processing they are strongly differentiated in as far as their contribution to the variance of the factors residing in the representational level, and in as far as their correlation with the other factors residing in the information processing level. Specifically, conceptual control has close to zero contribution to the variance of the two memory-related factors and the reasoning factor. However, the role of perceptual control is very substantial in the functioning of these abilities. In other words, the biggest portion of the variance of each of the three representational abilities is explained by the ability of perceptual control. Sheer speed is the second strongest factor accounting for the variance in the three representational level factors. These findings strongly suggest that the degree to which the hierarchically higher processes are effectively functioning is not only affected but it is also defined by the specificities and the peculiarities of the functioning of the more fundamental processes, namely sheer speed and perceptual control. This finding is in accord with the attribution to the functioning of working memory of the process of executive control (Zelazo, 2004) along with the processes of storage and retrieval. Executive control draws on the process of perceptual control which protects the system from both allocating its mental resources on processing non-relevant information and prematurely terminating a processing. This ability is of great importance to the process of information integration and reasoning since it acts like a shield and ensures that the mental energy of the system is wisely distributed according to the task demands. The very low correlation between perceptual control and conceptual control makes it clear that they are standing for two totally different aspects of cognition. The high correlation of conceptual control with the two speed factors, namely the sheer speed and perceptual discrimination factors, can be justified by the fact that it is a speed factor too and by the Simon-like test setting for these measurements. This means that the portion of their shared variance can be, at least partly, attributed to the test characteristics.

Working Memory. The findings on the relation of working memory with reasoning are controversial. Admittedly, this relation was expected, based on the findings of other researchers (Kyllonen & Christal, 1990), to appear strong and significant. The data show that the correlation of working memory with reasoning, when this was calculated based on the first wave data, was relatively high (.42), though not statistically significant, while their correlation when calculated based on the second wave data, though smaller (.30), it was statistically significant. The difference in the magnitude of correlations found at the two testing waves needs to be explained. It is reminded that the sample size at the first testing wave was approximately the one third of the sample size at the second testing wave. This explains why the correlations observed based on the second wave data, although smaller in some cases are significant. In the case of the correlations of the three representational factors the correlations for the second wave data are lower than the corresponding ones for the first wave data, but they are significant unlike the ones for the first wave data. The large sample size used in the second testing wave affects the magnitude of the correlation but it gives more robust results. The working memory and reasoning relation has been extensively studied and it is most often the case that the data of these studies point to a very strong relation. Why then does our data from the two testing waves not fully agree with what is a strong assumption in the cognitive science literature? We can provide two reasons for this “discrepancy” in the resulting relation of working memory and reasoning.

The first reason lies in the variability of the tasks used and in the difference in how these abilities are defined in the various studies. Specifically, working memory capacity has been defined as the number of bits of information which can be stored and retrieved within a very short period of time (some seconds). The lack of consensus as to what a unit of information is, has led to conflicting research outcomes. Moreover, some researchers have accredited working memory capacity with the ability to effectively process input information, activate the control processes while doing so, and store and retrieve this information upon request (Kail, 2007). Moreover, the complexity and the nature of the tasks used do also have an impact on the results. The same considerations hold for defining and studying reasoning ability. For many researchers, reasoning ability is the ability to solve novel problems or the ability to combine information and reach for a conclusion based on some strategies or previous experience. Again, task complexity is a major factor which greatly affects the results. In the case of our study, working memory tests included both simple storage tasks as well as tasks drawing on the executive function of working memory. The reasoning tests referred to inductive and deductive reasoning as defined by the logic doctrine; therefore, the reasoning factor is not a problem solving factor, in the general, all purpose, sense it is usually used. Our notion of reasoning is close to Spearman's (1904) notion of eduction of relations and this can explain the strong relation of reasoning factor with the *g* factor as it emerged from our hierarchical model (Figure 5).

The second reason lies in the difference in the analyses used to decipher the relation between working memory and reasoning. Specifically, the reason this relation appears to be attenuated when compared to what is usually found in other studies, is the fact that in our study the strong correlations of working memory with speed and control as well as the strong correlations of reasoning with speed and control were not included in the estimation of the correlation of working memory and reasoning. What our findings reveal is the pure correlation of working memory and reasoning, freed from the spuriousness both speed and control cause when not partialed out. So, what appears to be an extremely strong relation between working memory and reasoning is in fact a reflection of an inflated correlation due to their common variances with two other factors namely the processing speed and control. Unavoidably, omitting predictors which correlate with the only predictor used in the equation (in this case the working memory) results in an inflated relation.

Therefore, our findings suggest that working memory is moderately correlated with the reasoning ability based on the rules and processes of the austere logic. Unlike the general problem solving ability where various solutions can be theoretically and practically applied, evaluated, and moderated, in the case of inductive and deductive reasoning things seem to be more content free and less working memory demanding. Rather, inductive and deductive reasoning are based on the functioning of long-term memory, since the mental rules and the specific knowledge which makes more effective the accessibility and use of alternatives, must be effectively activated from the long-term memory and serve as vital constituents of the core processes of logical reasoning. The outcome of reasoning process is strongly dependent on the repertoire of mental rules already installed in the long-term memory of the system and on the amount of accumulated knowledge on specific contents. The role of working memory is limited to the online processing of the premises in order to facilitate the activation of the mental rules and the specific knowledge needed for further processing the information and reaching for a conclusion. In so doing, working memory is strongly depending on both speed and control of processing which ensure that the information from the premises is efficiently processed and that content, context and belief biases do not interfere during the retrieval of alternatives from long-term memory and their embodiment in the mental models. The control mechanism protects overloading working memory during both the retrieval and the embodiment procedure since it blocks the activation of non-relevant alternatives (and therefore their process in working memory) and it inhibits the premature ending of the retrieval and the embodiment procedures.

Information Integration. Information integration shared its greatest proportion of variance with the processing speed (17% and 18%)[5] and the perceptual control (25% and 20%) from the first level of processing efficiency factors and, as expected, had a relatively big amount of its variance explained by working memory (17% and 48%). These findings are fully justified if one takes into account the cognitive demand of the tasks designed to measure information integration. These tasks had a high demand on working memory resources. Participants had to keep active the target stimulus in the working memory and at the same time scan the group of stimuli to track the one which was identified with the stimulus activated in the working memory. This process also demanded high activation of the perceptual control in order to secure that the non-relevant stimuli would not interfere in the procedure. In regards to the relation of information integration with reasoning the results from the two testing waves are controversial. An impressively low correlation is observed when the model is based on the first testing wave (.11) while their correlation when the model is based on the second testing wave is high (.51) and statistically significant. Though this discrepancy in results calls for further testing we suggest that the results obtained from the second testing wave are more reliable since they were based on a larger sample. Finally, it should be noted that the pattern of relations for working memory and information integration with the four factors residing in the level of processing efficiency, namely sheer speed of processing, perceptual discrimination, perceptual

[5] Variances are reported for the first and second wave respectively.

control, and conceptual control, is almost identical suggesting that both processes rely in a very similar way on the resources from the processing efficiency level.

Reasoning Ability. The reasoning ability factor lies at the apex of the hierarchy and a large proportion of the individual differences in it can be attributed to the factors residing lower in the hierarchy. The proportion of its unexplained variance (22% and 0%) was the smallest one when compared with the respective proportions for the rest of the factors in the hierarchy. This means that a highly complex mental function can be analyzed in terms of its cognitive underpinning and thus it can be better understood. As a result, performance on the complex mental function can be predicted with a relatively satisfactory accuracy.

Testing the Stability of the Proposed Cascade Model over Time

Since the study was designed to address the structure of cognitive functions in the age span from 6 to 11 years of age, one could argue that the suggested hierarchical model of the functions' interplay is prone to age biases. That is, age-related differences may have drastically contributed in the resulting model and that this model results from growth-driven relations which go away in adulthood. In order to test this possibility the cascade model presented in Figure 7 was re-run after removing the effect of age, that is after regressing all manifested variables on the participant's age at the time of the testing in addition to the latent factors each manifested variable was originally regressed on. This was done on the data of both testing waves. The parameter estimates of the models of the first and second testing waves are given in Figure 7 with italics and italics bold, respectively. The fit of both models after partialling out the effect of age was excellent (see respective note under Figure 7).

Partialling out age resulted in an annihilation of the correlation coefficients of speed of processing with all three factors which belong to the representational level, namely working memory, information integration and reasoning. This means that speed of processing covaries with age and that its role in predicting the functioning of the other processes can be identified with the role of age in the development of these processes. In other words, speed of processing can be used as a strong developmental factor in predicting individual differences in the various cognitive processes. This developmental course of speed of processing functions as a necessary condition for the functioning and the development of higher order mental processes. (We will elaborate on that at the next section.) Controlling for age did not affect the structure and the intensity of the relations between the processing speed and the perceptual discrimination, perceptual control and conceptual control factors. This invariable web of relations suggests that the role of speed in all factors residing in the first level of information processing is constantly and significantly crucial at all ages. Speed of processing is defining individual differences in all functions that call for either simple processing or activation of inhibitory control. Thus, in the case of the functions in the representational level, speed acts as a strong developmental factor, and in the case of the functions in the processing level, speed acts as a predictor for individual differences.

The profile of the interrelations of the other speeded factor, the perceptual discrimination factor, with the cognitive factors that lie higher than it in the hierarchy is clearly distinguished from the profile of sheer speed. In all but one cases the coefficients of the regression of all higher order factors on the perceptual discrimination factor were reduced. The only exception was recorded in the case of the regression coefficients of information integration where a significant increase to 0.44 from 0.02 was observed. This may be an implication that, during the age span studied here, some substantial changes happen that temporarily reverse the normal or the expected pattern of relations. These changes may have the meaning of Karmiloff-Smith’s representational redescriptions (Karmiloff-Smith, 1991) or they may suggest the application, on-line evaluation, and modification of new strategies. Strategy use and automatization of a process are important, and sometimes erratic, factors which affect the functioning of mental processes and alter the pattern of observed changes. Though this research did not focus on strategy use and automatized functioning of mental processes, the impressive increase in the regression coefficient for the first wave data strongly suggests that a developmental change – most probably a U-shaped change – takes place during childhood. This will be further discussed and analyzed in the next section where the developmental pattern of each cognitive process through the age span studied here, will be presented.

The strong pattern of the relations of perceptual control with the higher order functions, as was clearly established from both testing waves, is greatly affected when age is partialled out. In a way, its correlations with working memory and reasoning are preserved at the same level, but are not found to be statistically significant. This means that as children grow up their ability to control processing is gradually becoming more effective and therefore more significant in the process of working memory and reasoning. Unlike that, the relation of perceptual control and information integration is weakened when the variance attributed to age is subtracted from the relation of the two processes, leading to the conclusion that in as far as information integration is concerned, perceptual control is purely a developmental factor. It becomes an important part of the information integration process as children get closer to entering adolescence by allowing them to efficiently control the vast amount of perceptually conflicting information and have a search plan accomplished successfully.

The profile of the conceptual control factor in both models (before and after partialling out age) was interesting. The absence of any relation between the perceptual and the conceptual control factors, though they are both representing control processes, may suggest that the cognitive system receives and processes the various aspects of information in a strongly differentiated way. That is, different brain areas or different neural webs are activated, according to whether the information is perceptually or conceptually classified. Subsequently, the different control mechanisms which are activated during information processing have clearly distinguished contribution to the functioning of the representational processes and, consequently, to the observed individual differences.

The proposed cascade model which was constructed after partialling out age indicates a significant and moderate to high correlation of working memory with information integration and reasoning. These correlations strongly suggest that working memory is an important factor affecting in a mostly direct way the variability in both information integration and reasoning. The increase in the correlations observed based on the second wave data lead to the assumption that during childhood working memory functioning, and therefore working memory capacity, is going through a reformation or a kind of readjustment and reshuffle of its resources in order to become more functional and efficient in dealing with the processing of incoming information, either from the environment or from long-term memory.

Finally, Information Integration has no significant correlation with reasoning, a finding which implies that reasoning is mostly based on speed and control of processing and the efficient functioning of working memory irrespective of age. Therefore, individual differences in reasoning are attributed to the above mentioned processes and to a great extent to processes that are strictly related to reasoning as such, namely the mental rules' repertoire, the mental rules' construction and validation, the mental models' construction and on-line evaluation, and the ability for decontextualization of the given information, abstractiveness and theorizing.

The Analytical Cascade Structure of the Relations between Cognitive Processes

Our aim to untangle the cognitive processes' web with the proposed cascade model (Figure 7) left some obscurity as for the nature of working memory and its role to the logical reasoning process. The obtained regression coefficients, before and after partialling out the effect of age, did not illuminate this aspect. Rather, they called for more detailed examination as to the interrelation of the two basic functions of working memory (simple storage and executive control) with the two types of logical reasoning (inductive and deductive). To this end, a more analytical cascade model was run which included two factors for working memory and two factors for reasoning. It should be reminded here that the second testing wave battery was identical to the battery used in the first testing wave except in the case of the working memory test (simple storage was based on one, instead of two tests) and the information integration test (it was based on one, instead of three tests)[6]. By removing these tests no substantial information was lost since analyses of the first wave data showed that the two tests on the simple storage functions of working memory did not differ in the information they provided on the individual differences, and that the three information integration tests did not differ in the information they provided either. The fact that the simple storage factor and the information integration factor each have a single indicator when the second testing wave data are analyzed causes some statistical problems and sets some limitations as to the generalization of the results. Thus, in the case of these two factors our discussion on the relations revealed from the analytical cascade model will be mainly based on the results from the first wave data.

The analytical cascade model is presented in Figure 8. The fit of the model was excellent for both testing waves' data. Moreover, the fit of the model after partialling out the effect of age was also excellent for both testing waves. All fit indices are reported in the Figure 8. The pattern and the strength of the interrelations between the processes which reside on the first level – the processing efficiency level – are to a great extent the same as in the cascade model presented in Figure 7. Moreover, the analytical cascade model has no further information to provide as to the relation of the information integration process with the processing efficiency parameters. These relations have been presented earlier, so in the present analytical model attention will be drawn on the status and the dynamic interrelations developed by the two working memory factors and the two reasoning ability factors. Specifically, each of these representational processes will be analyzed in terms of its relation with the processing efficiency resources and its interrelations with the other representational processes.

Working Memory as Simple Storage and Executive Control Functions and the Processing Efficiency Processes. The simple storage functions of working memory have a strong and significant relation with the sheer speed of processing and the perceptual

[6] As it was stated in the Method, the second wave tests had to be reduced due to time limitations and the best way to do this was by removing one working memory test and two information integration tests from the second wave battery.

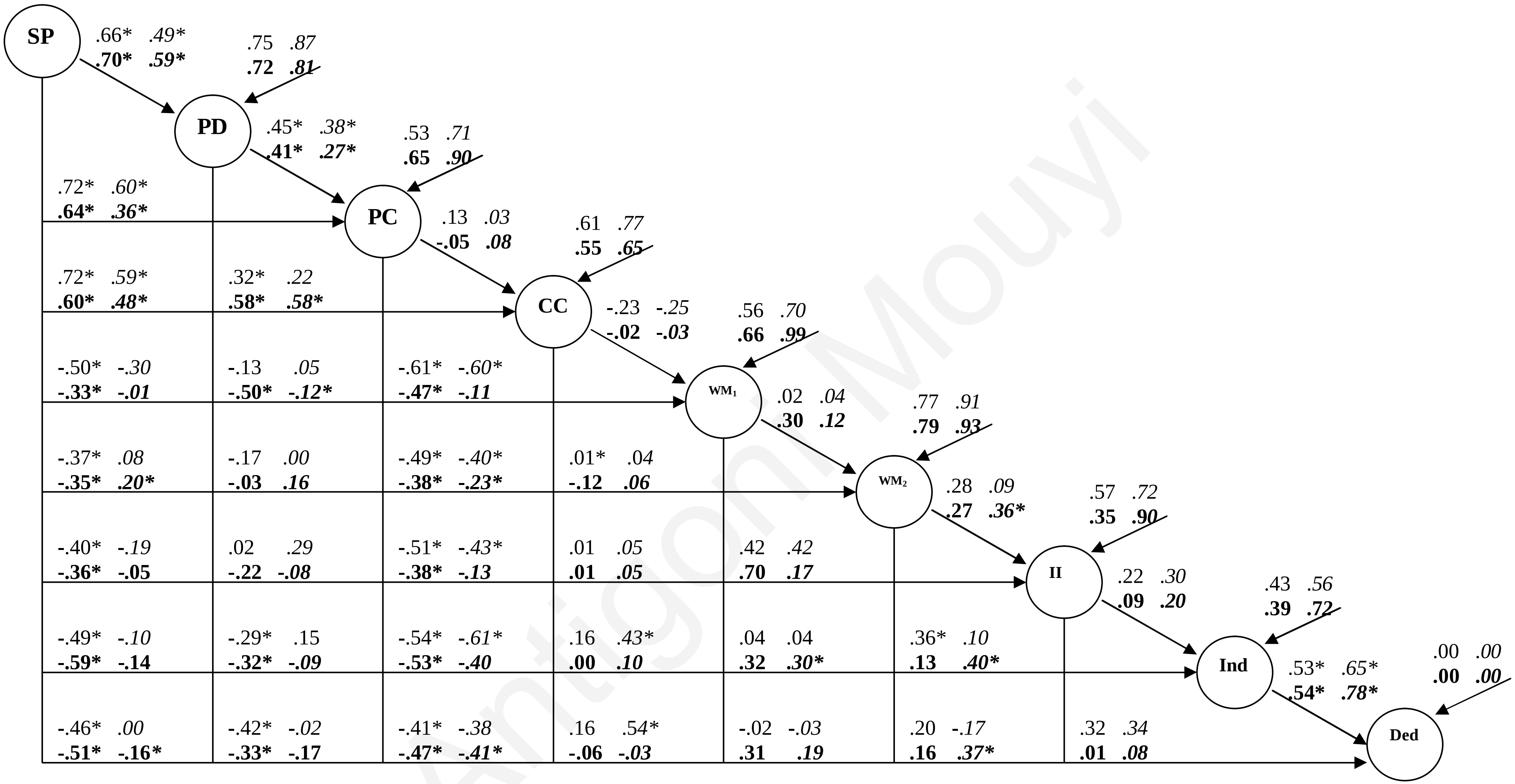


Figure 8. The analytical model of the structural relations between processes.

Notes.

Numbers in bold refer to the second testing wave. Numbers in italics refer to the results after partialling out the effect of age.

Model fit for first and second wave: χ^2 (208) = 233.198, p = .11, χ^2/df= 1.121, CFI = .977, RMSEA = .039 (90% confidence interval for RMSEA = .000 - .063) and χ^2 (127) = 174.235, p = .00, χ^2/df= 1.372, CFI = .986, RMSEA = .033 (90% confidence interval for RMSEA = .019 - .044), respectively.

Model fit for first and second wave after partialling out the effect of age: χ^2 (208) = 224.678, p = .20, χ^2/df= 1.080, CFI = .987, RMSEA = .031 (90% confidence interval for RMSEA = .000 - .058) and χ^2 (124) = 144.005, p = .11, χ^2/df= 1.161, CFI = .993, RMSEA = .023 (90% confidence interval for RMSEA = .000 - .038), respectively.

control functions while no relation is observed with the perceptual discrimination and the conceptual control functions.

These findings suggest that when the system is merely memorizing information without any processing on it, then it draws on the speed and control resources in order to store as many bits of information as the capacity limitations allow. The role of both processes in the efficient simple storage functioning of working memory is of great importance. High speed of processing prevents the loss of information due to the decay of its mnemonic trace and perceptual control protects the working memory from overloading with non-relevant processing. Due to the working memory capacity limitations it is important for the system to make good use of its processing efficiency resources in order to facilitate the storage of information.

A logical question would be as to the very low relation of the simple storage functions of working memory with the factor of conceptual control. One would expect that their relation would be high and significant since conceptual control would, like perceptual control does, act as a sheath to prevent the overloading of the working memory. These considerations are reasonable. It should be noted, however, that in both tests used to measure the simple storage function of working memory the stimuli presented were geometrical configurations with many perceptual features whereas no conceptual qualities were present. Therefore, the weak relation of the simple storage function of working memory with the process of conceptual control can be attributed to the test characteristics.

The correlational pattern between the executive control function of working memory with the speed and control of processing is similar to the one obtained for the relation of the simple storage function of working memory with the processing efficiency parameters, though it seems that the need for high speed of processing is more vigorous when simple storage takes place than when the executive functions of working memory are activated. The respective correlations of the executive function of working memory with the processing efficiency parameters are somewhat reduced. Nevertheless, the role of perceptual control remains critical in filtering out the irrelevant information and in protecting working memory from overloading. Overloading working memory means that the mental energy resources were allocated in processing non-relevant information and as a consequence its space is occupied by an amount of irrelevant to the task at hand information.

When the same model was re-run after partialling out the effect of age the correlation of the simple storage function of working memory with sheer speed of processing was weakened while its correlation with the perceptual control factor remained at the same level. The same changes occurred in the correlations of the factor of the executive control functions of working memory with sheer speed and perceptual control. These findings are in accord with the findings from the cascade model presented earlier about the strong developmental nature of the speed of processing factor and the functioning of perceptual control as a factor defining and explaining individual differences in the capacity of working memory.

Induction and Deduction and the Processing Efficiency Processes. Inductive reasoning has the highest correlation with the sheer speed of processing and with the perceptual control process when compared with the respective correlations of the other processes lying at the representational level. Specifically, its correlation with speed varies between -.49 and -.59 which means that 25% to 35% of the individual differences observed in inductive reasoning performance can be explained by the variance in sheer speed of processing. If the portion of variance in inductive reasoning, which is explained by the other speed factor, namely the perceptual discrimination factor, is added, then the respective proportions are increased to 32% and 45% for the two testing waves. These findings suggest that the speed with which information is processed is a substantial source of variance in inductive reasoning. Furthermore, 30% (for both testing waves) of the observed variance in inductive reasoning can be attributed to the individual differences in the effectiveness of inhibitory control. The findings on the relation of inductive reasoning with the speed and control of processing strongly suggest that the process of induction is substantially depending on the processing efficiency resources.

The correlational pattern of deductive reasoning with the processing efficiency parameters is similar to the pattern of correlations obtained for inductive reasoning, though moderately decreased. Approximately 20% to 25% of the variance in deductive reasoning can be attributed to sheer speed differences while when the perceptual discrimination contribution is taken into account, the respective portion of the variance increases up to 37% to 39%. Furthermore, the deductive reasoning process seems to draw on a substantial degree on the perceptual control process. Specifically, 17% to 22% of the variance in deductive reasoning is explained by the individual differences in the ability for inhibitory control. In general, more than half of the variance in deductive reasoning (54% to 61%) is accounted for by the processing efficiency parameters.

The annihilation of the speed coefficients when the effect of age was statistically controlled is once again indicating the developmental role of speed of processing. Moreover, the imperative role of perceptual control as a factor explaining individual differences is once more revealed by the fact that the high correlations obtained between inductive reasoning and perceptual control and between deductive reasoning and perceptual control are retained after controlling for age. Finally, the set of coefficients of conceptual control with inductive and deductive reasoning as they were obtained from the first wave data is a probable indicator that a significant conceptual change occurs during childhood (6 to 11 years) which affects the functioning of both types of reasoning. Specifically, when age is partialled out, the coefficients of conceptual control with reasoning significantly increase from 0.16 to 0.43, and, from 0.16 to 0.54, for inductive and deductive reasoning, respectively. Such a pattern of increases is probably suggesting that during the age span studied here a conceptual change takes place and this change, which may have the format of concepts being recognized in broader and more detailed categories, is responsible for a significant portion of the variance observed in both reasoning types. Subsequently, the two most basic processes of conceptual thinking, namely specialization and generalization, are going under a change too. As a result, inductive and deductive reasoning are both being affected since specialization and generalization are core processes in the functioning of deductive and inductive reasoning. This assumption on conceptual change is only based on the findings of the first wave data so one should be circumspect in adopting it.

The Interrelation of the Representational Processes. The analytical cascade model has revealed some interesting correlational patterns between the factors lying at the representational level. First of all, working memory, as a system for processing information and storing it for a short period of time,[7] is obviously divided into (at least) two subsystems which function independently and have a clearly distinct relation with the other representational processes. The simple storage function of working memory is found to be totally absent from the reasoning processes while its only relation which is not found to be statistically significant seems to be with the integration information ability. This relation could be attributed to the nature of the tests used for measuring information integration which demanded the implementation of a search plan based on the comparison of a vast amount of information bits with a source stimulus kept in memory. The source stimulus was simply stored in working memory for as long as the search for finding its identical stimulus, among the many presented, was on.

On the other hand, the results on the role of the executive functions of working memory are vague. The results from the first wave suggest that the role of the executive functions of working memory is differentiated according to the type of the reasoning

[7] The online communication of working memory with the long-term memory for providing it with new information and for retrieving already stored information is not included in the scope and the design of this study. Therefore, no conclusions can be drawn regarding this function of working memory.

process. Specifically, it seems that its role in inductive reasoning process is important while its role in deductive reasoning is not. Furthermore, when the effect of age was controlled its role in inductive reasoning was significantly decreased which suggests that the executive function of working memory is a developmental factor in as far as inductive reasoning is concerned. When the results from the second testing wave are studied, then the executive function of working memory seems to have no role in the functioning of the reasoning processes. Nevertheless, when the effect of age is partialled out then an impressive increase in the correlation of the executive function of working memory with both reasoning processes is obtained. This finding implies a representational change which occurs during childhood and which causes some changes in the way the executive function of working memory is involved in the reasoning processes. It should be noted that the same kind of increase is observed in the correlation of the executive function of working memory with the information integration process. These increases may suggest that the executive function of working memory does not covary with age in the sense of a linear development. Changes within the core of working memory, reinforced by the biologically initiated changes in the processing efficiency system, open the way for changes in the way information integration and reasoning ability are related to the executive function of working memory. This may also suggest that the system as time goes by does not rely on the working memory resources in the same fashion as it does in early childhood. It is probable that the system develops strategies and rules which substitute or bypass the need for working memory functions as such. Moreover, as children enter the last pre-adolescence period they are less prone to the content biases and able to reason based to the syntactical and structural characteristics of the information. Decontextualization contributes to reasoning in an abstractive way and this prevents the loading of working memory with unnecessary processing of counterexamples and alternatives as is usually the case in inductive and deductive reasoning, respectively.

Finally, a relation, which holds in time in an impressively strong way, is the one observed between the two types of reasoning. Their relation remains invariant through childhood and this can be attributed to the fact that deductive reasoning functions on the basis of the repertoire of mental rules which are shaped and confirmed via an inductive reasoning procedure. This ongoing relation conforms to the idea of recursiveness between the two processes. Mental rules are shaped as a result of the generalization procedure which is based on a set of observations. The mental rules are under a potential dispute or confirmation according to the new data and the new line of reasoning. New conclusions that result from deductive reasoning may set a starting point for a new quest and a new line of thought for searching for a new rule which will apply to more (or all) cases, and so on. The obtained coefficients reflect this ongoing recursive relation which does not covary with age. It is dynamically present from the early stages of childhood and it signifies, to a great extent, individual differences in the two types of reasoning. The portion of their common variance reaches 25%; a portion which increases when the effect of age is statistically controlled (42% and 61% for the first and second wave, respectively).

The Parsimonious Cascade Structure of the Relations of Cognitive Processes

Both cascade models presented above, the simple and the analytical one, included some relations which were not significant. These models are saturated and thus one might argue that their excellent fit is due to this fact. In order to provide a model with more clarified relations between the cognitive processes a more parsimonious model was constructed based on the significant relations as these emerged from the cascade models presented earlier. Such a parsimonious model would be preferable over the saturated models and thus the web of the processes' relations as well as their strength would be considered as a more realistic apodosis of the true correlational pattern between the processes. This parsimony-based model is shown in Figure 9.

As it can be seen all non-significant relations, but the working memory-reasoning relation that was significant in the second model, were dropped in this model. The fit was excellent for both testing waves' data. Specifically, the fit for the first and second wave was χ^2 (138) = 121.237, p = .84, χ^2/df= 0.879, CFI = 1.000, RMSEA = .000 (90% confidence interval for RMSEA = .000 - .032) and χ^2 (103) = 168.786, p = .000, χ^2/df= 1.639, CFI = .981, RMSEA = .043 (90% confidence interval for RMSEA = .031 - .054), respectively, and the fit for first and second wave after partialling out the effect of age was χ^2 (131) = 93.763, p = .99, χ^2/df= 0.716, CFI = 1.000, RMSEA = .000 and χ^2 (104) = 140.064, p = .01, χ^2/df= 1.347, CFI = .987, RMSEA = .034 (90% confidence interval for RMSEA = .017 - .048), respectively.

The correlational patterns between the various processes are revealed in a way that each process is granted with a more realistic value. Speed of processing is confirmed as a core process present in all other cognitive processes. It covaries with age in as far as the representational processes are concerned and therefore it is a strong developmental factor. It defines a significant part of the variance observed in working memory (23%), the variance observed in information integration (14% - 17%), and the variance observed in reasoning ability (21% - 31%). Perceptual control is the other information processing factor which has a very important role in the functioning of the representational processes.

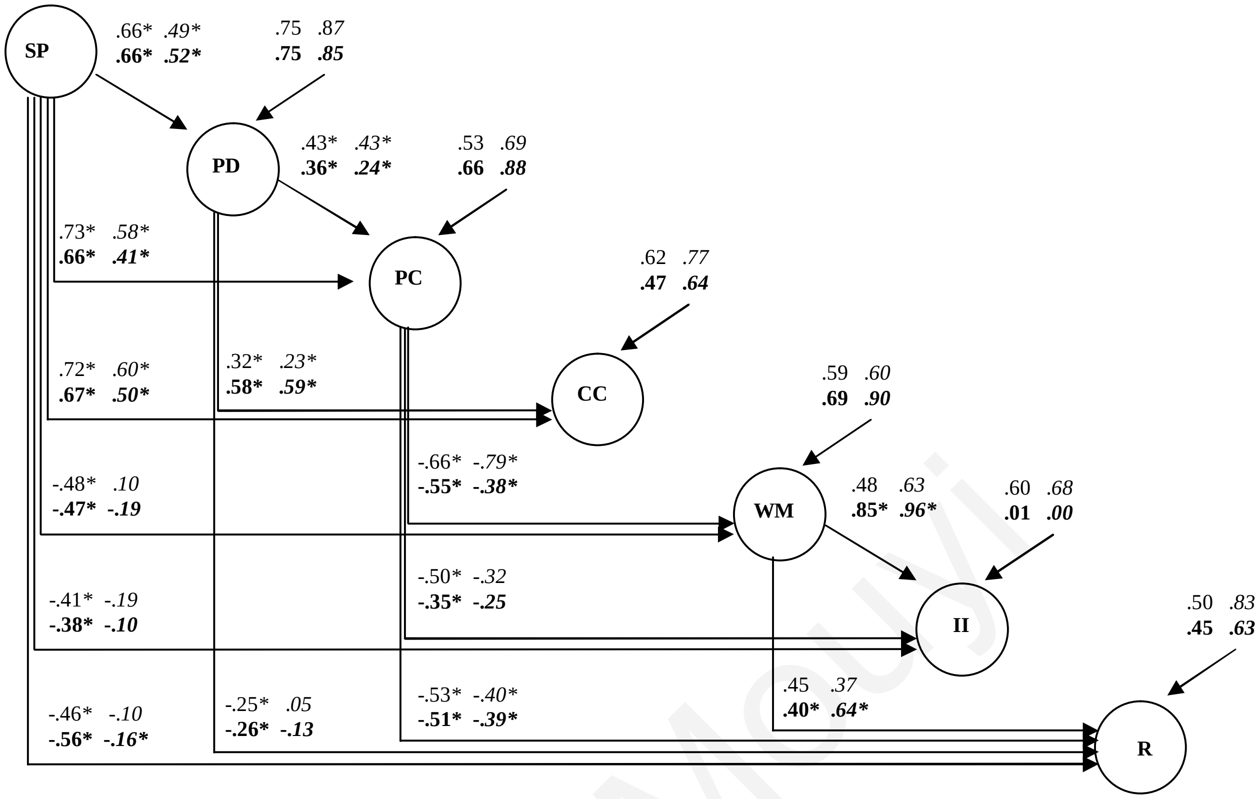


Figure 9. The model of structural relations between processes after dropping non-significant relations.

Note.

Numbers in bold refer to the second testing wave. Numbers in italics refer to the results after partialling out the effect of age.

It explains a significant part (30% - 44%) of the variance in working memory. It is responsible for protecting the system from allocating its resources in processing non-relevant information and thus it prevents the overloading of working memory. Perceptual control is also present in the reasoning processes where it exemplifies its dual role: filtering out the non-relevant information and inhibiting premature termination of the reasoning process. It is of great importance, in terms of effective management of the cognitive resources, to keep out as much non-relevant information as possible and thus use the pool of cognitive resources for the effective processing of the relevant to the goals information. Reasoning process is based on the processing of the information given in the premises and on the processing in the working memory of the information retrieved from long-term memory such as mental rules and specific knowledge to be used as alternatives in mental model construction. The control mechanisms help the system focus on the relevant information and capitalize on its resources. Furthermore, the control mechanisms inhibit the tendency of the system to end the reasoning process as soon as it reaches a conclusion that seems to accommodate the minimum demands in a satisfactory way, before fleshing out all necessary alternatives.

The relation of working memory with the factors residing higher in the hierarchy is strong. Information integration and reasoning seem to have a substantial amount of their variance attributed to the individual differences in working memory. The data from the second testing wave indicate that a very high portion of the variance in information integration is common variance with working memory (71%). The relation of reasoning with working memory is appeared to be less strong. Both testing waves indicate that the proportion of their common variance is around 16% to 20%. It should be noted that a considerable amount of the variance in reasoning ability (20% - 25%) is not explained by the processing efficiency or the working memory and the information processing functions. This variance reflects individual differences in processes that are strictly related to the reasoning processes per se. This finding, along with the finding on the respective unexplained amount of working memory variance which is around 35% to 48%, suggests that these processes entail more complexity than the present study was able to analyze and, therefore, more and different tests are needed to be added in order to decompose the variance of these complicated processes.

When the effect of age is removed from the relations of the processes then the developmental nature of speed of processing is confirmed and the role of perceptual control as a factor significantly affecting individual differences in working memory capacity and reasoning ability is authenticated. Furthermore, working memory is revealed as a factor describing individual differences in both information integration and reasoning ability. This finding on the nature of working memory is very important since it sheds light on a very crucial matter of cognitive and developmental psychology as to the role of working memory in thinking in general. The correlations of working memory with the other higher order factors are not annihilated when the effect of age-related changes are statistically controlled. On the contrary; in some cases the correlations tend to increase. This finding indicates that working memory is a factor of individual differences and that during childhood (6 to11 years of age) some deep representational changes happen that alter the relation of working memory with the information integration and the reasoning processes. These changes in working memory, as the correlations obtained in the analytical cascade model revealed, may be the result of a series of other changes that are manifested in the core cognitive processes, such as the speed and the control.

The hierarchical models presented so far strongly indicate that speed of processing has a critical developmental role to play in as far as the representational processes are concerned and thus, changes that occur in these processes are originated in changes in speed of processing. Nevertheless, changes cannot be attributed to a single factor. They are the result of the synergy of many factors in a series-of-changes fashion. The construal of a series-of-changes that are originated in the simplest, less *g*-loaded processes and affect all processes lying higher in the hierarchy, appears to affect the higher order processes in a cascade amplification mode. Improvement in the less *g*-loaded process (the speed of information processing), whose output serves as input to the next higher process (the control of information processing), results in this process – the control – yielding yet a better output. The cascade configuration of the system amplifies the gained benefit which is ultimately manifested in the most *g*-loaded processes.

The Longitudinal Perspective

The results emanating from the cascade models presented so far strongly suggest that cognitive processes are intertwined in a way that changes in simple processes drive changes in more complex processes. These suggestions are based on cross-sectional data so far. A more persuasive case for this assumption would come from longitudinal evidence, where one can see the sequence of developmental events in time. Normally, we expect that the structural relations suggested by the models above would emerge in the deployment of these processes from the one testing to the next. The longitudinal data was extracted from a group of one hundred eleven 6 to 11-year-olds (Mean = 8.78 years, SD = 1.51, 57 girls) who were tested twice, with a year intervening between the two testing waves.

The four processes included in the model were drawn from these two testing waves. Thus, SP_1 denotes speed of processing for the first testing wave and SP_2 for the second; PC_1 and PC_2 stand for control of processing; WM_1 and WM_2 denote working memory, and R_1 and R_2 represent reasoning ability. The processes, as they emanate from each testing wave, are hierarchically organized in the simplex fashion presented earlier, with the simplest one lying at the lowest level and the most complex lying at the apex of the hierarchy. Speed of information processing is the simplest process on which the control of processing is regressed. Working memory is regressed on control of processing, and reasoning is regressed on working memory. This simplex-mode hierarchy of the processes was constructed for both testing waves. The processes at the second testing wave are regressed on speed of processing at the first testing wave and on the residuals of the other first wave processes (i.e., control, working memory, and reasoning). This structure is based on the hypothesis that age-related changes, which can be observed within a year intervening between the two measurements, can be attributed to changes occurring in all processes and, therefore, our assumption of a dynamic interplay between

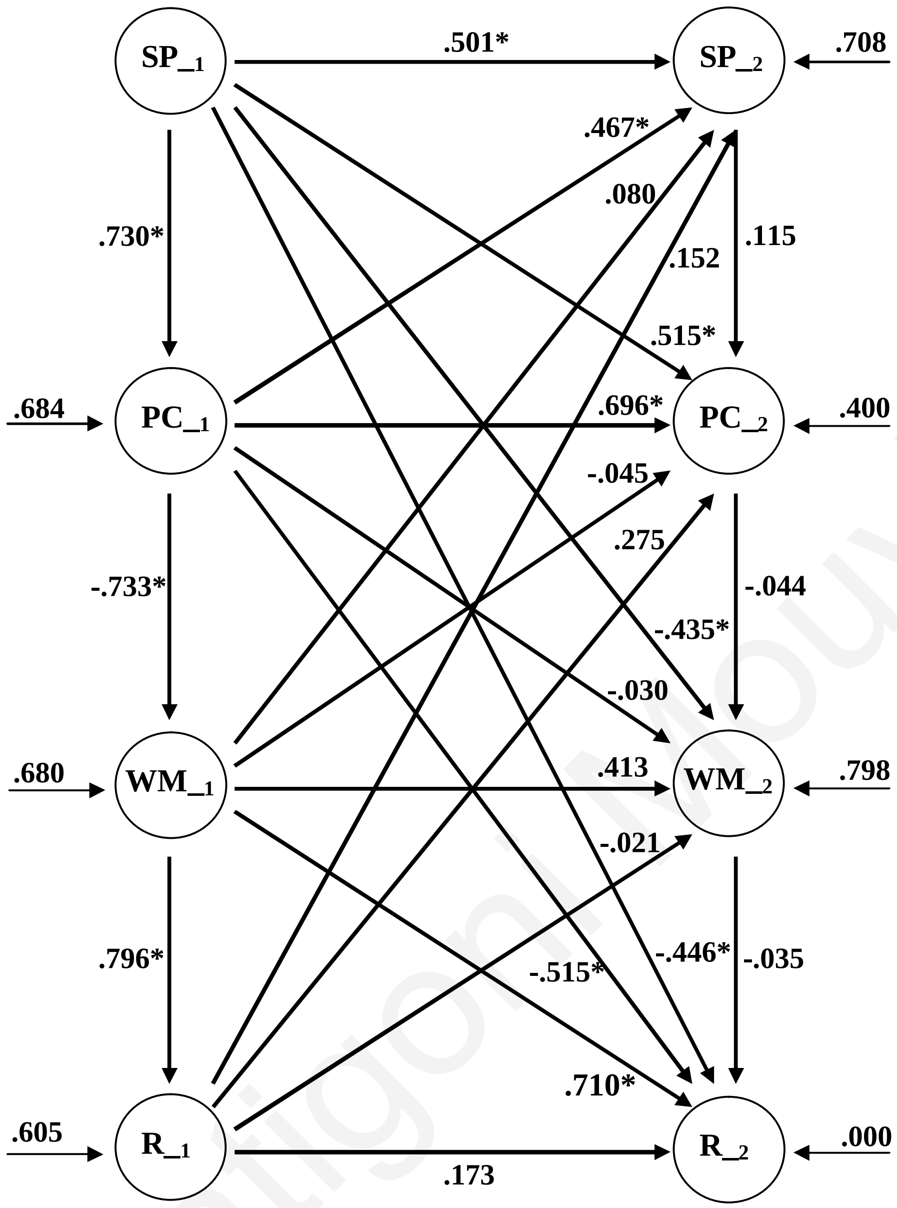


Figure 10. The longitudinal model of the structural relations between processes.
Notes.
First testing wave measures: SP_1 (speed of processing), PC_1 (control of processing), WM_1 (working memory capacity), and R_1 (reasoning). Second testing wave measures: SP_2 (speed of processing), PC_2 (control of processing), WM_2 (working memory capacity), and R_2 (reasoning).
Model fit: χ^2 (144) = 188.351, p = .01, χ^2/df= 1.308, CFI = .935, RMSEA = .070 (90% confidence interval for RMSEA = .037 - .095).

the processes is tested. Figure 10 shows this longitudinal model. As it can be seen, all first wave processes are highly and significantly related with the processes lying lower in the hierarchy. Individual differences in SP_1 explain 53% of the variance in PC_1, while approximately the same portion of variance in WM_1 (54%) is common variance with PC_1. An even larger amount of variance (64%) in R_1 is explained by the variance in WM_1.

When the factors reflecting the processes at the second testing wave were regressed on the factors of SP_1 and the residuals of the other factors from the first testing wave, the results showed that SP_1 is an important factor explaining a significant proportion of the variance in all processes of the second wave, indicating its central role in the developmental changes of all processes. Inhibitory control is also found to be a developmental factor for speed, control, and reasoning at the second wave. These findings suggest that both parameters of processing efficiency have a significant developmental role in the expansion of information processing and representational processes. Finally, WM_1 plays a significant role in the development of the inferential processes (R_2), as it explains 50% of its variance. The role of WM_1 in the expansion of the functions ascribed to working memory appears to be not statistically significant, explaining only 17% of the variance in WM_2. It is worth noting that the only significant contributions to the changes observed in all processes after a one-year period were attained by the processing efficiency parameters, namely SP_1 and PC_1.

A careful examination of the pattern of significant regression coefficients suggests that any age-related changes of the cognitive processes are to a significant extent attributed to the original state of their simpler processes. Changes are expected to occur in more complex processes due to changes that have been already established in processes residing lower in the hierarchy. The only exception is observed in the relation of the speed of processing at the second testing wave with the control of processing at the first testing wave. The significant regression coefficient of SP_2 on PC_1 (.467) probably suggests that changes can be identified in more simple processes due to changes that have been established in more complex processes. Such changes in more complex processes may result in the automation of some functions and in the establishment of routines which in turn enhance the expansion of more simple processes. The pattern of significant regression coefficients also indicates a very important role of working memory in the development of reasoning. Inferential processes are therefore built on processing efficiency and on working memory. Reasoning capitalizes on these processes and the changes that occur to them are invested in the development of the inferential processes.

In order to get a more lucid understanding of the dynamic interplay of the processes as a function of time the longitudinal model was re-run after excluding all non-significant relations. The parsimonious model that resulted from this manipulation is presented in Figure 11. The relations between processes changed only slightly. Specifically, the regression coefficients of SP_1 with SP_2 and PC_2, as well as the regression coefficients of PC_1 with SP_2 and PC_2 somewhat increased indicating the strong interdependence

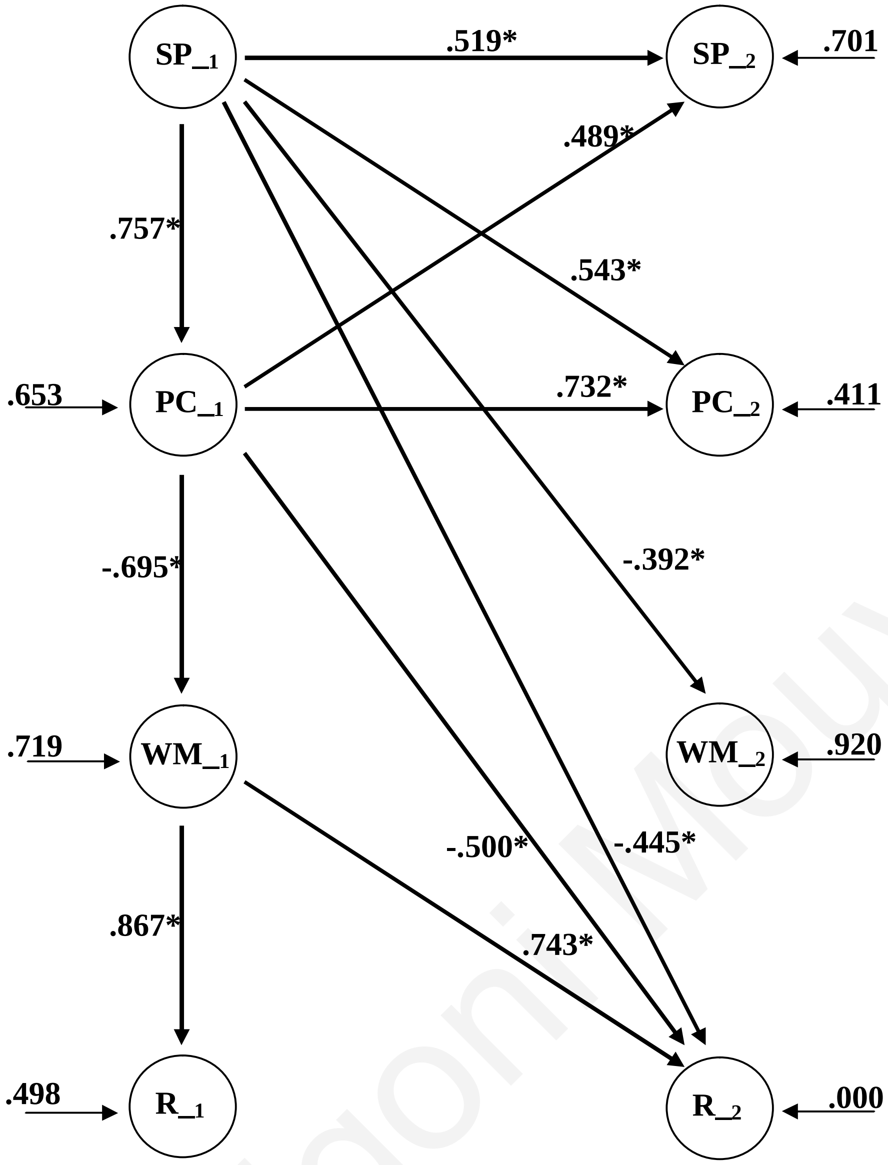


Figure 11. The parsimonious longitudinal model of the structural relations between processes.
Note.
Model fit: χ^2 (155) = 198.266, p = .01, χ^2/df= 1.279, CFI = .937, RMSEA = .067 (90% confidence interval for RMSEA = .033 - .092).

between the processing parameters during development. On the other hand, the regression coefficient of the SP_1 with the WM_2 decreased slightly indicating that the development of working memory capacity is driven by changes directly related to the functions of information encoding and retrieval. Speed of processing remains an important developmental factor; yet, much of the variance in working memory (85%) still needs to be decomposed. This could be probably attained by further analyzing and better measuring the storage and executive functions of working memory as two distinct facets of working memory. Finally, the regression coefficients of reasoning ability (R_2) with the processing efficiency parameters at their original state are decreased negligibly whereas its relation with WM_1 increased. This pattern of coefficients indicates the important role of working memory capacity as well as the significant contribution of the information processing parameters in the development of inferential processes. Understanding the meaning of the given premises, retrieving the appropriate set of mental rules from long-term memory and constructing the necessary set of mental models in order to reach a conclusion, are all heavily based on the quality of working memory in the long run. Therefore, the best predictors of reasoning ability development are the parameters of processing efficiency and the capacity of working memory, as these have been identified earlier in time. As a consequence, it can be claimed that fostering inferential processes should be based on improving the speed and control processes and the functioning of working memory. The development of the cognitive processes is further studied in the next section where the cross-sectional data are further analyzed.

The Development of Cognitive Processes

To specify the developmental profile of the various processes a series of ANOVAs with repeated measures were run. In the following section, each process's development will be presented based on the data of both testing waves.

Processing Efficiency

Speed of Processing. To identify the development of processing speed during the age span studied here a 6×2 (age cohorts × speed (left vs. right) dimensions) ANOVA with repeated measures on the speed dimension factor was run. The effect of age was highly significant and strong ($F(5,119) = 11.227$, $p < .0001$, $\eta^2 = .32$, and $F(5,382) = 39.479$, $p < .0001$, $\eta^2 = .34$)[8] explaining one third of the variance in speed performance.

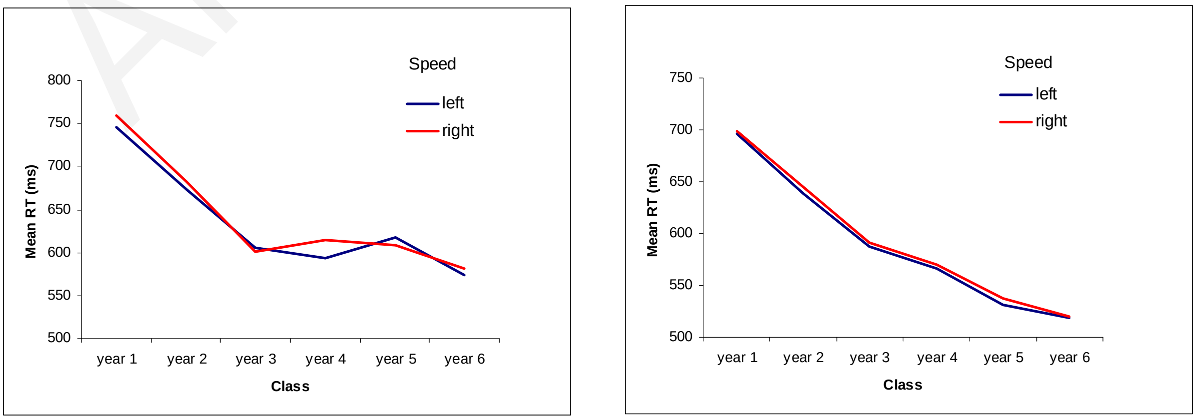


Figure 12. Speed of processing as a function of age.

[8] The results are reported in pairs taken from the first and second testing wave, respectively. Figure on the left-hand refers to data from the first testing wave and figure on the right-hand refers to data from the second testing wave.

As children get older they demonstrate significantly lower reaction times (see Figure 12). During the period of 6 to 8 years of age the changes in speed of processing are drastic and they become smoother from the age of 8 to the age of 11 years.

Control of Processing. A $6 \times 3 \times 2 \times 2$ (age cohorts $\times$ type of stimulus[9] $\times$ selection of dimension (dominant vs. non-dominant) $\times$ compatibility condition) ANOVA with repeated measures on the last three factors was run. The effect of age was highly significant and strong ($F(5,107) = 23.498$, $p < .0001$, $\eta^2 = .52$, and $F(5,367) = 87.555$, $p < .0001$, $\eta^2 = .54$) indicating that the ability to control the interference of irrelevant information, and the ability to inhibit strong but irrelevant responses develop extensively during the age span of 6 to 11 years (see Figure 13).

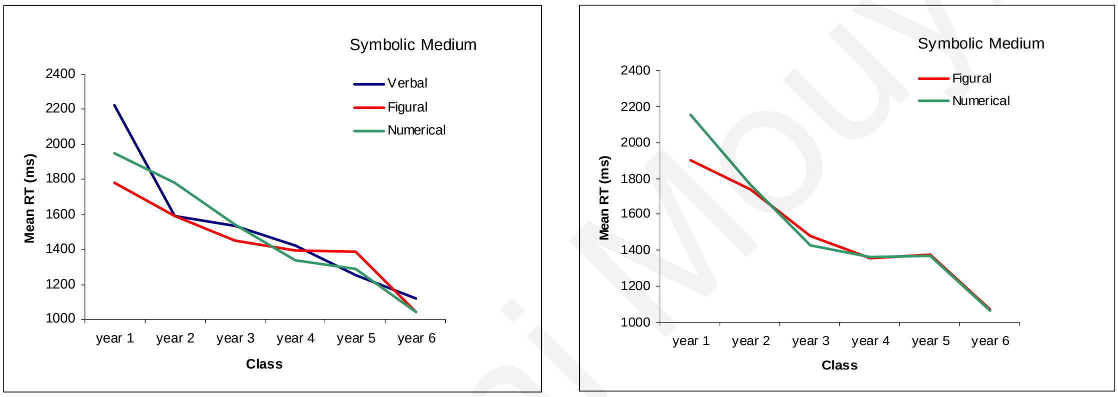


Figure 13. Control of processing as a function of age and symbolic medium.

Older children were clearly faster in the Stroop-like tasks and exhibited more efficiency in manipulating the conflicting information. The effect of the symbolic medium (i.e. the verbal, the figural, and the numerical), although low, was significant ($F(2,106) = 3.399$, $p < .05$, $\eta^2 = .06$, and $F(1,367) = 5.781$, $p > .01$, $\eta^2 = .02$), indicating a differentiated facility with the three symbol systems. In other words, this finding suggests that the symbolic medium of the input information affects the way the system receives and processes such information in dissimilar ways.

As it can be seen in Figure 13 the data from all variants of the Stroop-like tests gave a similar developmental profile. Drastic drop in the reaction times on the verbal test (taken from the first wave data), was observed during the period of 6 to 7 years of age. Specifically, 6-year-olds clearly needed longer time to respond to the verbal test than they did to respond to the figural or the numerical test. Reaction time difference is explained by the fact that the 6-year-olds were at the first stages of learning to read. Therefore, they

[9] Two tests were used in the second testing wave: the figural and the verbal.

needed a sufficient amount of time to read the words. This difference from the reaction times to the figural and the numerical tests did not appear in the next age cohort, suggesting that the reaction time difference depended on reading proficiency. The interaction of age with symbolic medium was significant ($F(10, 212) = 3.737$, $p < .0001$, $\eta^2 = .15$) indicating the strong differentiation between the verbal and the other symbol systems at the age of 6 years as compared to the older children. However, the difference between the three systems decreases as children get older suggesting that increasing mastery of control process causes symbol dependent familiarity or facility differences to disappear.

An interesting set of findings emerged when the effect of the dimension of the stimulus (i.e. whether the relevant to the task dimension was the dominant or the non-dominant one) was studied. At first, when the analysis was based on the first wave data which included the verbal variant of the test, the effect of the dimension was significant and strong ($F(1, 107) = 23.760$, $p < .0001$, $\eta^2 = .18$). Nevertheless, when comparing the mean reaction times for every age cohort on the basis of whether the dominant or non-dominant dimension was selected, a strange pattern of findings was observed. Specifically, the obtained reaction times when the dominant dimension of the stimulus was selected as the relevant to the task (i.e. reading the word, reporting the big figure, or reporting the big number) were longer than the respective reaction times when the non-dominant dimensions were selected as relevant to the task (i.e. naming the ink-color, reporting the small figure, or reporting the small number). This finding applied to the whole age-span studied, although the difference became progressively slower with time (see Table 2). An explanation for these findings is that during the verbal variant of the test, reading the word is considered the dominant dimension of the stimulus over the non-dominant dimension of color-naming. Thus, though a dominant dimension, and consequently a smaller reaction time was expected, reading a word took longer for younger children than naming the ink color. As a result, the relevant relation of the obtained reaction times was reversed.

Moreover, the interaction of age with the selected dimension of the stimulus was significant when the first wave data was analyzed ($F(5, 107) = 4.222$, $p < .001$, $\eta^2 = .17$), since the verbal variant of the test was included. When the same analyses were re-run after excluding the data referring to the verbal variant of the test from both testing waves, no dimension effect was found ($F(1, 114) = .081$, $p > .01$, $\eta^2 = .01$, and $F(1, 367) = .618$, $p > .01, \eta^2 = .02$) indicating that individual differences in the control mechanisms are not traced by manipulating the dominant and non-dominant dimensions of the stimulus.

Table 2. Reaction Times' means and mean differences in the Stroop-like tests.

Dimension Selected		Year 1	2	3	4	5	6
dominant	Mean	2128.999	1724.803	1529.694	1404.805	1339.626	1075.091
	SD	76.805	62.711	64.259	67.735	64.259	64.259
non-dominant	Mean	1819.166	1585.038	1487.485	1368.304	1283.710	1063.467
	SD	75.078	61.301	62.815	66.213	62.815	62.815
	Mean Difference	309.834	139.765	42.209	36.500	55.916	11.624

Note.
Reaction times are measured in milliseconds.

Furthermore, when the verbal test data was excluded from the analyses the interaction of age with the dimension of the stimulus was not significant ($F(5,114)=1.562$, $p>.01$, $\eta^2=.06$, and $F(5,367)=2.50$, $p>.01$, $\eta^2=.03$). These findings indicate that as children get older the dimension of the stimulus (i.e. whether the relevant to the task dimension is the dominant one or not) has no effect on the process of the control. Therefore, it is suggested that as children get older they increasingly master the control processes.

The analysis shows that an important factor in the functioning of the control process is the condition under which the selection of the relevant feature of the information occurs. The term "condition" refers to whether there is compatibility between the dominant and the non-dominant dimensions of the stimulus, as for example is the case where the word "red" is written in red ink. In fact, the effect of the compatibility factor was highly significant and strong ($F(1,107)=147.298$, $p<.0001$, $\eta^2=.58$, and $F(1,367)=217.815$, $p<.0001$, $\eta^2=.37$) suggesting that the system allocates much mental energy in activating the control mechanisms for processing conflicting incoming information, even if such a process is not required under the circumstances. The interaction of age with the compatibility of the two dimensions of the stimulus (i.e. whether the relevant dimension was compatible with the non-relevant dimension) was not significant ($F(5,107)=.809$, $p>.01$, $\eta^2=.04$, and $F(5,367)=2.642$, $p>.01$, $\eta^2=.04$) with the mean reaction time under the compatible situations being, as expected, smaller than the mean reaction time under the incompatible situations, throughout the age span studied. Both reaction times (under the compatible and non-compatible situation) decrease. In fact, the mean difference between the reaction times under the compatible and non-compatible conditions ranged from 97 ms to 157 ms, with a mean value of 128,2 ms (SD = 23,6 ms) for the first testing wave, and from 76.4 ms to 110 ms, with a mean value of 99.5 ms (SD= 27.3msecs) for the second testing wave. This finding indicates that in the age span studied here, additional processing time when conflicting information is being processed is approximately one tenth of a second.

An important finding about the common grounds of the verbal and the numerical variants of the test and, consequently, the common cognitive and developmental features of the verbal and the numerical information recognition and process, emerged from the analysis of the interaction of the symbolic medium with the dimension factor and the compatibility factor. Specifically, the significant and strong interaction of the symbolic medium with the dimension of the stimulus that is being processed ($F(2,106) = 23.595$, $p < .0001$, $\eta^2 = .31$) suggests that the control mechanism is differently activated according to the content of the stimulus. Although when the relevant to the task dimension is not the dominant one, a longer reaction time would have been expected as a normal outcome, this is the case only when the figural variant of the test was used (see Figure 14).

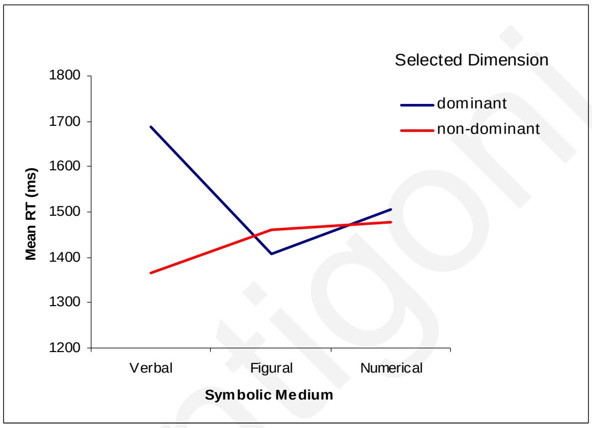


Figure 14. Symbolic medium interaction with the selected dimension of the stimulus.

In the other two test variants, namely the verbal and the numerical, the mean reaction time relation is reversed, i.e. the mean reaction time is shorter when the relevant to the task dimension is the non-dominant one. This common feature of the verbal and the numerical tests can be attributed to the fact that children at these ages process letters and number symbols in the same way: they activate the reading mechanism. The words and the number symbols are not processed as whole pictures, as is the case with the figural stimuli. Thus, the reversed relation of the mean reaction time recorded in the verbal and the numerical tests can be attributed to the nature of the reading skills developed in these ages. Specifically, though the reading process is gradually automatized, children at these ages are still bounded to their reading protocol which confines their reading scope to the components of the stimulus – not the picture of it as in the gestalt meaning.

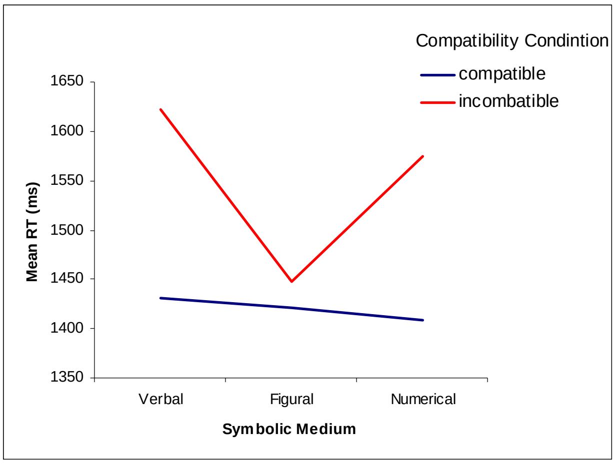


Figure 15. Symbolic medium interaction with the compatibility of the dimensions of the stimulus.

The similarities in the profiles of the verbal and the numerical variant of the test are further manifested when the interaction between the symbolic medium and the compatibility factor was tested. This interaction was significant and strong ($F(2,106) = 28.941,\ p < .0001,\ \eta^2 = .35$). As shown in Figure 15 the verbal and the numerical variant of the test provide almost identical patterns, suggesting that the verbal and the numerical stimuli, as they were presented in the Stroop-like tests, are processed in a very similar way and thus they activate the control processes in a way that is to a great extent common. This finding also suggests that either test variant can be used in order to obtain the information on the functioning of the control processes.

Perceptual Discrimination and Conceptual Control. To specify developmental changes in perceptual discrimination and conceptual control factors a $6 \times 2 \times 3$ (age cohorts $\times$ proximity to reality (comparison of objects' size in image vs. comparison of objects' size in reality) $\times$ relational schemas (conceptual relation, part-whole relation, and physical resemblance)) ANOVA with repeated measures on the last two factors was run. The effect of age was highly significant and strong ($F(5,119) = 23.161,\ p < .0001,\ \eta^2 = .49$, and $F(5,384) = 49.656,\ p < .0001, \eta^2 = .40$) explaining a large part of the observed variance. Figure 16 illustrates the changes that take place during childhood in the time needed to compare and select among two stimuli in reference to their perceptual or conceptual characteristics. It is obvious that when the comparison of the stimuli is focuses on perceptual characteristics information processing is less demanding and less time consuming than when focusing on conceptual features.

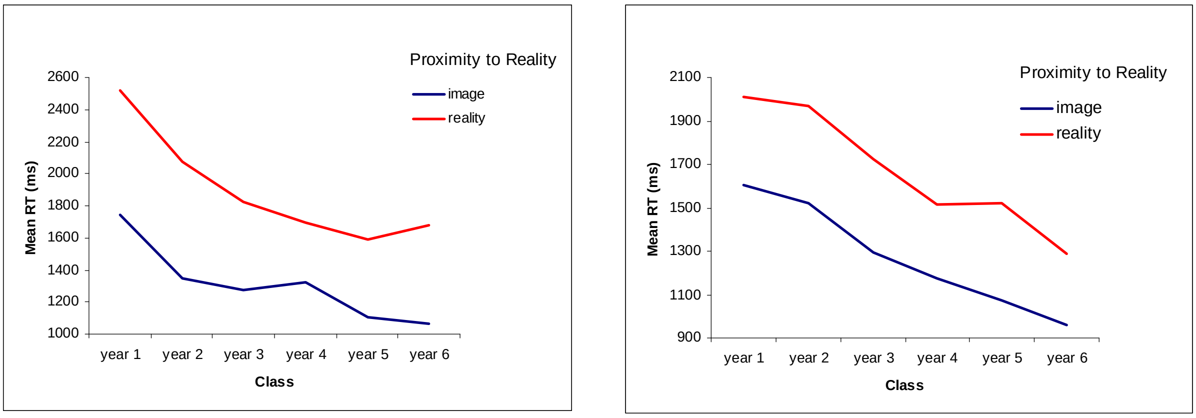


Figure 16. Information processing as a function of age and proximity to reality.

It is interesting to note that the difference in reaction times follows a U-shape course, as it is shown in Figure 17, probably indicating a radical change that takes place around the age of 9 years that causes an impressive decrease in the reaction time.

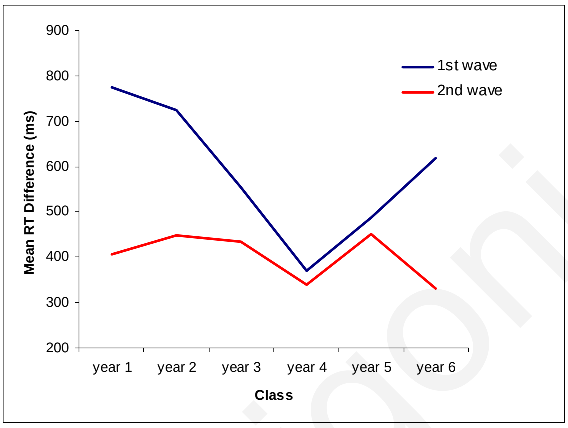


Figure 17. Time difference in perceptual and conceptual processing.

The proximity to reality factor exerts a very strong effect ($F(1,119) = 257.650$, $p < .0001$, $\eta^2 = .70$, and $F(1,384) = 688.887$, $p < .0001, \eta^2 = .64$) on the process of perceptual or conceptual information comparisons. Moreover, a strong effect on comparison is exerted by the relation between the objects compared ($F(2,118) = 46.604$, $p < .0001$, $\eta^2 = .44$, and $F(2,383) = 85.474$, $p < .0001, \eta^2 = .31$). That is, when there is physical resemblance between the objects, the comparison is faster than when the objects are connected by a part-whole relation or when they are conceptually related. Finally, the highly significant and strong interaction between proximity to reality and the relation between the objects ($F(2,118) = 62.574$, $p < .0001$, $\eta^2 = .52$, and $F(2,383) = 106.395$, $p < .0001$, $\eta^2 = .36$), suggests that the processing system needs more time and allocates more resources when focusing on conceptual characteristics of objects which are conceptually related or when they have a part-whole relation. On the other hand, comparison focusing on perceptual characteristics is in all cases less demanding in terms of time and mental resources (Figure 18) and it is not differentiated by the type of relation between the objects.

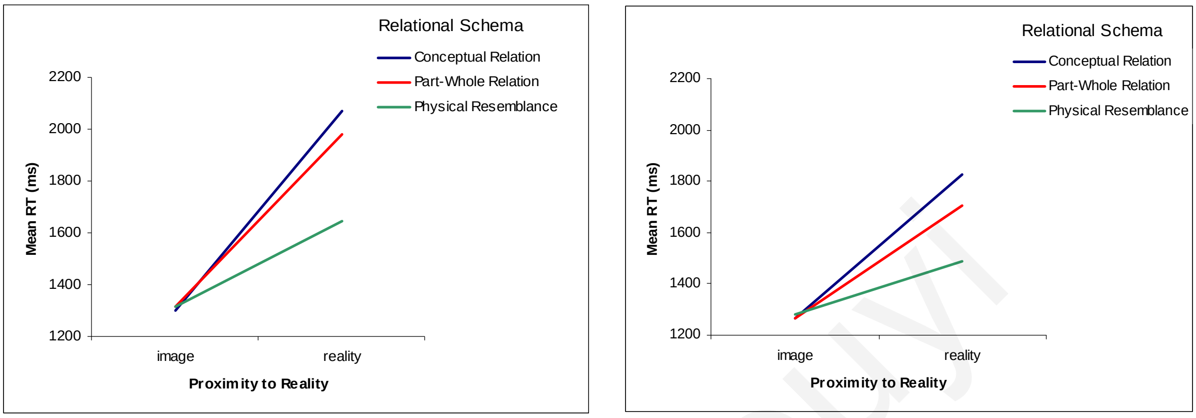


Figure 18. The proximity to reality interaction with the relational schema.

These findings indicate that perceptual discrimination, which is a reliable measure of speed of processing, can be measured by using either one of the relational schemas since perceptual information is being processed in an identical way in terms of speed of processing. Thus, since these relational schemas do not affect the speed of processing perceptual information, it is suggested that the perceptual characteristics are dominant and any conceptual or relational schemas do not interfere in discriminating stimuli based on their perceptual features.

Representational Processes

Information Integration. The development of information integration was examined by a 6×3 (age cohorts × symbol system (verbal, numerical, and figural)) ANOVA based on the first testing wave, because this task was restructured in the second wave due to time limitations. The effect of age was significant ($F(5,116) = 15.459$, $p < .0001$, $\eta^2 = .20$), suggesting that older children performed better that younger children. The effect of symbolic medium was strong ($F(2,115) = 47.712$, $p < .0001$, $\eta^2 = .45$). Specifically, performance on the number version of the test was better than on the two other versions throughout the age period studied here.

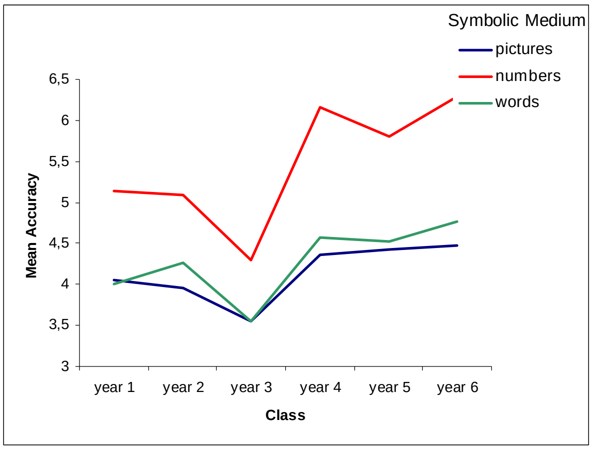


Figure 19. Performance on information integration tasks as a function of age and symbolic medium.

As shown in Figure 19, there seems to be an important representational change with growth, probably because of a strategy shift around third grade. The U-shaped performance on these tasks suggests a developmental change around the age of 8 years causing to the system a transient drop of performance. This pattern might imply that the processing efficiency factors (i.e. speed and control of processing), are responsible for generating and, under some circumstances, maintaining changes in the ability of information integration. In order to test the extent to which the processing efficiency parameters are indeed affecting the functioning of the information integration the analysis was re-run after partialling out the effect of speed, at first, and the effect of control, at second. This was effected by using the speed and then the control mean performance as covariates in the analysis.

Partialling out speed led to a total suppression of the effect of the symbolic medium but it only slightly affected the effect of age ($F(5,110) = 4.643$, $p < .005$, $\eta^2 = .17$). A similar pattern of effects was observed when control of processing was included as a covariate. Specifically, the age effect was reduced to some extent ($F(5,111) = 3.635$, $p < .005$, $\eta^2 = .14$) and the symbolic medium effect was eliminated. The annihilation of the effect of the symbolic medium when the processing efficiency parameters were partialled out suggests that each test variant drew on speed and control resources differently, according to the specificities of each symbolic system. Furthermore, the fact that the effect of processing efficiency parameters on the development of the information integration was small suggests that the developmental change occurring at the age of 8 years does not originate from these processing efficiency factors. A plausible explanation of the U-shaped pattern of performance is that there may be change in the strategy children used to integrate information, which is not well mastered at the beginning thereby resulting in a temporal drop of performance. The possibility of this strategy shift was further examined by observing the relation of accuracy and reaction time in the information integration test. Figure 20 presents the reaction time as a function of symbolic medium and age.

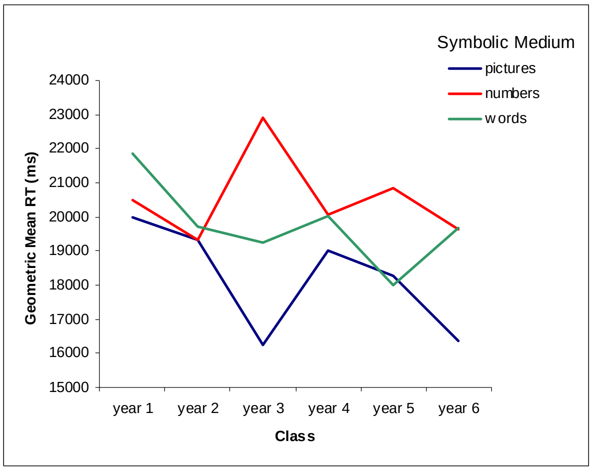


Figure 20. Reaction time on information integration tasks as a function of age and symbolic medium.

Attention is drawn to the reverse pattern of results in as far as the number version is concerned. Specifically, at the age of 8 years, when the drop of the performance is big, there is a noticeable increase in reaction time. One would expect that the increase in response time would be accompanied by an increase in accuracy. Nevertheless, this is not the case with the 8-year-olds who demonstrated better performance in the other two symbolic media. The drop of performance on the picture and the verbal versions of the test is related with a significant decrease in reaction time. As children move towards adolescence, they demonstrate better and more stable performance while their reaction times are gradually getting smaller.

Working Memory. A 6×4 (age cohorts $\times$ test variants[10]) ANOVA was run to specify the developmental profile of working memory capacity. The effect of age was highly significant and strong ($F(5, 91) = 42.667$, $p < .0001$, $\eta^2 = .40$, and $F(5, 389) = 12.456$, $p < .0001$, $\eta^2 = .14$) suggesting that older children scored better than the younger ones. The effect of test type was very strong ($F(3, 89) = 47.807$, $p < .0001$, $\eta^2 = .62$, and $F(2, 388) = 146.027$, $p < .0001$, $\eta^2 = .43$), indicating that each test addressed a different aspect of working memory. The interaction of test type with the age was

[10] Three, instead of four, working memory tests were included in the second testing wave due to time constraints. So, for analyzing those working memory data, a 6×3 ANOVA was run.

significant ($F(15, 246) = 2.575$, $p < .005$, $\eta^2 = .13$, and $F(10, 776) = 2.215$, $p < .05, \eta^2 = .03$), suggesting that memory capacity is increasingly developed.

Figure 21 clearly shows that at the age of 11years working memory capacity, as measured by each test, tends to a ceiling of about five information units. The second variant of the visuospatial test shows a smooth increase from the age of 6 to the age of 9 years while there is a plateau in the period of 9 to 11 years of age. Performance on the numerical test strongly suggests that there is a big change during the age span of 6 to 11 years of age leading from a capacity of at most two to more than four information units. Moreover, developmental profile of executive functions suggests the construction of mnemonic strategies. This pattern might also suggest that the load on the processing efficiency sources is strong and that the developmental change in memory capacity as studied here is driven by speed and control of processing. To test this assumption the ANOVA analysis was re-run after partialling out the effect of the speed and control processes.

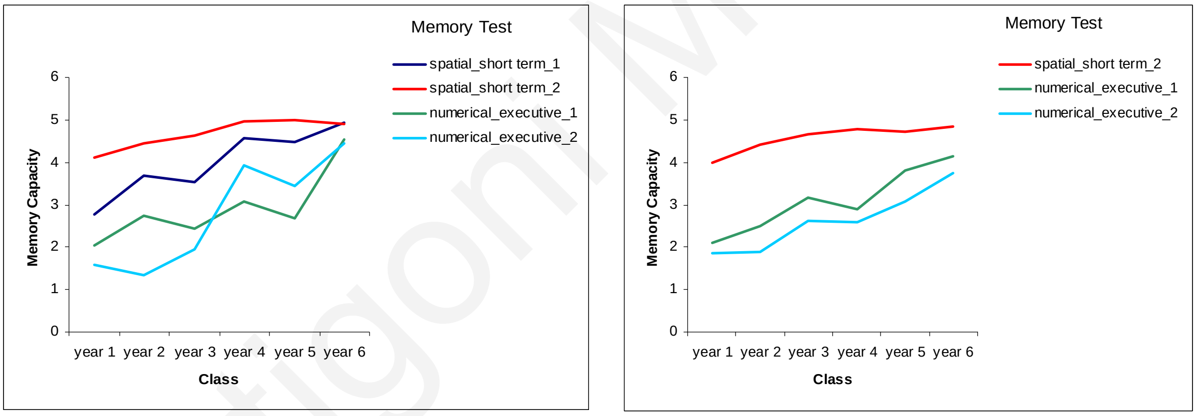


Figure 21. Working memory capacity as a function of age and symbolic medium.

At first, mean speed was used as a covariate to control for the effect of speed. This manipulation resulted in a decrease of the amount of the variance explained by age (from 40% to 29% for the first testing wave, and, from 14% to 8% for the second testing wave), although its effect remained significant ($F(5, 89) = 7.209$, $p < .0001$, $\eta^2 = .29$, and $F(5, 385) = 6.315$, $p < .0001, \eta^2 = .08$). Moreover, the effect of the test type was vanished ($F(3, 87) = 1.337$, $p > .2$, $\eta^2 = .04$, and $F(2, 384) = .891$, $p > .4, \eta^2 = .01$), indicating that each working memory test is differently related to speed. Thus, individual differences in performance reflected individual differences in speed of processing. These findings signify the developmental role of speed of processing as well as its role as a factor of individual differences in maintaining in working memory information units of various contents.

Therefore, it is suggested that age-related changes in speed open the way for changes in other levels of the mind and differences in it within ages signify differences between persons in other levels of the mind.

Working memory capacity expands during childhood, partly due to the changes which take place in speed of processing. As it was shown in Figure 12 the most drastic changes in speed of processing were manifested during the period of 6 to 8 years of age. It could be argued that these changes act as a driving force which accelerates changes in the functioning of working memory and, subsequently, in its capacity, during the period of 8 to 10 years of age. The fact that the changes in the capacity of working memory do not occur simultaneously with changes in speed of processing indicates that further changes must act in an additional manner providing the necessary momentum for the changes in working memory capacity to occur. Therefore, based on the cascade model of the dynamic relations between the cognitive processes presented in Figure 7, the role of control processes in the development of the working memory capacity should be studied by statistically controlling its effect.

Mean performance on perceptual and the conceptual control was taken as the indicator of control. When this indicator was used as a covariate, the amount of the explained variance in working memory performance dropped ($F(5, 89) = 5.157$, $p < .0001$, $\eta^2 = .23$, and $F(5, 381) = 2.454$, $p < .05$, $\eta^2 = .03$). Moreover, the effect of all other factors was significantly decreased indicating that control processes have a central role in the functioning of working memory, thereby explaining individual differences in working memory capacity.

At a second run, both speed and control mean performances were used as indicators. The effect of age, although less pronounce, was still significant, ($F(5, 86) = 4.668$, $p < .005$, $\eta^2 = .21$, and $F(5, 381) = 2.454$, $p < .05$, $\eta^2 = .03$), suggesting that developmental changes in working memory are not fully dependent on speed and control processes. That is, a significant part of developmental changes in working memory capacity is related to processes which are specific to the functioning of working memory as such. These processes may develop through experience and practice, through strategy planning, application, and evaluation, and through the changes in metacognitive representations.

An important finding of partialling out the effect of speed and control, is that the effect of the working memory tests vanished completely ($F(3, 84) = 1.052$, $p > .3$, $\eta^2 = .04$, and $F(2, 380) = .368$, $p > .5$, $\eta^2 = .00$), indicating that the difference between types of working memory in their developmental profile was due to their different dependence on cognitive resources, namely speed and control of processing. When the effect of these cognitive resources was statistically controlled, the working memory tests appeared similar, indicating that all four tests address the same mental ability with a common underlying mode.

Reasoning. To specify the developmental profile of inductive and deductive reasoning, a $6 \times 2 \times 3$ (age cohorts $\times$ types of reasoning $\times$ symbolic system (verbal, mathematical, spatial)) ANOVA with repeated measures on the last two factors was run. The effect of age was highly significant and strong ($F(5,134) = 26.559$, $p < .0001$, $\eta^2 = .50$, and $F(5,379) = 102.198$, $p < .0001, \eta^2 = 0.57$). With growth, children's ability to solve inductive and deductive tasks improves extensively (see Figure 22).

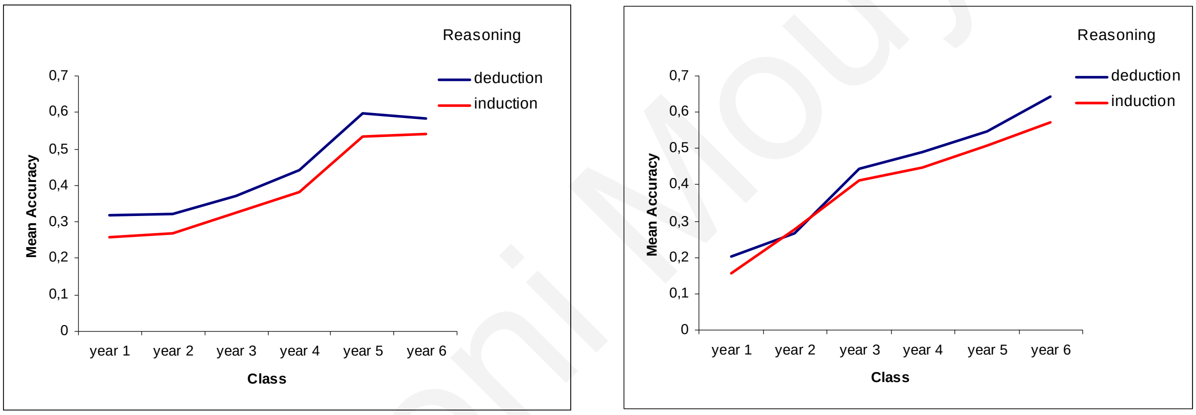


Figure 22. Inductive and deductive reasoning ability as a function of age.

In both testing waves performance on deductive reasoning was better than performance on inductive reasoning at all ages. This was evident by the small, not significant, effect of the interaction of the type of reasoning with the age ($F(5,134) = 0.127$, $p > .9$, $\eta^2 = .01$, and $F(5,379) = 1.625$, $p > .1, \eta^2 = .02$). These findings probably indicate that the underlying specificities in inductive and deductive reasoning in terms of cognitive resources' demands and in terms of mental rules application and mental models construction are differentiated during the age span of 6 to 11 years of age and, it could also be suggested, that this differentiation is an enduring aspect. Nevertheless, the effect of the type of reasoning was significant and moderately strong ($F(1,134) = 27.529$, $p < .0001$, $\eta^2 = .17$, and, $F(1,379) = 20.125$, $p < .0001, \eta^2 = .05$), indicating that mastery of the two types of reasoning is not the same.

The effect of symbolic medium of the tasks was significant and strong, ($F(2,133) = 22.043$, $p < .0001$, $\eta^2 = 0.25$, and $F(2,378) = 38.346$, $p < .0001, \eta^2 = 0.17$), indicating that each domain draws differently upon the cognitive resources. In general, the spatial reasoning tasks were more difficult to solve than the verbal tasks which were the easiest to solve. Moreover, the interaction of symbolic medium with the reasoning type was highly significant and strong ($F(2,133) = 59.816$, $p < .0001$, $\eta^2 = 0.47$, and $F(2,378) = 31.958$, $p < .0001, \eta^2 = 0.15$). This effect was more pronounced in inductive reasoning mechanisms (see Figure 23).

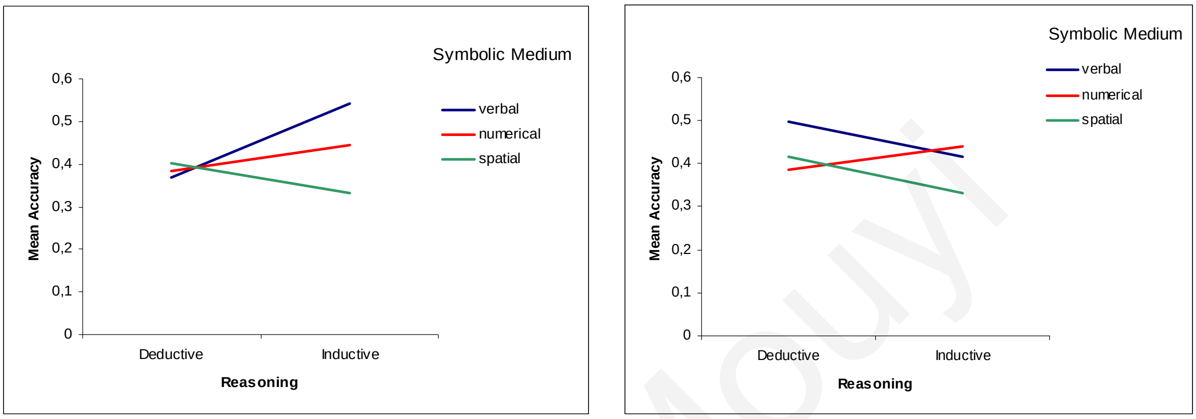


Figure 23. The interaction of reasoning type with the symbolic medium.

The impressive developmental change in reasoning during the period from 7 to 10 years of age might result from a synergy of other cognitive processes which trigger and sustain it. To test this hypothesis, the analysis was re-run after partialling out the effects of speed, control of processing, and working memory. In order to specify the influence of each of these factors, each of them was included in the analysis in a stepwise manner, i.e. each new factor was entered in the analysis as a covariate in addition to the covariate factor already set in the previous step.

Controlling for the effect of speed of processing resulted in a slight decrease of the variance explained by age ($F(5,118) = 18.270$, $p < .0001, \eta^2 = .44$, and $F(5,375) = 61.328$, $p < .0001, \eta^2 = .45$). It also resulted in the annihilation of the effects of the reasoning type and the symbolic medium of the tasks. It is suggested that the development of the reasoning process is not based on changes in speed of processing. As a higher cognitive process, it seems to involve in development other processes which are directly related to the manipulation of logical relations, such as mental rule application and mental models construction, namely control of processing and working memory.

When control of processing was included as a covariate, a considerable decrease of the explained variance in reasoning performance was observed ($F(5,115) = 11.050$, $p < .0001$, $\eta^2 = .33$, and $F(5,371) = 26.966$, $p < .0001$, $\eta^2 = .27$). The effect of reasoning type and the effect of symbolic medium were annihilated, suggesting that the reasoning processes do draw on processing efficiency resources differently, according to the type and the domain of reasoning. These findings also suggest that control of processing does affect the development of reasoning throughout childhood. As it was argued earlier, the developmental profile of the control processes shows a remarkable increase in the efficiency of the control processes from the age of 6 to the age of 11 years which is interrupted by a plateau during the period from 9 to 10 years of age.

When the means for visuospatial and numerical working memory were added as covariates no change in the effect of age was observed. Specifically, the amount of explained variance remained exactly the same when the first testing wave data was analyzed and it dropped from 27% to 25% when the second testing wave data was analyzed ($F(5,105) = 10.125$, $p < .0001$, $\eta^2 = .33$, and $F(5,369) = 24.132$, $p < .0001$, $\eta^2 = .25$). These results strongly suggest that working memory is not a developmental factor in concern to changes that occur in reasoning with time.

One could argue that the real effect of working memory on the developmental course of reasoning was suppressed by the effect of the processing efficiency factors and that the picture of the reasoning development in relation to the working memory capacity was altered by the presence of other covariates. To this end, the ANOVA was re-run after partialling out only the effect of the working memory capacity. No significant decrease was observed in the proportion of the variance explained by the effect of age ($F(5,121) = 17.149$, $p < .0001$, $\eta^2 = .42$, and, $F(5,377) = 75.002$, $p < .0001$, $\eta^2 = .50$), while all other factors' effects were annihilated. This manipulation confirmed our original findings on the magnitude of the effect of working memory on reasoning and the nature of the working memory factor. Specifically, it showed that the working memory factor is indeed a factor which reflects individual differences in reasoning, but it does not contribute in the developmental course of reasoning. Moreover, these findings suggest that the distinction of reasoning in two types (inductive and deductive) is not valid only in pragmatic terms but it is valid also in cognitive terms. The working memory capacity, as well as the factors of processing efficiency, has a clearly differentiated role in the functioning of each reasoning type, in the way the information from the various symbol systems is being processed, and in the way the meaning of the premises is being transmitted.

The Rasch Model

The Rasch model offers two basic possibilities in concern to studies such as this study. First, it enables the researcher to obtain an estimate of the relative abilities of a group of individuals that is not dependent upon the specificities of the items used in the measurement of the ability. This possibility of objective comparison of the individuals is the key to objective measurement. Objectivity refers to the fact that individuals are being compared within a specified frame of reference and the result of their comparison is independent of everything else within the frame of reference (Rasch, 1997). Second, it enables the calibration of the items used in the test. The items' relative difficulties or complexity can be estimated based on the responses of a group of individuals without regard to their abilities or any other characteristic. Since the items' difficulties and the test takers' abilities are both plotted on an imaginary line of increased complexity, Rasch model enables for the simultaneous representation of both types of information. Two sets of quantities derive from the responses of the testees, the distributions of which depend solely on the item parameters and the personal parameters, respectively. Items and individuals are measured on an interval scale with a common unit.

The relative imaginary position of the participants on the measurement variable informs on their probabilities on succeeding on a test's items. An individual placed on a higher position is consistently having more odds to succeed on every item of the test than an individual placed on a lower position. Likewise, an item placed on a higher position is consistently more difficult or complex than an item placed on a lower position and, therefore, the probability of solving the more difficult one is less for all test takers without regard to their abilities or any other characteristic. Mathematically, it is suggested that when observations are made in terms of dichotomies, as it is the case with the reasoning items used in our reasoning tests, then the person-free item calibration and the item-free person measurement are secured. The Rasch model defines objective measurement and is a valuable tool in both exploring item complexity and tracing possible developmental paths. The science of mental development is strongly depending on objective measurement. Observations are transformed into objective mental measurements which is a necessary condition for tracing and understanding developmental paths. *Specific objectivity* is the term used by Rasch (1966) to describe his model's characteristic which permits the comparison of the ability of two individuals independent of which tests were used to measure them, and the comparison of two tests independent of the test-takers' abilities and other characteristics. When studying development from a quantitative perspective, a wide range of item difficulty must be covered in order to capture the range of growth and trace, if any, developmental stages.

The Rasch model was applied to the two reasoning sets separately, since the structural equation modeling revealed two strong reasoning factors, namely inductive and deductive reasoning. Moreover, the model was applied to the data from the two testing waves separately. Thus, four models were tested: Two for inductive reasoning and two for deductive reasoning. This manipulation enabled us to thoroughly study the specificities of the structure of each reasoning type, examine the existence of cognitive stages in the development of each type of reasoning, and explore the pattern of individual differences and the general cognitive profile of the test takers who were located at the same reasoning stage.

The Scaling and the Development of the Inductive Reasoning Ability

The Rasch model was first applied on the first wave inductive reasoning data. Four out of forty items from the original data were excluded since they did not fit in the model. Three of them were verbal syllogisms tasks and the fourth one was a verbal analogy. No case was excluded from the analysis. The fit of the model was excellent. Specifically, the infit and outfit mean squares for the item estimates were 0.98 and 0.99 respectively, and the infit t and outfit t means were –0.10 and 0.13, respectively. The reliability of the item estimate was 0.98. Moreover, no item was found with zero score and no item was found with perfect score. The fit statistics of the case estimates also showed a very good model fit. Specifically, the infit and outfit mean scores were 1.01 and 1.00, respectively, and the infit t and outfit t means were –0.03 and 0.00, respectively. The reliability of the case estimate was 0.87. Furthermore, one case had zero scores and no case was found with perfect scores. Figure 24 illustrates the scale for the 37 inductive reasoning items with the item difficulties and the test takers' measures calibrated on the same logit scale. The item difficulties ranged from –2.31 to 3.59 logits and the participants' measures ranged from –2.82 to 3.94 logits indicating that the items used were fully targeted against the participants' measures. Some of the participants (4 in number) were placed on a lower position on the scale than the easiest item's position and one was placed on a higher position than the most difficult of the items used. The verbal syllogisms were evenly distributed on the scale while the verbal analogies were contained at the lower end of the scale. The mathematical tasks, both syllogisms and analogies, were evenly distributed along the scale. Similarly, the spatial analogies were evenly distributed, while all spatial syllogisms, but one, were contained at the highest end of the scale.

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--------------------------------------------------------------------------------
High Achievement                             Complex Tasks
  4.0                       X  |
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                               |    IMA6
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                            X  |
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  3.0                       X  |
                               |    ISL6
                               |    ISL5
                               |
                               |
                           XX  |    ISL2     ISL4
                               |
                          XXX  |    ISL3
  2.0                          |
                               |
                               |    IMA5
                            X  |
                               |    IVL6     IML7
                            X  |
                         XXXX  |
                               |    ISA7
  1.0                    XXXX  |
                         XXXX  |    IML3     ISA6
                               |
                       XXXXXX  |    IMA4
                          XXX  |
                               |    IML4     ISA4
                      XXXXXXX  |
   .0               XXXXXXXXX  |    IVL5
                     XXXXXXXX  |    ISA5
                               |    IVL1
                       XXXXXX  |    IMA3
                       XXXXXX  |
                     XXXXXXXX  |    IML5     IML6
                               |    IVA6
                  XXXXXXXXXXX  |    IVL2
 -1.0              XXXXXXXXXX  |
                   XXXXXXXXXX  |
                               |    IVA2     IVA4
                      XXXXXXX  |    ISA3
                       XXXXXX  |    IVA1     IMA2     ISA1     ISA2
                         XXXX  |    IVA3
                               |    IML2
                        XXXXX  |    IML1     ISL1
 -2.0                          |    IVA5
                         XXXX  |
                          XXX  |
                               |    IMA1
                           XX  |
                               |
                               |
                           XX  |
 -3.0                          |
Low Achievement                              Simple tasks
--------------------------------------------------------------------------------
N = 140 participants and L = 36 tasks
```

Figure 24. Scale on the Inductive Reasoning for first testing wave battery.

Notes.

Each X represents 1 student.

I: Inductive Reasoning, V: Verbal content, M: Mathematical content, S: Spatial content, A: Analogy, L: Syllogism.

Tasks IML3, IML4, and IVA7 were excluded.

The second Rasch model was applied on the second wave inductive reasoning data. No item or case was excluded. The fit of the model was again very good. The infit and the outfit mean squares for the item estimates were 0.99 and 1.09, respectively, and the infit t and outfit t were –0.20 and 0.06, respectively. The item estimate reliability was 0.99. Furthermore, no item was found with zero or with perfect score. The case estimates were also very good. Specifically, the infit and outfit mean squares were 1.00 and 1.09, respectively, and the infit t and outfit t means were 0.00 and 0.17, respectively. The reliability of the case estimate was 0.77, while two cases were found with zero scores but no case was found with perfect scores.

Figure 25 illustrates the scale for the 21 inductive reasoning set items. The item difficulties ranged from -2.19 to 3.64 logits and the case measures ranged from -3.73 to 3.12. Forty five, out of 386 test takers had a measure lower than -2.19. This finding suggests that the items used in the second testing wave were not fully targeted against the cases' measures though they were chosen from the battery used in the first testing wave. This could probably be attributed to the fact that the samples of the two testing waves were different and thus the extracted logits were different.

The verbal syllogisms were evenly distributed along the scale. Two of the verbal analogies were located at the lower end. These were the items taken from the first wave battery. The other two items (namely IVA6 and IVA7) were added at the second wave battery since all the first wave verbal analogies were contained at the lower end of the scale. One of them was proved to be the most difficult item of the battery. The mathematical syllogisms as well as the mathematical and the spatial analogies were placed on the range between -2 and +1 logits. Finally, all but one, spatial syllogisms were contained at the higher end of the scale, indicating that the level of complexity of these items was not met by the cognitive level of the majority of the test takers.

Both waves' models on the inductive reasoning items suggest a three-level organization of the inductive reasoning processes. Expressed in logits, the first level accommodates items with logits less than -1, the second level accommodates items with logits greater or equal to -1 and less or equal 1, and finally, the third level accommodates items with logits greater than 1. With respect to the cognitive demands and the mechanisms activated for addressing each task, the three-level organization is both cognitively and developmentally supported.

```
---------------------------------------------------------------------------------
High Achievement                              Complex Tasks
  4.0                                |
                                     |
                                     |      IVA7*
                                     |
                                     |
                                     |
                                  X  |
  3.0                                |
                                     |
                                     |
                                 XX  |
                                     |
                                     |     ISLc3
                                     |
  2.0                             X  |     ISLc4
                                     |     ISLc2
                                XXX  |
                                     |
                                     |
                            XXXXXXX  |     IVLc3
                                     |
  1.0                        XXXXXX  |
                                     |
                   XXXXXXXXXXXXXXXX  |     IMLc4        ISAc3
                                     |
                      XXXXXXXXXXXXX  |     IVLc2 IMLc2
                                     |     IMAc3
   .0                XXXXXXXXXXXXXX  |
                                     |
                   XXXXXXXXXXXXXXXX  |
                                     |
                  XXXXXXXXXXXXXXXXX  |     IMLc3        ISAc2
                                     |     IVA6*        IMAc2
                    XXXXXXXXXXXXXXX  |
 -1.0                                |
               XXXXXXXXXXXXXXXXXXXX  |     ISAc1
                                     |     IMAc1
                       XXXXXXXXXXXX  |
                                     |     IVLc1        IVAc1          IVAc2
                  XXXXXXXXXXXXXXXXX  |
                                     |     IMLc1
 -2.0                 XXXXXXXXXXXXX  |
                                     |
                                     |     ISLc1
                        XXXXXXXXXXX  |
                                     |
                                     |
                                     |
 -3.0                      XXXXXXXX  |
                                     |
                                  X  |
                                     |
                                     |
                                XXX  |
                                     |
 -4.0                                |
Low Achievement                               Simple tasks
---------------------------------------------------------------------------------
N = 386 participants and L = 21 tasks
```

Figure 25. Scale on the Inductive Reasoning for second testing wave battery.

Notes.

Each X represents 2 students.

I: Inductive Reasoning, V: Verbal content, M: Mathematical content, S: Spatial content, A: Analogy, L: Syllogism.

The two variables which were not taken from the first wave battery are denoted with an asterisk.

First level of inductive reasoning: Analogical reasoning is the cornerstone of inductive reasoning, and it is based on many observations. Children can abstract a relation or a pattern more easily when they have access to a large number of observations and when these observations are free of any non-relevant information. They can trace the relation and apply it on a new case only if the relation is unidimensional, meaning that no more than one aspect may vary. At this level, in a verbal milieu, analogical reasoning is confined in recognizing the relation of synonyms or antonyms, in tracing the common attribute of a group of people or a group of objects or a group of actions, and in understanding and manipulating simple relations such as family relations and geographical locations. Analogical reasoning calls upon retrieving primary knowledge from long-term memory, an action triggered by the information of the source and the relational schema it entails, that being an inter- or an intra- analogical relation, and applying it directly on the target. In a mathematical environment analogical reasoning is effected within simple, unitary, number relations, such as addition (and subtraction) and multiplication where one-step algorithms can be recognized and applied. Finally, spatial analogies can be successfully manipulated when they refer to unidimensional transformations of the size or the color of a shape, while the number and the direction of the involved shapes remain constant.

Syllogisms at this level are based on premises with constituent parts that are concrete. No abstraction and, therefore, no complex model construction are attainable. Verbal syllogisms are strongly confined by the reasoner's experiences and specific knowledge, and thus, shortcomings in these areas cause knowledge and belief biases. Furthermore, these shortcomings act forcefully against any activation of the control processes. Syllogisms based on mathematical information are not attainable unless the premises refer to concrete numbers and facts. Again, no abstraction can be done and no thinking can take place beyond the boundaries set by the specificities of the premises. The executive functions of memory and the control processes of the system are not yet available to the reasoner. Finally, syllogisms based on simple spatial transformations are feasible, though the given premises-examples must be very explicit as to the transformation they entail, so that the general rule can be extracted from them and then applied to a new situation.

Second level of inductive reasoning: At this level, the reasoner is no longer confined by the need for an explicitly stated relation. Analogical reasoning is based on *hidden* or *implied* relations. Verbal analogies are based on not directly exposed relations which activate the retrieval of knowledge stored in long-term memory. Mapping out the hinted relation requires that non-relevant information lying in the premises or activated from the long-term memory must be inhibited. The activation of the control processes prevents the overloading of working memory and therefore, the system can effectively identify the relational schema and effectively apply it in a new situation. Mathematical analogies are based on simple combinations of multiplicative and additive relations. Spatial analogies can be based on multiple transformations of a shape, in terms of its size, its color, and its direction. Syllogisms, at this level, are confined by the syntactical characteristics of the premises, yet a primary abstraction level is achieved. Indirect relations can be processed within all symbolic media and no confinement of the premises in terms of their number and their specificity is imposed. The instructiveness of the premises calls for the activation of the control processes. Control processes help the system stay in focus and capture the meaning of the premises, process it, and formulate generalizations. Further, the system can apply the extracted general rule to a specific situation.

Third level of inductive reasoning: Analogical reasoning can be based on complex relations which are not directly detectable and which are often relied on very fine attributes. Verbal analogies strongly demand a higher level of language expertise and a pool of detailed knowledge on various areas. Mathematical analogies can be based on more complex applications such as the square root of a number added to another number or a number subtracted by the power of 2 of another number. Reasoners can delineate such complex relations since they have much ease in dealing with the basic algorithms and the simple number transformations. Spatial analogies demand the extraction of a relation between two shapes which is based on the concurrent transformation of more than three geometrical attributes. Syllogisms at this level are based on abstraction and theoretical supposition. Reasoning can be done on the basis of the existence of a possibility and it can also be placed in a totally reality-or-belief contradicting context. Multiple relations can be manipulated and more than two parameters can be simultaneously considered. Generalizations can be extracted from an abstractive context and be applied on another context since they constitute mental rules. Inductive reasoning is considered as the function of the human mind that is closely related with intelligence. It is also suggested that inductive reasoning is in a never-ending relation with deductive reasoning. It supplies deductive reasoning with the general rules and in turn, deductive reasoning confirms or rejects these mental rules by applying them within the austere framework of logic. Rejected rules can always be corrected or improved within the induction process.

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  High Achievement                          Complex Tasks
  4.0                           |
                                |
                                |
                                |
                                |
                                |
                                |
                                |
  3.0                           |
                                |
                                |
                                |
                                |
                                |
                                |     DML7
                                |
  2.0                      X    |     DVL2
                                |     DVL3
                                |
                                |     DVL8
                                |     DSL6
                                |     DVL13
                                |     DVL5      DSL7
                        XXXX    |
  1.0                           |     DML6
                          XX    |
                                |
                           X    |     DVL14     DVL16     DSL4
                     XXXXXXX    |
                                |     DVL15
                     XXXXXXX    |
                    XXXXXXXX    |     DVL12
   .0                           |     DSL3
                     XXXXXXX    |     DVL7      DML5
                  XXXXXXXXXX    |     DML3
               XXXXXXXXXXXXX    |     DML4
                                |     DVL11
            XXXXXXXXXXXXXXXX    |
                XXXXXXXXXXXX    |
 -1.0                           |
             XXXXXXXXXXXXXXX    |
                                |     DML2
                      XXXXXX    |     DVL10
                   XXXXXXXXX    |     DVL6      DML1
                                |     DVL4      DVL9
                                |
                 XXXXXXXXXXX    |
 -2.0                           |     DSL1
                        XXXX    |     DSL2
                                |     DVL1
                        XXXX    |
                                |
                                |
                           X    |
                                |
 -3.0                           |
Low Achievement                             Simple tasks
--------------------------------------------------------------------------------
N = 140 participants and L = 29 tasks
```

Figure 26. Scale on the Deductive Reasoning for first testing wave battery.

Notes.

Each X represents 1 student.

D: Deductive Reasoning, V: Verbal content, M: Mathematical content, S: Spatial content, A: Analogy, L: Syllogism.

Task DSL_5 was excluded.

The Scaling and the Development of Deductive Reasoning Ability

The third Rasch model was applied on the first wave deductive reasoning data. One out of 30 items was excluded, which was a spatial syllogism task. This was a highly difficult task. No case was excluded. The fit of the model was very good. The infit and outfit mean squares for the item estimates were very close or equal to one (1.00 and 1.05, respectively) while the infit t and outfit t means were near zero (-0.15 and 0.01, respectively). The reliability of the item estimate was 0.97 and, moreover, no item was found with zero or with perfect scores. The fit statistics of the case estimates suggest a very good model fit. Specifically, the infit and outfit mean squares were 0.99 and 1.05, respectively, and the infit t and outfit t means were -0.10 and 0.02, respectively. No case was found with zero or perfect scores and, finally, the reliability of the estimate was 0.73. Figure 26 illustrates the scale for the 29 deductive reasoning items. The item difficulties ranged from -.23 to 2.22 logits and the test takers' measures ranged from -3.30 to 2.09 logits. Seven out of 140 test takers were placed at a lower position on the scale than the easiest item's position. This means that for the 5% of the participants the odds of succeeding even to the easiest item were less than 0.5. All three types of deductive reasoning tasks were evenly distributed along the scale.

The last Rasch model was applied on the second wave deductive reasoning data. No item or case was excluded from the analysis. A very good model fit was obtained by the fit statistics of the item estimates. Specifically, infit and outfit mean squares were 0.99, and both infit t and outfit t means were -0.19. No item was found with zero or with perfect scores and the reliability of the item estimate was 0.98. The case estimates fit statistics reveal a very good model fit, though the reliability of case estimates was 0.62. Specifically, the infit and outfit mean squares were 1.01 and 0.99, respectively, and the infit t and outfit t means were 0.04 and 0.08, respectively. Five out of 386 cases were found with zero scores and one case was found with perfect scores. Figure 27 illustrates the scale for the 12 deductive reasoning items. The item difficulties ranged from -1.64 to 1.45 and the case measures ranged from -2.73 to 2.72. Forty out of 386 participants had less than 0.5 odds to succeed even at the easiest item in the test, while 30 out of 386 participants had more than 0.5 odds to succeed at all items.

A three-level organization of the deductive reasoning processes is supported by both Rasch Models. Expressed in logits, the first level accommodates items with logits less than -1, the second level accommodates items with logits greater or equal to -1 and less or equal 1, and finally, the third level accommodates items with logits greater than 1. Based on the items residing at each level, a description of the cognitive aspects of each level in

```
--------------------------------------------------------------------------------
 High Achievement                           Complex Tasks
 4.0                           |
                               |
                               |
                               |
                               |
                               |
                               |
 3.0                           |
                               |
                          XXX  |
                               |
                               |
                               |
                               |
 2.0                           |
                      XXXXXXX  |
                               |
                               |
                               |     DSLc3
                      XXXXXXX  |     DMLc3
                               |
 1.0                           |
                               |
                 XXXXXXXXXXXX  |     DVLc1
                               |     DSLc2
              XXXXXXXXXXXXXXX  |
                               |
                               |     DVLc6
  .0           XXXXXXXXXXXXXX  |
                               |     DMLc2
                               |     DVLc3     DVLc5     DMLc1
          XXXXXXXXXXXXXXXXXXX  |
                               |
                               |     DVLc2
         XXXXXXXXXXXXXXXXXXXX  |
-1.0                           |
                               |
            XXXXXXXXXXXXXXXXX  |     DVLc4
                               |
                               |
                               |     DSLc1
                   XXXXXXXXXX  |
-2.0                           |
                               |
                               |
                               |
                               |
                         XXXX  |
                               |
-3.0                           |
                               |
                               |
                               |
                               |
                               |
                               |
-4.0                           |
Low Achievement                             Simple tasks
--------------------------------------------------------------------------------
N = 386 participants and L = 12 tasks
```


Figure 27. Scale on the Deductive Reasoning for second testing wave battery.
Notes.
Each X represents 2 students.
D: Deductive Reasoning, V: Verbal content, M: Mathematical content, S: Spatial content, A: Analogy, L: Syllogism.

terms of the inferential processes involved and in terms of the demand in cognitive resources will be presented.

First Level of Deductive Reasoning: At the lower end of this level Modus Ponens inferences are attainable in their simplest form. The constituent parts of the premises are given in an affirmative way. Higher in this level some of the constituent parts of the premises in the Modus Ponens inferential scheme are presented as negations. The argument is based on the Modus Ponens rule but the information being processed becomes more complex by the addition of the negation. The negation calls upon the activation of the control processes in order to secure that the meaning of the premises will be processed without the interference of non-relevant information and that no premature response will be given unless the alternatives in meaning emanating from the negation are taken under consideration. Constructing, or retrieving from memory, the complement of a negation calls upon further cognitive resources allocation. This finding conforms to Johnson-Laird's thesis that negative deductions are harder than affirmative deduction "because the negative deductions call for the detection of an inconsistency between elements of models" (Johnson-Laird & Byrne, 1991, p. 55).

Second Level of Deductive Reasoning: Reasoners can successfully apply Modus Tollens inferences. This finding conforms to the thesis postulated by both the mental rule and the mental model theories on the comparison of the level of difficulty between Modus Ponens and Modus Tollens inferences. On the one hand, the mental rule theory postulates that the rule for Modus Ponens inferences is innate while the Modus Tollens rule has to be formulated. On the other hand, the mental model theory assumes that Modus Tollens inference demands fleshing out the first model and constructing a series of alternative models while the Modus Ponens inferences do not lead to any fleshing out procedure. Though our findings from the application of the Rasch model on deductive reasoning items are in accord with this thesis, they add some important information about the developmental aspect of reasoning. Both theories mentioned above base their assumptions on an algorithmic level. They both use a reductionist approach to explain the observed differences in the levels of success between the Modus Ponens and the Modus Tollens inferences. More examples needed to extract the Modus Tollens rule or more steps in fleshing out the original explicit model in the mental rules and mental models theories, respectively. Rasch model illuminates this difference in success from the cognitive development perspective. Succeeding in Modus Tollens inferences is an autonomous or distinct developmental stage which follows when the Modus Ponens stage is completed.

Developmentally speaking the scale of the deductive reasoning items according to their difficulties strongly suggests that success in Modus Tollens inferences must follow the completion of the Modus Ponens stage. Manipulating the information for a Modus Tollens inference is more complex when compared to the manipulation of Modus Ponens information, not only in computational terms but in cognitive terms. Development of the information processing system and the working memory capacity as it was presented in the previous part is a necessary step, a prerequisite, for moving from the Modus Ponens to the Modus Tollens inferences.

Towards the end of this stage the success in dealing with the Denying the Antecedent and Affirming the Consequence fallacies occurs. Though these fallacies appear to be successfully manipulated at the end of this Modus Tollens stage the items addressing these fallacies were in a binary setting where the alternative to the negation of *p* was singular -*p*, with only one value. Therefore, the Affirming the Consequence and Denying the Antecedent inferences were less difficult than in the case where the negation of *p* has more than one alternative, i.e. the value of *p* is not binary. Seen from the developmental perspective, during this stage the system is successfully coping with the Modus Tollens inferences and therefore is successfully dealing with the negation of the consequent and this ability is transformed or it is invested in situations where a fallacy is presented in a binary setting.

Third Level of Deductive Reasoning: At this level reasoners can successfully deal with items addressing the Denying the Antecedent and Affirming the Consequence fallacies. Obviously, this is the most demanding stage where the efficiency acquired from the other two stages is used in successfully dealing with the fallacies. It should be noted that this stage is not reached by preadolescents. The cognitive demands of successfully dealing with the fallacies are not met until later, in adolescence. Fallacies place a big cognitive load on the system. Many alternatives have to be retrieved from memory and be processed. Moreover, the nature of the outcome of this process makes this line of reasoning a very complex procedure. The extracted conclusion states that no conclusion can be reached. Seen from the developmental point of view, this stage is beyond the range of the cognitive abilities of the children in the age span studied here. Reasoning at this level demands that the reasoner acknowledges that not all arguments have a deterministic conclusion and that at some times uncertainty is the only certain conclusion. Children at the lower levels are not able to deal with the absence of an affirmative conclusion, so they are unable to ignore the inconsistencies caused by the fallacies.

The findings from the Rasch models strongly imply that reasoning processes are differentiated by the presence of binary conditionals. This study was designed in a way that allows for analyzing the data in terms of whether the conditionals used in deductive reasoning are binary or non-binary. In the next section the developmental stages of deductive reasoning will be examined from this perspective.

Reasoning on the Basis of Binary and Non-Binary Conditionals. All four inferential schemas (Modus Ponens, Modus Tollens, Affirming the Consequence, Denying the Antecedent) were tested under the same testing plan. First, a non-binary setting was presented. That is, the negation of an element corresponded to more than one alternative values. For example, “not red” could mean “blue” or “green”. Based on this setting the four inferential schemas with a conclusion were presented and the participants’ task was to judge whether the extracted conclusion was definitely true, definitely wrong, or whether no definite conclusion could be made based on the set of the given premises. Each inferential schema was tested with two items. Second, a binary setting was presented where the negation of an element corresponded to only one value. For example, “not yellow” meant “blue”. Again, each of the four inferential schemas was tested with two items.

It should be noted that the fallacies of Affirming the Consequence and Denying the Antecedent are successfully manipulated towards the end of the second stage when these are given in a binary condition. This is feasible because the alternative models are contained and thus the system can process them with less effort. On the other hand, this is not possible at a lower stage because testing for the validity of alternatives, even if their number is small, calls upon higher reasoning functions which arise towards the end of the second stage when Modus Ponens and Modus Tollens are well established. These higher reasoning functions are a big step forward which leads the reasoner to break the limits of her thinking, see beyond the obvious. The binary nature of the elements proves to be of great importance in taking this step.

The three-stage development of reasoning, as it was presented above, allows for some further study as to the cognitive profile of the reasoners who reside at each level.

The Profile of the Processing Efficiency and the Working Memory at Each Developmental Stage

The four Rasch models presented above resulted in four scales, two for inductive (1st and 2nd wave) and two for deductive reasoning (1st and 2nd wave) of the case measures and the item difficulties. All four scales support the existence of three developmental stages in reasoning ability as it was studied in the age span of 6 to 11 years. Expressed in

Table 3. Cognitive processes' mean comparison at the different inductive reasoning stages.

		Cognitive Process			
		Speed	Control	Working Memory_1	Working Memory_2
1st wave	F	7.288	16.905	13.603	14.862
	Sig.	0.001	0.000	0.000	0.000
2nd wave	F	41.252	84.732	34.190	25.300
	Sig.	0.000	0.000	0.000	0.000

logits, the first stage accommodates cases with logits less than -1, the second stage accommodates cases with logits greater or equal to -1 and less or equal 1, and finally, the third stage accommodates cases with logits greater than 1.

Inductive Reasoning Stages and their Cognitive Blueprint. Both waves' data were analyzed on the basis of the inductive reasoning stage each participant was assigned to. In order to examine whether the processing efficiency and the working memory parameters differ significantly from one stage to the other, the means of speed of processing, of control of processing (as it was measured with the Stroop-like tasks), and of the two working memory capacities (as they were estimated based on the two tests of working memory which called on the executive functions of working memory) were compared using ANOVA. The results of this analysis confirm our hypothesis that the three developmental stages of reasoning ability significantly differ in the cognitive parameters mentioned above. Table 3 presents the results of ANOVA for both waves' data when the independent factor variable was the inductive reasoning stage. The processing efficiency parameters as well as the executive function of working memory have clearly different presence in each reasoning stage.

Post hoc Scheffé tests illustrated the pattern of mean differences in the cognitive parameters of the three reasoning stages. Deep changes occur when moving from the first to the second inductive reasoning stage. These changes signify a representational shift which allows the reasoner to be engaged in more demanding situations and deal with more complex information in an efficient manner. Speed and control of processing significantly increased. Moreover, working memory capacity also significantly increased. These findings support the thesis discussed in the analysis of the development of the various cognitive processes. Specifically, it was suggested that changes in speed and control of processing may act as the driving force for drastic changes in the reasoning processes. This synergy of changes is evident when one moves from the second to the third stage. The only parameter that does not change significantly is speed of processing.

Deductive Reasoning Stages and their Cognitive Blueprint. Using the same procedure, the case measures for the deductive reasoning ability were used as the criterion

Table 4. Cognitive processes' mean comparison at the different deductive reasoning stages.

Cognitive Process					
		Speed	Control	Working Memory_1	Working Memory_2
1st wave	F	4.862	11.334	6.874	7.621
	Sig.	0.009	0.000	0.001	0.001
2nd wave	F	26.984	64.471	25.313	20.605
	Sig.	0.000	0.000	0.000	0.000

on which the three stages were observed. Table 4 shows the results for the comparison of the three stages' cognitive characteristics, for both testing waves' data, when the independent variable was deductive reasoning. As it can be seen, all cognitive parameters have a statistically significant F value indicating that they differ in respect to the stage of reasoning. Post hoc Scheffé tests revealed the exact pattern of relations and differences. The difference in the means of the processing efficiency parameters as well as the difference in the mean of the working memory capacity is significant. These findings suggest that each developmental level in deductive reasoning is clearly differentiated from the other stages in terms of cognitive resources and processes. These findings may suggest that the role of the parameters of processing efficiency and of the capacity of the working memory is vital during all three reasoning stages enabling the reasoner to reason based on the Modus Ponens and Modus Tollens inferential schemas at the beginning and then move to the third stage where reasoning is based on more complex mental rules and mental processes.

The decomposition of the observed variance in reasoning test performance into its constituent parts, namely the construct-relevant variance and the variance due to individual differences per se, would illuminate the real dimensions of the test difficulty sources and would allow researchers to develop cognitive ability tests grounded in information processing psychology and composed from items with predictable cognitive characteristics (Lohman, 2002). Predictability in terms of task complexity and task difficulty is possible since these characteristics are independent of external factors, unlike task performance, and therefore they are invariant. Invariance in the cognitive characteristics of the task is secured by following a set of task analysis rules austerely.

The Three-Dimensional Cognitive Task Analysis

We propose a model of cognitive task analysis which aims at quantifying some of the qualitative features of the tasks and at suggesting a hierarchical arrangement of them in terms of their complexity. This model places emphasis on three broad parameters which, when combined, define task complexity and, therefore, a more comprehensive view of the complexity of the tasks is attained. We assume that task complexity (*C*) is a function of three parameters each of which is analyzed in more specific aspects some of which are implicitly present, and therefore cannot be quantified, whereas others are more tangible, and therefore a quantity measure can be assigned to them. So, each cognitive task can be analyzed in terms of three parameters, namely the semantics embedded, the procedures applied, and the mental models constructed.

Semantics (*S*) refer to all the concepts included in the task, their meaning, their structure which may be explicitly or implicitly stated, and their interrelations. Interrelations reflect whether two concepts are related in a linear or multifaceted fashion. Semantics also refer to the existence of unknown words, especially to the existence of unknown "central meaning" words, and the degree of familiarity with the task due to previous practice. Novel situations often demand innovation and creativity which are diminished as a function of the existence of repetitive actions within a task and/or between tasks. Semantics also refer to the degree to which the reasoner feels committed and motivated throughout the task solving process. Procedure (*P*) refers to the processes (e.g. algorithms) and rules (e.g. logic rules) needed to be applied. It also refers to the degree of accessibility to information (i.e. whether the information is embedded in the task premises or whether it is clearly and directly stated), the clarity of the problem definition and the external representations which are provided (such as diagrams and pictures). Time and other (surrounding) constraints are aspects of the Procedure parameter. Lastly, the Mental Constructs (*M*) refer to the number of information bits simultaneously related to the process at hand, the number of constraints that need to be simultaneously complied with, and whether the outcome of each step is subject to variation. Furthermore, this parameter refers to the kind and the number of models to be constructed.

It is assumed that the three parameters are independent and, therefore, orthogonal to each other. It is pointed out that if this assumption is subsequently proven to be divergent from experimental evidence or incongruent with theoretical suppositions, appropriate adjustments to encapsulate the exact nature of the relationship, will have to be made. Thus, the proposed orthogonal relation between the three parameters can be better conceptualized by using a geometrical visualization according to which each of the three parameters is represented by an axis in a three-dimensional space.

When a task is theoretically analyzed based on the three parameters, a numerical value (*Si, Pi, Mi*) is assigned to each parameter. Since not every aspect of the parameters is quantifiable, we have adjusted (or confined) our analysis to two quantifiable aspects in each parameter. Therefore, the Semantics parameter is assigned a value based on the number of concepts and the linearity or non-linearity of the relation. The Procedure parameter is assigned a numerical value based on the number of constraints imposed by the context of the problem and on the number and nature of the logic rules to be applied. Finally, the Mental Construct parameter is assigned a numerical value based on the number of information bits which must be simultaneously related and the number of the models constructed. The final numerical value (*Si, Pi, Mi*) assigned to each parameter is the product of the values of the two quantifiable aspects of each parameter.

Each parameter has a different weight (contribution) on the task complexity; therefore, unitary changes in parameters' modules cannot be equally weighted among the three parameters. *Semantics* is considered as the parameter which affects the complexity of a task less than the three of them, *Procedure* is considered a moderately affective parameter, and *Mental Constructs* is considered the most important contributor to task complexity. In order to make an accurate apodosis of this differentiation in the contribution of the parameters the natural logarithm e was chosen as the scaling factor. The choice of e as the scaling factor was originally an intuitive decision since the mental demand for each subsequently more complex action draws upon a non-linear capacity. It is believed that the demand for utilization of mental resources grows exponentially as the complexity of the task at hand is increased. The choice of the natural logarithm as the scaling factor is based on the fact that e links and quantifies phenomena and constructs from the physical and the abstract world (e.g. radioactive decay as an example from the former and Euler's formula as one from the latter) and exhibits an almost "mystic" unifying power. Although e is a quantity defined in very strict and exact mathematical manner and it is an indispensable tool of almost every imaginable analytical method, it is also invaluable in comprehending and encompassing complex systems not in a decomposing approach but in a holistic explanation.

In order to regulate parameters with their relational weights, each parameter's absolute magnitude is multiplied by a power of the natural logarithm according to the following schema: The parameter which affects the complexity of a task less than the three of them is multiplied by 1 (e^0), the moderately affective parameter is multiplied by e (e^1), and the most important contributor to task complexity is multiplied by e^2. Therefore, we assume that the complexity of a task is a function of the absolute magnitude of each of the three parameters multiplied by a weight condition. So, our conception of the semantic, the procedural and the representational analysis of complexity can be expressed using the notation C=*f* (Si, ePi, e^2Mi) and it is the first step towards assigning tasks to their complexity level in the austere framework of a mathematical formula.

Any task can be represented on the three-dimensional space in terms of its parameters' values. Let us have Semantics (S) be represented by the x-axis, Procedure (P) be represented by the y-axis, and Mental Constructs (M) be represented by the z-axis, as shown in Figure 28 (left) . The three points S ($Si, 0, 0$), P ($0, ePi, 0$), and M ($0, 0, e^2 Mi$), are the apexes of the triangle PMS, and subsequently, each vector joining two points defines one of the triangle's sides, as shown in Figure 28 (right).

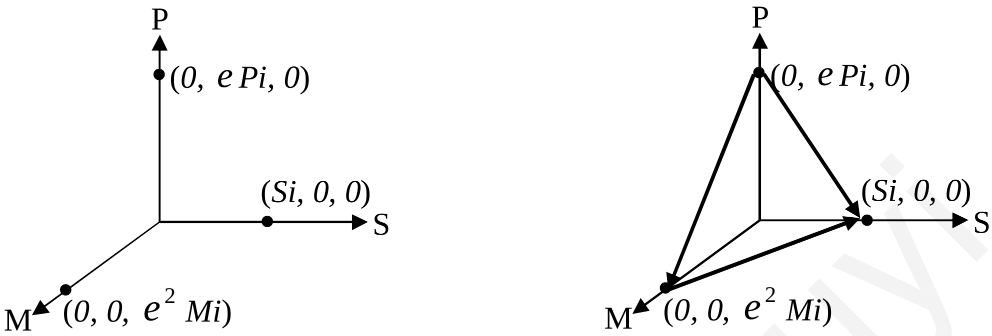


Figure 28. Three-dimensional representation of the cognitive task parameters.

We define task complexity as the area of the triangle PMS. Any change (increase or decrease) in any parameter's absolute value will directly cause a change (an increase or a decrease) of the complexity of the task, just as any change of the coordinates of any point on the three axes will alter the shape, and therefore the area, of the triangle. When working in the three-dimensional space, the area of a triangle is equal to one half of the magnitude of the cross product of two of the vectors that define the triangle. Let PM and PS be the common apex vectors whose cross product is to be calculated. The cross product is a vector with coordinates (i, j, k) and it is computed as:

$$\overrightarrow{PS} \text{ X } \overrightarrow{PM} = \begin{vmatrix} i & j & k \\ Si & -ePi & 0 \\ 0 & -ePi & e^2 Mi \end{vmatrix} = i\,(-e^3 PiMi) - j(e^2 SiMi) + k(-eSiPi)$$

$$\overrightarrow{PS} \text{ X } \overrightarrow{PM} = -\,e^3 PiMi\vec{i} - e^2 SiMi\vec{j} - eSiPi\vec{k}$$

This is a vector perpendicular to the surface of the triangle PMS. The module of the vector is equal to $\sqrt{(-e^3PiMi)^2 + (-e^2SiMi)^2 + (-eSiPi)^2}$. Since the area of the triangle is equal to one half of the vector module, we can calculate the area as follows:

$$A = \frac{1}{2}\sqrt{(-e^3PiMi)^2 + (-e^2SiMi)^2 + (-eSiPi)^2} = \frac{1}{2}\sqrt{(PiMi)^2 e^6 + (SiMi)^2 e^4 + (SiPi)^2 e^2}$$

Thus, $A = \frac{e}{2}\sqrt{(PiMi)^2 e^4 + (SiMi)^2 e^2 + (SiPi)^2}$

and, therefore, the complexity of a task is given by the formula: $C = \frac{e}{2}\sqrt{(PiMi)^2 e^4 + (SiMi)^2 e^2 + (SiPi)^2}$.

Therefore, the complexity of a task is described by the interaction of the three parameters, *S*, *P*, and *M*. The greatest emphasis is placed on the interaction of the most critical parameter, namely the Mental Constructs parameter, with the second most critical parameter, namely the Procedure parameter. Similarly, the less emphasis is placed on the interaction of the less critical parameter, namely the Semantics parameter, with the Procedure parameter. This pattern of interactions and the weight placed on them is derived directly from the exponential scaling applied on the constituent axes defining the task complexity vector. Theoretically, the values standing for item complexity lie on a continuum where tasks on the one end can have a near zero value equivalent to lying below an arbitrarily defined triviality threshold and at the other far end complexity may progress to infinity, and, therefore, tasks of varying complexity can be designed by altering the values of the quantifiable aspects of the three parameters.

The use of the natural logarithm *e* as the scaling factor for differentiating the value of the parameters and the assumption that the complexity of a task can be conceptualized as the area of an imaginary triangle defined by the vectors the three parameters form in an orthogonal system, is arbitrary. However, in the next section a test for our complexity formula will be presented, based on the analysis and the ranking of all reasoning items used in the second testing wave. An objective comparison of the hierarchy of the items' complexity, as it is obtained by our formula, against the results obtained from the Rasch models, will be attempted. We therefore aim at having our formula being scientifically and theoretically validated.

Applying the Three-Dimensional Complexity Formula

Every item used in the inductive and deductive reasoning tests during the second testing wave was analyzed according to our proposed task analysis and thus a numerical value referring to its complexity was assigned to it after applying our complexity formula. As a consequence, all reasoning tasks could be calibrated on a line according to their complexity. The detailed analysis of each item based on the assignment of a numerical value for each aspect of the parameters, the designation of each parameter's absolute magnitude, and the application of the complexity formula in order to yield the quantified expression of the item's complexity is shown in Table C1 in Appendix C. A detailed example of the analysis of a task is also presented in Appendix C.

In order to evaluate the objectivity of the proposed complexity analysis and the accuracy of the complexity formula we have studied the relation between the Rasch logits of the items with their respective complexity level as it is derived from our complexity formula application. The Spearman's *rho* between the ranking of the items in the two scales is very high (ρ = .84). An even higher correlation is obtained when the correlation of the ranking of the two scales is calculated for the two reasoning types separately. Specifically, when the two scales are compared based on inductive reasoning items ρ = .97, while the respective correlation of the two scales when the comparison was based on deductive reasoning items ρ = .84. These correlations between the Rasch scale logits and the complexity value of the items strongly suggest that the proposed task complexity formula is both robust and sound. A valid argument, therefore, is that this method of cognitive complexity analysis yields, a priori, an accurate estimation of a task's complexity. In addition, the estimated complexity values of a set of items are not linked to any specific task performance or to the specificities of the abilities of a group of test takers.

Item Complexity as a Means to Understanding Individual Differences and Cognitive Development

In order to study the cognitive substrate of reasoning as this is manifested in the performance on inductive and deductive reasoning tests of varying complexity, some further analyses were conducted based on the items' complexity and the participants' performance. Our goal is to investigate the relation between the cognitive capacity of an individual, as it is measured in terms of speed and control of processing and in terms of the storage and executive functions of working memory, with the complexity of any reasoning task at which the individual succeeds or fails. This will allow us to propose a theoretical cognitive profile of an individual capable of meeting the challenges at each complexity level. For reasons that are primarily related to the analyses that will be presented below, the computed complexity values of the group of items used in the two reasoning tests were clustered in groups of ascending order. The criterion used for the clustering of the items in the respective complexity levels was the result of much experimentation in order to achieve a normal – or close to normal – distribution of the items in the levels. Satisfactory results were obtained by considering the function $y = \alpha e^{\chi}$, where $\alpha = 1$. This occurs when the domain of the function is confined to the values $5 \leq \chi \leq 8$ and, subsequently, the range of the function $y = e^{\chi}$ corresponds to the span of the computed task complexity values, thus suggesting four discrete clusters for the integer values of χ from 5 to 8. Therefore, the lower and upper limits of the levels of complexity were set.

Six items were assigned at the first level of complexity, 8 items were assigned at the second level, 13 items were assigned at the third level and 4 items were assigned at the fourth level of complexity. Each participant was assigned to a reasoning complexity level if she had succeeded in more than half of the items at that level. Therefore, 220 participants (representing 57.1%) were assigned at the first level of complexity, 83 participants (representing 21.6%) were assigned at the second level, 46 participants (representing 11.9%) were assigned at the third level and 36 participants (representing 9.4%) were assigned at the fourth level of complexity. By assigning individuals at their reasoning ability level a study of the cognitive profile of the reasoners at each level was possible. All cognitive processes significantly differed across the four complexity levels. Post hoc tests (Scheffé) revealed that Complexity Level 1 was significantly different from all other levels in respect to all cognitive processes, namely speed and control of processing, simple storage and executive function of working memory. All other levels had no significant differences in terms of the cognitive processes with the only exception being the significant difference between the second and the fourth complexity levels in respect to the perceptual control process. These findings suggest that the various reasoning levels are differentiated in terms of the underlying inferential processes per se.

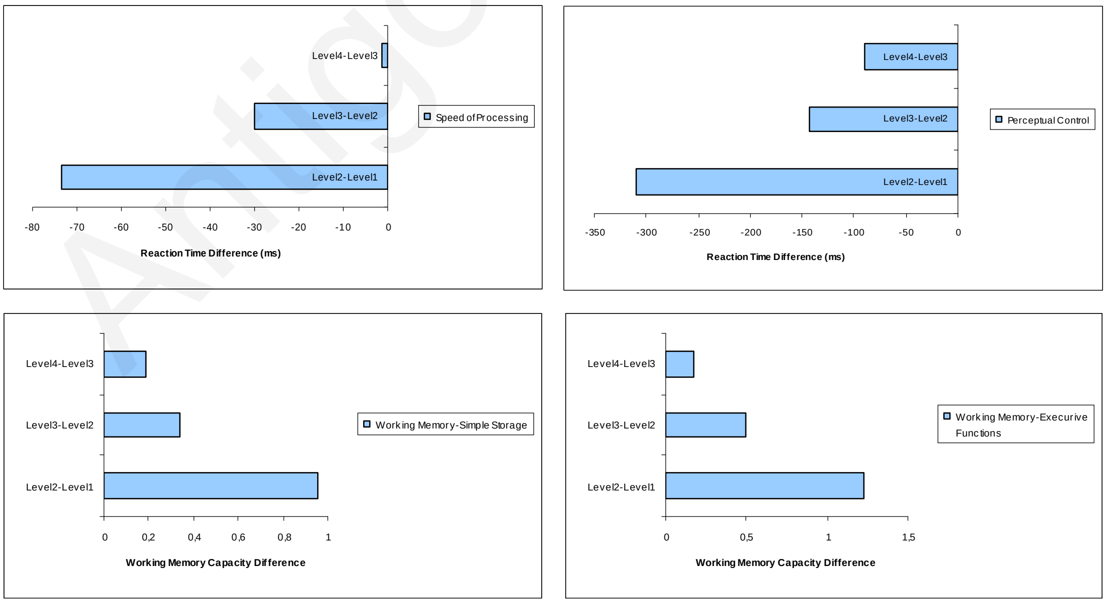


Figure 29. The differences between consecutive complexity levels in terms of cognitive processes.

An interesting pattern is revealed when the differences between the consecutive complexity levels in terms of cognitive resources are plotted. Figure 29 illustrates the differences in terms of speed of processing, perceptual control, simple storage and executive functions of working memory. These differences indicate the cognitive cost demanded when moving from one level to the next one. All cognitive processes yield the same exponentially decaying pattern of differences probably suggesting that as individuals move to progressively more complex reasoning levels the cost in cognitive resources is smaller. It is also suggested that processes that are specific to reasoning functions per se have the leading role in the transit phases.

Of utmost importance is to identify the specific parameters which comprise the cognitive profile of individuals at each complexity level. Individuals at Complexity Level 1 have a mean speed of processing, expressed as reaction time, equal to 630 ms and an inhibitory control, again expressed as reaction time, equal to 1700 ms. Their simple storage working memory capacity is equal to 3 information units and their corresponding capacity of the executive functions of working memory is almost 2.3 units. A huge difference in terms of cognitive parameters is observed in Complexity Level 2. Individuals at this level have a mean speed of processing equal to 550 ms and an inhibitory control equal to 1400 ms. Their simple storage working memory capacity is equal to 4 information units and their corresponding capacity of the executive functions of working memory is 3.5 units. The corresponding parameters for Complexity Level 3 are 525 ms for speed of processing, 1260 ms for inhibitory control, 4.3 units for simple storage and 4 units for executive function capacity. Finally, individuals at Complexity Level 4 have the same mean speed of processing as individuals in the previous level, a mean inhibitory control equal to 1170 ms, a simple storage capacity equal to 4.5 information units and an executive control capacity equal to 4.2 units.

The relation of the cognitive profile of individuals with their reasoning level is illustrated in Figure 30. It is obvious that individuals undergo a big cognitive change that facilitates their move from the first to the second complexity level. This cognitive shift is translated to a gain of 80 ms in speed of processing, a gain of 300 ms of control of processing, and an increase of one information unit in the capacity of working memory in both of its functions (simple storage and executive). It could be argued that the system appears to exhibit cognitive inertia which demands large amounts of cognitive resources to overcome the threshold while subsequent incremental changes are less demanding. After the first transition the system acquires a dynamic cognitive deposit that is maintained. It could also be argued that the transitions from the second level onwards do not need drastic changes in

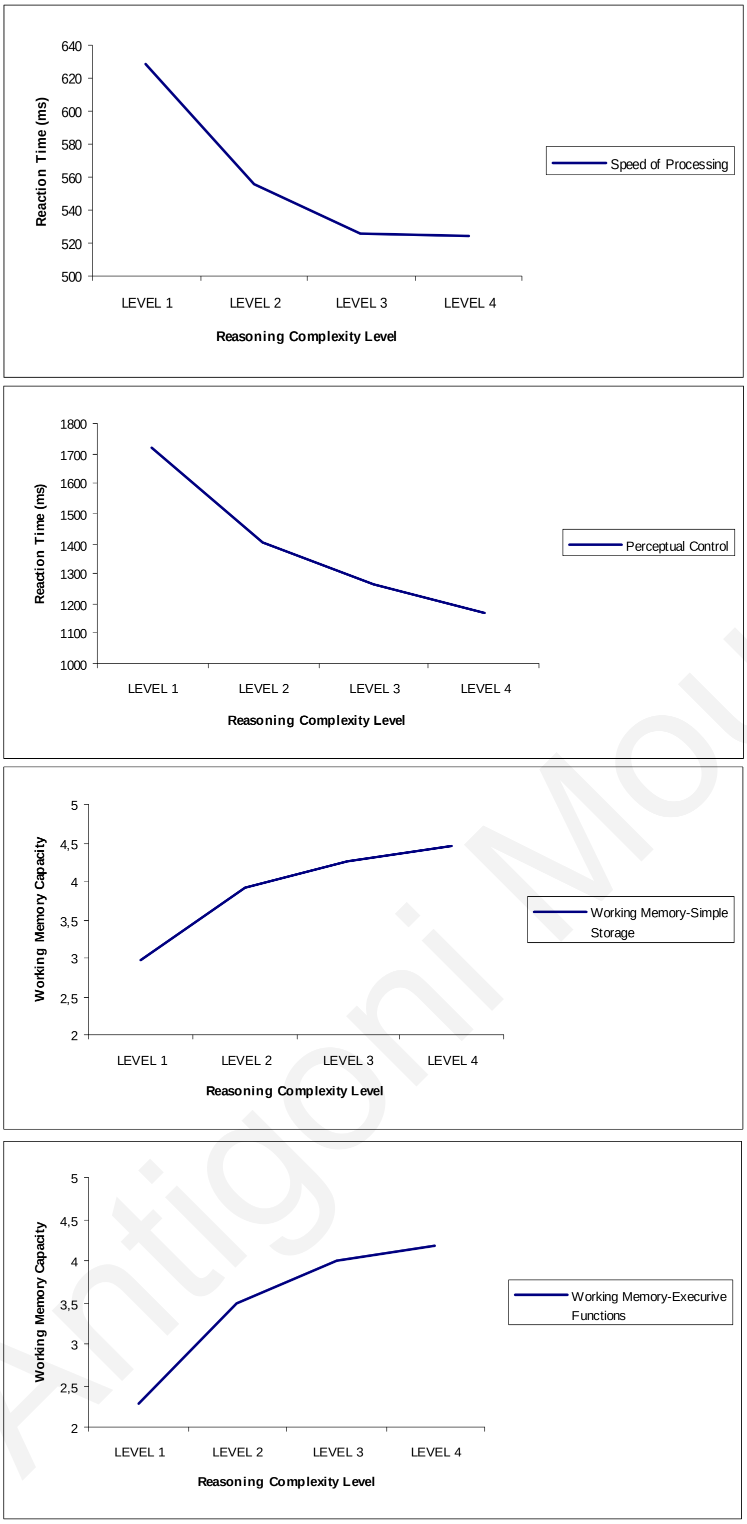


Figure 30. The cognitive processes as a function of reasoning complexity level.

the cognitive resources of the individual; rather the transitions are driven by a strong impulsive force created by changes in reasoning processes as such.

Summary

To test the hypotheses of the study and to provide answers for the questions posed, various analyses were conducted. Confirmatory factor analysis was used to corroborate that the tasks which were used in the processing efficiency, the working memory, and the reasoning tests were indeed measuring the cognitive abilities they were intended to measure. The multiple indicators that were used to measure each hypothetical construct were allowed to load on the latent factor which stood for the specific hypothetical construct. Eight latent factors were specified with reference to 23 indicators. A three-level hierarchical model was tested. This model confirms the three-stratum architecture of intelligence and untangles the confounding of individual differences and developmental changes. Using structural equation modeling a series of cascade models was tested in order to provide answers about the manner in which processes are interrelated both synchronically and longitudinally. The basic assumption of these models is that cognitive processes are hierarchically organized in such a way that more simple processes lie at the core of more complex processes in a cascade fashion. The processes are involved in a dynamic interplay where they are affected by the condition of the simpler processes and they, in turn, affect the functioning of more complex processes. The proposed simplex model confirms the existence of two broad levels of processes, namely the encoding and selection and, the representational levels. Some processes are strong developmental factors that drive age-related changes in other more complex processes. Some other processes are strong individual differences factors that account for a significant amount of variance in other processes. A series of ANOVAs with repeated measures were run to specify the developmental profile of the various processes. All processes present a significant developmental trajectory during the age span studied here indicating that big changes take place during childhood. The true role of more simple processes in the functioning of more complex processes was investigated by statistically controlling the effect of those processes. Rasch Models were applied on the inductive and deductive reasoning data in order to obtain simultaneous representation of the items' difficulties and the test takers' abilities. This enabled the identification of reasoning stages and the apodosis of the cognitive and the developmental characteristics of these stages. Finally, a formula that analyses reasoning tasks in terms of their complexity was proposed. When this formula was applied on the reasoning data four reasoning complexity levels were extracted. Further analyses revealed the cognitive profile of reasoners at each level.

CHAPTER 5

FINDINGS, CONCLUSIONS, AND IMPLICATIONS

Introduction

The examination of the dynamic interplay between various cognitive processes from 6 to 11 years of age was introduced in chapter one as the aim of the study, along with the conceptual underpinnings related to it and emphasis was placed on the need for further research in the domain. Chapter two offered an in-depth literature review which presented the general intelligence factor from the psychometric, the cognitive and the developmental perspective, the processing efficiency and representational processes in relation to the general intelligence factor and developmentally and, finally, the basic principles and theories of cognitive task analysis. Chapter three referred to the data collection and instrumentation. The results of the analyses were presented in chapter four. Structural equation modeling was used to study the differentiated role of the various processes with regard to their contribution to reasoning development and their dynamic interplay. Hierarchical cascade models that best fitted the data presented the concurrent and the longitudinal relations between the processes. The developmental profile of each of the processes and the interaction between various parameters of them were presented. Finally, a task analysis formula was proposed and its results were compared with the scaling of the reasoning tasks as this resulted from Rasch analysis.

Summary of the Study

Cognitive and developmental findings suggest that human intelligence is related to various mental processes. Researchers have focused on different aspects of this multidimensional pattern of relations and have approached them experimentally in multiple ways. Yet, the general intelligence landscape still needs to be demystified. The discrepancies reported in the literature review between the theories proposed to explain the cognitive and developmental aspects of the processes considered to be important parameters of general intelligence, call for a different approach. Moreover, the study of the dynamic interplay between processing efficiency, working memory, information integration processes and inductive and deductive reasoning is needed to fill a gap in the theory of general intelligence and reasoning ability.

The study aspires to provide answers to certain research questions with regards to the structural and causal relations of speed and control of processing, working memory, information integration, and reasoning ability. Variances in performance on these processes are examined while the confounding of individual and age-related differences is controlled. The study of the developmental course of each process during the age span from 6 to 11 years old aims at providing answers regarding the importance of this age period to the development of cognition. The study of both the concurrent and the longitudinal relation of reasoning ability to the other cognitive processes and the study of stage-like development of reasoning ability are providing answers regarding the nature, the functioning and the development of reasoning. Furthermore, the parameters that define cognitive task complexity and their weight in a complexity formula that aims at serving as a reliable instrument of both predicting and assessing reasoning ability are analyzed.

The study was based on two testing waves. A total of 140 participants were tested at the first testing wave and 395 participants were tested at the second testing wave. All participants were approximately evenly distributed across the six primary school grades and gender. One hundred and eleven participants were tested in both of the testing waves and, thus, were the subjects of the longitudinal study.

Findings

Our study and the analyses conducted were based on the set of hypotheses and aimed at answering the research questions, as these were articulated in Chapters 1 and 3. The findings will be presented and discussed according to the hypotheses of the study and answers to the research questions will be provided accordingly.

First Hypothesis

The cognitive processes are hierarchically structured in such a way that a general factor residing at the apex of the hierarchy accounts for the individual differences encountered both in age-peered populations as well as developmentally. This general factor should reflect general intelligence and it should map strongly onto other factors residing lower in the hierarchy. The general intelligence factor should account for the common variance manifested in a group of other general, albeit less so, factors, such as processing efficiency, working memory and reasoning ability. Each of these less general factors stands in its own right, as complete autonomous process, while maintaining its own specificities. Further analysis of any factor at the second level should reveal an underlying hierarchy comprising more specific processes, such as sheer speed of processing, inhibitory control, short- term working memory capacity, inductive reasoning.

The hierarchical model is based on the assumption that the human mind operates based on hierarchically organized mechanisms. The pattern of factor loadings, as they are presented in the model before and after partialling out the effect of age, confirms that the proposed three-stratum architecture of intelligence is not only statistically plausible but it is cognitively reasonable and informative as to the real existence of functionally discernible levels of organization of the mind. This hierarchical structure optimizes the brain's efficiency in dealing with all sorts of trivial and non-trivial problems by interweaving the various cognitive processes in a structure of both unity and diversity. More specialized abilities lie at the lower level of the hierarchy and are represented by the clearly distinct first order factors. The regression coefficients obtained in the first level of the hierarchical model clearly reflect intra-variance, that is, variance accounted by the specific abilities and hence, they reflect the manifested individual differences, their nature, and the degree of their covariance with age. Each one of the first-order factors constitutes a fundamental ability which is not only specific in its functioning but it is also omnipresent during the information processing.

Processing efficiency parameters, namely speed of processing, perceptual discrimination, perceptual control and conceptual control, are in a great extent depended to age-related changes. This is suggested by the noticeable decrease in the loadings of the speed and control indicators on their respective first order factors when the effect of age was removed from the relations. Working memory and information integration are affected by age-related differences in a more subtle way than the reasoning and the processing efficiency abilities do. Specifically, it seems that information storage and retrieval, and information integration are partly affected by the biological changes which are manifested in the speed and control of processing and partly affected by changes in the representational capacity that occur in the course of maturation. Reasoning ability covaries extensively with age. Radical changes occur in reasoning performance during childhood, a finding that is replicated when other analyses are conducted, and which are more extensively presented in the discussion of subsequent hypotheses. These changes that come as a byproduct of age maturation are basically in the sphere of knowledge acquisition, of learning how to get access to categorically organized information, and of the accumulated repertoire of alternatives to pragmatic, semantic, and hypothetical schemas (Kuhn & Franklin, 2006). Each of these specialized processes lies under the jurisdiction of a set of intrinsic physical and mental laws which place restrictions upon its functioning and, at the same time, provide it with a set of certain characteristics common with other mental processes. So, while each specialized process acts in a relevant functional autonomy, it shares some common characteristics with other specialized processes. These common characteristics are manifested as common variance of the specialized processes which is represented in the more general factors that reside on the second level of the hierarchy. It is clear that specialized processes do have strong effects on higher order, more general systems and, at the same time, their possible drawbacks are directly reflected in the second level of the hierarchical structure.

The second level of the model represents the intra-structure of the more general factors, namely the processing efficiency, the ability of information storage, retrieval and integration, and reasoning ability. The intensity of the relations which define each second order factor is indicative of the role of this level as an interface between the specialized cognitive processes and the general intelligence factor. The invariance of the structure as well as the invariance of the intensity of the web interweaved by both the more specific and the more general cognitive processes is statistically confirmed and it is present from the early stages of childhood till the entrance to adolescence. At this level, the obtained factor loadings do not reflect individual differences in performance. Rather, they reflect the reliability of the cognitive processes' web irrespectively of any age-related differences. The processing efficiency factor is defined by the specific attributes of the speed of processing and the ability of the cognitive system to control its own impulsive reactions. The obtained factor loadings are high, reflecting a relatively small proportion of unexplained variance for the speed and control factors. The general ability of information storage, retrieval, and integration reflects what is common between information integration and the functions of working memory. Although the correlation of information integration with the simple storage function of working memory and the executive function of working memory is low (.39 and .36, respectively) Miyake et al. (2001) note that correlations of this magnitude are common among tasks addressing different functions of working memory, "partly because these complex tasks often involve a good deal of variance related to non-executive processes as well as measurement error'' (p. 630). The factor representing information storage, retrieval and integration, accommodates all working memory variance while almost a third of the variance of the information integration factor remains unexplained. This pattern of relations suggests that information integration is not a purely memory process but it incorporates other processes uniquely attributed to it such as planning, decision making, checking, updating and adjusting. As Colom et al. (2004) suggest "latent-variable analysis is particularly useful in these circumstances because the analysis extracts the common variance between the tasks chosen to tap working memory".

Reasoning ability factor reflects the common variance between deductive and inductive reasoning. Though the extremely high factor loadings of both types of reasoning suggest that they are based on common underlying inferential mechanisms, the structure of the reasoning tasks used in the study suggests that this conclusion cannot be drawn, at least not based on these factor loadings. Specifically, inductive reasoning was measured using analogies and syllogisms in verbal, numerical and spatial content. Most of these syllogisms did not draw from the participants' knowledge repertoire but were focused on rule extraction – a process that is highly related to deductive reasoning. Obviously, inductive reasoning is a much broader and complicated process; rule extraction is based on looking for patterns and similarities in vast volumes of data. Within the present study, information was presented in a really simple, parsimonious way such that patterns and similarities were easily identified and the cognitive cost of the task was placed on extracting the rule and applying it. So, both types of reasoning were tested based on tasks that demanded either rule extraction or rule application, or both. Therefore, the reasoning ability factor, at this level of the three-stratum model, reflects the ability of the system to manipulate rules.

At the apex of the hierarchy lies a single factor which, as we propose, represents general intelligence. General intelligence factor refers to the component variance that is common to a broad spectrum of mental tests (Brody, 1997; Carroll, 2003; Jensen, 1998). The factor loadings at this level of the hierarchy strongly suggest that the most *g*-loaded tests involve complex cognitive operations such as inductive and deductive reasoning. Tests with low *g*-loadings involve less complex cognitive operations such as perceptual or sensory discriminations, reaction times to simple stimuli, and simple storage or rote memory. These findings are in accord with the findings of other researchers (e.g. Vernon & Weese, 1993) and with the general postulation that a mental test's *g*-loading is based on the complexity, the capacity and the efficiency of mental operations rather than on specific knowledge, skills, or strategies (Jensen, 1998). The extraction of *g* as a *second-order* factor in a hierarchical factor analysis requires, according to Jensen (1998), a minimum of nine tests, which should be a representative sample of all types of mental tests, from which at least three primary factors can be obtained. In the case of this study eight first-order factors were obtained from a set of 23 indicators. Three second-order factors were extracted representing processing efficiency, memory and reasoning ability. The third-order factor, *g*, is therefore obtained from a representative sample of tests and it is a good measure of the general intelligence. Moreover, the convergent and discriminant validity of the tests used ensure the good quality of the third-order factor (Kline, 1998).

General intelligence is decomposed in terms of processing efficiency, information storage, retrieval and integration, and reasoning. Only half of the variance of processing efficiency parameters is explained by general intelligence, a finding that is in accord with the fundamental thesis that *g* reflects the mental complexity of a test. The more complex a test is, the more *g*-loaded is (Jensen, 1998). The drastic drop of the regression coefficients of processing efficiency with the general intelligence factor when the effect of age is removed from these relations is strong evidence that processing efficiency and age covary in a way that the underlying mechanisms of speed and control of processing are developing with maturation and are gradually becoming a significant part of *g*.

The findings on the relation of information storage, retrieval, and integration with the general intelligence factor suggest that there are processes attributed to the general factor of working memory which are not included in what is conceived as general intelligence. Presumably, these are processes that are closely based on mnemonic strategies knowledge and application and on any kind of knowledge that is acquired via educational and cultural means and is not reflected in the *g* factor. These findings are in sheer contrast to the findings of other researchers who suggest the existence of an isomorphism in the relation of working memory with *g* (Chrystal & Kyllonel, 1990). Our thesis is that the presumed isomorphic relation between working memory and *g* is derived from very few – if not a single – measures of the general intelligence such as the Raven. In line with our thesis is the suggestion by Ackerman, Beier, and Boyle (2005, p. 44) that "high-quality estimates of *g* are generated from the average across multiple tests of differing formats, contents, and processes". Therefore, the isomorphism in the relation of working memory with *g* is artificial. Furthermore, as it will be discussed at the next hypothesis, the correlation between working memory and any higher order ability is often inflated due to their shared variance with other factors, such as speed and control of processing. Ackerman et al. argue that the overarching question about the relationship of working memory with intelligence will ultimately be resolved if studies provide multiple tests of a wide range of ability factors (e.g., reasoning, spatial, verbal, numerical), multiple tests of working memory in each of the different content domains (verbal, numerical, spatial) that do not depend on time-sharing performance, and information processing tasks. All these measures would provide the necessary convergent and discriminant validity among working memory and intelligence. It is argued that the present study has obtained an unbiased correlation between working memory and the general intelligence factor to the degree the above suggestions by Ackerman et al. have been satisfied.

As children grow older the relation of information storage, retrieval, and integration with the general intelligence factor gets stronger. This finding may explain the high correlation of working memory functions with the general intelligence factor reported in other studies. An important number of those studies examine the relation of working memory with the *g* factor in adolescents and young adults when a strong relation is exemplified because individuals at these ages have developed their executive functions which are encompassed in the functioning of working memory. As time goes by the system becomes progressively more efficient in managing the input information and subsequently, the storage, retrieval, and integration mechanisms are improved. Information is processed in a more "dexterous" manner drawing more on the cognitive resources of the system. Age-related changes that occur during early and middle childhood are obviously affecting information processing in an extensive degree and information storage, retrieval and integration in a more subtle way.

The reasoning ability factor is absolutely correlated with the general intelligence factor, even when the effect of age is removed from the relation. Inductive and deductive reasoning and problems that involve spatial visualization, quantitative reasoning, and verbal reasoning are highly *g*-loaded tests as Jensen (1998) notes. In the design of this study, as he proposes, inductive and deductive reasoning items are evenly balanced among verbal, spatial and numerical contents so as to allow most of the variance in the total score to represent a general intelligence factor which is relatively uncontaminated by group factors. It is, therefore, suggested that reasoning ability, as it was measured in this study, is an almost perfect reflection of the general intelligence factor, and thus it could be used as a means of measuring general intelligence. Generally speaking, the pattern of correlations between the second order factors with the general intelligence factor, before and after partialling out the effect of age, strongly suggests that the ability to reason is the cornerstone in the architecture of mind and of what constitutes intelligence. It is suggested that basic inferential rules are established in the system early in life, making reasoning the best predictor of general intelligence.

Second Hypothesis

Each of the specific cognitive processes is related with the other mental processes in such a way that the more fundamental processes are embedded in the more complex ones. A dynamic interplay among the cognitive processes should emerge, suggesting a cascaded arrangement of the processes. This cascaded arrangement of the processes should imply that changes happen in a bottom-up fashion, that is, changes in the more *simple processes should drive changes in the more complex processes, and, therefore, it is expected that some processes will be identified as individual differences factors, and others will be identified as developmental factors.*

In order to test this hypothesis on the cascade arrangement of the cognitive processes two types of models were tested. The first type included a series of simplex models which tested the exact position of each process in the hierarchy. The resulted simplex model confirms the existence of two broad levels of processes, namely the encoding and selection and the representational level. The processes are organized in two distinct levels and within each level there are strong relations between processes. The processes are involved in a dynamic interplay where they are affected by the condition of the simpler processes and they, in turn, affect the functioning of more complex processes. It is also suggested that speed of processing is the basic source of individual differences in the control and the representational processes. When the effect of age is removed from the relations of the processes, a large decrease of the regression coefficients of the representational processes and a small decrease of the regression coefficients of the encoding and selection factors were observed. These findings indicate that the structure of the relations of the processing efficiency factors is stable throughout childhood, indicating that their change is most probably driven by the same underlying force. As far as the representational factors are concerned, age is an important factor indicating the vital role of age-related experience in the construction and use of the strategies and processes involved at the representational level. It should be noted that when the effect of age is partialled out, the most drastic drop of the regression coefficients is observed in the cut off point between the two levels, the regression of working memory capacity on conceptual control. This drastic drop suggests that as children grow the relation between the two levels becomes stronger and more important. It is also suggested that the processing efficiency parameters play an increasingly more substantial role in the functioning of the higher order representational processes. Memory and reasoning capitalize on age-related changes in the less complex processes. Speed and control of processing protect the limited-capacity working memory from overloading. Reasoning processes utterly benefit from these changes and invest them in developing broad, flexible, and powerful mental skills that allow complex inferences based on both the strict laws of logic and on their real-world knowledge (Kuhn & Franklin, 2006).

The second type of models that were tested was cascade models. These models are an attempt to approach the relation between the processes both within and between the two levels in a refined manner assuming fine differences in their interrelations. Two variants of the simple cascade structure of the processes are proposed. The first one, the analytical, aims at examining in detail the relations of the two basic functions of working memory (simple storage and executive control) and of the two types of logical reasoning (inductive and deductive) with the other processes. Such a model, which relates both types of reasoning with the other cognitive processes, has been long needed (Markovits & Barrouillet, 2002). The second variant, the parsimonious cascade model, aims at focusing on the most significant and robust relations. Such a parsimonious model would be preferable over the saturated models and thus the web of the processes' relations as well as their strength would be considered as a more realistic apodosis of the true correlational pattern between the processes.

Sheer speed of processing is a core process present in all other processes' functioning. Its correlation with the other processes that reside at the first level of information processing is very strong. This relation is not significantly weakened when age is partialled out. Nevertheless, the degree to which this relation is weakened indicates that the part of these processes that involves processing that goes beyond sheer speed benefits from age-related changes in speed. These processes refer to perceptual discrimination, perceptual control and conceptual control when speed is removed from them and what is left is the actual process per se. Therefore, it is suggested that speed acts as a predictor for individual differences in the processes residing on the encoding and selection level. A different pattern of relations is observed at the level of representational processes. Speed of processing has a significant role in their functioning and it is proved to be a strong developmental factor. Performance on tasks that mainly require working memory capacity greatly benefits from higher mental speed (Fry & Hale, 1996; Jensen, 1998; Kail & Salthouse, 1994; Salthouse, 1996) since encoding, transforming, and retrieving information within working memory takes time and the faster the rate of processing, the greater the amount of information that can be processed. The chances of reaching or even exceeding the limits of the constrained capacity of working memory are smaller when the information in working memory is processed more quickly. Speed of processing has a decisive role in both preventing the mnemonic trace decay, by allowing sufficient time for deeper and more meaningful process (Craik & Lockhart, 1972**)** of the input information, and in allowing more memory space available for processing the data and have it archived in a "more permanent location", that is long-term memory. In the case of attaining the working memory capacity, some information will unavoidably be lost; that being either a part of the incoming information or earlier encoded information which was not been promoted to long-term memory. The positive relation between speed of processing and the functions attributed to working memory as well as its strong relation with reasoning suggest that mental speed is basic to human intelligence (Jensen, 1998). The use of non-speeded reasoning tasks in this study allows for a more objective, not inflated estimation of the relation of speed with reasoning (Wilhelm & Schulze, 2002). Both types of reasoning correlate significantly with speed of processing, though inductive reasoning seems to have a slightly stronger correlation.

Perceptual discrimination is, as expected, significantly correlated with the other processing efficiency factors at the first level, while from the second level of processing it is only related with reasoning ability. This finding suggests that when faced with a set of premises the reasoner draws on both speed processes, the sheer speed and the perceptual discrimination, in order to activate the necessary and sufficient alternatives and either use them in mental model construction or use them as a confirmation or a counterexample of a mental rule that has been applied. The analytical cascade model indicates a significant correlation of perceptual discrimination with both types of reasoning; yet the correlation with deductive reasoning is stronger. This finding is supported by the neurocognitive findings on the dependence of deductive reasoning on spatial ability, especially in the cases where no semantic content is present (Goel, 2000). Therefore, the ability of perceptually discriminating information is contributing to the deductive process and it is suggested that it becomes more important when the semantics of the premises are not interfering in the deductive reasoning process. Rather, when the individual has developed the ability of focusing on the syntactic features of the premises, which are freed from the meaning they convey, then perceptual discrimination ability has a supportive role.

When moving to the control processes, interesting findings emerge. Specifically, a significant part of the individual differences in the performance in perceptual control is attributed to perceptual discrimination. Our findings support the idea that the system is capitalizing on all speed processes when inhibitory control processes are activated in order to control incoming information and filter out all irrelevant or noise data. Performance on tasks that mainly require working memory capacity greatly benefits from the efficiency of perceptual control. Perceptual control is also a core process present in reasoning where it exemplifies its dual role: Filtering out the non-relevant information and inhibiting premature termination of the reasoning process. It is of great importance, in terms of effective management of the cognitive resources, to keep out as much non-relevant information as possible and thus use the pool of cognitive resources for the effective processing of the relevant to the goal information. The control mechanisms help the system focus on the relevant information and capitalize on its resources. Furthermore, the control mechanisms inhibit the tendency of the system to end the reasoning process as soon as it reaches a conclusion that seems to accommodate the minimum demands in a satisfactory way, before fleshing out all necessary alternatives.

Our findings are in accord with the findings of Wilhelm et al. (2006) who have found that speed on choice tasks where the stimulus-response relation was incompatible, i.e. the incompatible condition of the stroop-like test on which perceptual control is measured, was highly correlated with the working memory capacity and reasoning. According to Wilhelm et al., reasoning ability is strongly correlated with perceptual discrimination because they both build and maintain temporary bindings, that is, rule-like relational representations established by the system to relate two or more elements. In the case of perceptual control, bindings are mental rules joining stimulus representations and response representations. In the case of reasoning, bindings established in the working memory (or in the case of prolonged practice, in the long-term memory) are necessary in the process of fleshing out the mental models and searching for alternatives.

The strong pattern of the relations of perceptual control with the representational processes is greatly affected when the effect of age is controlled authenticating the role of perceptual control as a significant factor contributing in individual differences in working memory capacity and reasoning ability. Its correlations with working memory and reasoning are preserved at the same level, but are not found to be statistically significant. This suggests that as children grow up their ability to control processing is gradually becoming more effective and therefore more significant in the process of working memory and reasoning. Hence, perceptual control seems to be both a developmental factor and a factor which affects individual differences in cohorts.

The cascade type of models used in our analyses to explore the relations between the various cognitive processes serve as a reliable means of depicting the fine differences between the various control processes and shed some light to the processes which are often put indistinguishably under the general umbrella of executive functions. The cascaded arrangement of the processes included in this study provides an additional argument in the discussion on attentional shift cost. While some researchers (Cepeda et al., 2001; Zelazo et al., 2004) argue that the larger attentional shift costs in young children reflect inefficiency in inhibitory control since individuals cannot efficiently inhibit their responses to the previously activated task, Crone et al. (2006) suggest that the larger attentional shift costs in children reflect working memory deficiency in retrieval of the appropriate rule. Though not explicitly stated, perceptual control measures were based on attentional shift since participants were first tested under the compatible condition of the dominant dimension of the stimuli and then they were asked to respond to the incompatible condition of the non-dominant dimension, which comprised the perceptual control measure. Therefore, attentional shift was necessarily activated in order to provide correct responses to the perceptual control tasks, and it has consequently contributed in the observed variance of perceptual control. The cascaded arrangement of the processes strongly suggests that individual differences as well as developmental differences in attentional shift cost are not due to working memory deficiencies; rather they reflect inhibitory control inefficiency, as Cepeda et al. (2001) and Zelazo et al. (2004) suggest.

Working memory is moderately correlated with the reasoning ability. Reasoning process, unlike general problem solving where various solutions can be theoretically and practically applied, evaluated and moderated, is based on the functioning of long-term memory, since the mental rules and the specific knowledge which makes more effective the accessibility and use of alternatives, must be effectively activated from the long-term memory and serve as vital constituents of the core processes of logical reasoning. The outcome of reasoning process is strongly dependent on the repertoire of mental rules already installed in the long-term memory of the system and on the amount of accumulated knowledge on specific contents. The role of working memory is limited to the online processing of the premises in order to facilitate the activation of the mental rules and the specific knowledge needed for further processing the information and reaching for a conclusion. In so doing, working memory is strongly depending on both speed and control of processing which ensure that the information from the premises is efficiently processed and that content, context and belief biases do not interfere during the retrieval of alternatives from long-term memory and their embodiment in the mental models.

Based on the analytical cascade model some fine differences in the functioning of the simple storage and the executive feature of working memory are revealed. Specifically, the correlational pattern between the executive control function of working memory with the speed and control of processing is similar to the one obtained for the relation of the simple storage function of working memory with the processing efficiency parameters, though it seems that the need for high speed of processing is more vigorous when simple storage takes place than when the executive functions of working memory are activated. Nevertheless, the role of perceptual control remains critical in filtering out the irrelevant information and in protecting working memory from overloading. These findings suggest that when the system is merely memorizing information without any processing on it, it draws on the speed and control resources in order to store as many bits of information as the capacity limitations allow. The role of both processes in the efficient simple storage functioning of working memory is of great importance.

It is suggested that when information reaches the system through the various senses a vast majority of it is registered in a *volatile* memory. The mnemonic trace which is automatically created is almost instantly decayed unless it enters deeper in the process of working memory where it can potentially be driven to two main options. The first option is for the system to simply store information with no further process. The second option is for the system to consciously solicit the involvement of executive control functions in order to avert the decay of the information by yielding meaningful connections with other bits of information. The efficient functioning of the executive control process makes stored information more articulated by adding identification dimensions to it while utilizing the processing efficiency recourses. Speed and control of processing are present in either function of working memory, yet when the executive functioning is activated the system has somewhat less demands on speed and control. The need for high speed of processing is more vigorous when simple storage takes place than when the executive functions of working memory are activated because during the process of simple storage the information is stored in short-term memory as independent units with no conceptual or perceptual links with other information already stored. In this case, information processing draws on the resources of processing efficiency in order to prevent the decay of the mnemonic trace which unavoidably happens as a result of unsuccessful information process and as a result of the intrusion of other information which keep floating in the system. This procedure takes place for each information unit separately and thus the accumulated mental energy cost is greater. When perceptual and conceptual links are created, as is the case when the executive functioning of working memory is activated, then both storage and retrieval of information is more efficient and less mental energy consuming.

In as far as the relation of working memory with reasoning is concerned the results of the cascade models are relatively informative. The simple cascade model yields a moderate correlation of working memory with reasoning (.42). It is suggested that this correlation is not inflated as other correlations reported (Engle, Tuholski, et al., 1999; Kyllonen, 1996; Kyllonen & Christal, 1990) for two main reasons. The first one refers to the number and the diversity of the tasks used in the present study (Oberauer et al., 2005). Both working memory and reasoning ability are measured using various tests which tap the processes from different perspectives and allow for a greater part of their variance to come to surface. Therefore the common variance between the two processes may be smaller since the comparison is done based on a broader spectrum of variances. The second reason the reported correlation is not inflated is because the common variance between the two processes that is due to the presence of other processes that act as mediators in this relation, such as speed and control of processing, is removed. Therefore, the reported variance is not contaminated by mediators' shared variance with either process.

As Engle, Tuholski, et al. (1999) suggest, the real relation of working memory with reasoning ability can be traced when a subtle distinction between the short-term memory and working memory constructs is achieved. The analytical cascade model provides such distinction as well as a distinction between the two reasoning types. Simple storage function of working memory has near zero correlation with both types of reasoning, a finding that is in accord with the findings from a study on the relationship that exists between working memory capacity, short-term memory capacity, processing speed, and fluid intelligence conducted by Conway, Cowan et al. (2002). The executive functions of working memory are moderately correlated with inductive and deductive reasoning (.36 and .20, respectively), though the correlation with inductive reasoning is statistically significant. While Cowan and his associates (Cowan et al., 2007; Cowan, Elliott et al., 2005) suggest that the ability to focus attention according to the task demands acts as a mediator in the relation of working memory with reasoning, and while other theorists (e.g. Engle, Tuholski, et al., 1999; Kane et al., 2001; 2004; Unsworth & Engle, 2005) suggest that the ability to control attention is responsible for the relation of working memory with intelligence, the results of this study suggest that this relation is to a great degree freed from the contamination of the variance of a third process. Part of the variance of the ability of attentional flexibility or the ability of attentional control which are supposedly mediating the relation of working memory with reasoning is removed from the relation by partialling out the effect of inhibitory control or perceptual discrimination. Therefore, the reported correlation of the executive functions of working memory with reasoning ability is an objective apodosis of the real relation, not contaminated by shared variance with other executive function processes.

The question of the separability of the various executive functions from other cognitive structures which also encompass such cognitive resources is very important. Schweizer et al. (2005, p. 607) argue that "inseparability challenges the uniqueness assumption of attention and also the expectation that attention provides a unique contribution to the prediction of intelligence". When predicting intelligence, overlapping between the results of the measures of attention and of other cognitive processing is caused by the inseparability of the executive functions. It is suggested that almost a third of the variance of intelligence is predicted by the whole set of attention measures when these are autonomously measured and that a considerably larger amount of intelligence can be predicted if other measures of cognitive processing, such as perceptual processing, are considered (Schweizer, Zimmermann, & Koch, 2000). Based on the simple cascade model, the portion of reasoning that is predicted by the two control processes is 28%, a finding that agrees with the suggestions of Schweizer et al. (2000). It is proposed that each executive function that is measured separately has a unique contribution to the prediction of reasoning (or intelligence) though an overlap in variances will be evident.

The reasoning ability factor lies at the apex of the hierarchy and a large proportion of the individual differences in it can be attributed to the factors residing lower in the hierarchy including processing speed, control and memory. A very small proportion of its variance remains unexplained (while in the second wave data this was a zero-order proportion). These findings suggest that a highly complex mental function can be analyzed in terms of its cognitive underpinnings and thus it can be better understood. As a result, performance on the complex mental function can be predicted with a relatively satisfactory accuracy based on the simpler processes' condition. Both reasoning processes are substantially depending on the processing efficiency resources. The annihilation of the speed coefficients when the effect of age is statistically controlled indicates the developmental role of speed of processing. Moreover, the imperative role of perceptual control as a factor explaining individual differences is once more revealed by the fact that the high correlations obtained between inductive reasoning and perceptual control and between deductive reasoning and perceptual control are retained after controlling for age. Finally, the set of coefficients of conceptual control with inductive and deductive reasoning as they were obtained from the first wave data is a probable indicator that a significant conceptual change occurs during childhood (6 to 11 years) which affects the functioning of both types of reasoning. Such a pattern of increases is probably suggesting that during the age span studied here a conceptual change takes place and this change, which may have the format of concepts being recognized in broader and more detailed categories, is responsible for a significant portion of the variance observed in both reasoning types. Subsequently, the two most basic processes of conceptual thinking, namely specialization and generalization, are undergoing a change too. As a result, inductive and deductive reasoning are both being affected since specialization and generalization are core processes in the functioning of deductive and inductive reasoning (Holland, Holyoak, Nisbett, & Thagard, 1989). This assumption on conceptual change is only based on the findings of the first wave data so one should be circumspect in adopting it. Nevertheless, it could be used as a hypothesis for further research.

A relation, which holds in time in an impressively strong way, is the one observed between the two types of reasoning. Their invariant through time relation can be attributed to the fact that deductive reasoning functions on the basis of the repertoire of mental rules which are shaped and confirmed via an inductive reasoning procedure. This ongoing relation conforms to the idea of recursiveness between the two processes. Mental rules are shaped as a result of the generalization procedure which is based on a set of observations. The mental rules are under a potential dispute or confirmation according to the new data and the new line of reasoning. New conclusions that result from deductive reasoning may set a starting point for a new quest and a new line of thought for searching for a new rule which will apply to more (or all) cases and so on. The obtained coefficients reflect this ongoing recursive relation which does not covary with age. It is dynamically present from the early stages of childhood and it signifies, to a great extent, individual differences in the two types of reasoning. The portion of their common variance reaches 25%; a portion which increases when the effect of age is statistically controlled indicating that, as children grow, the underlying mechanisms of the two processes are getting more differentiated. This finding is in accord with the findings from the neural research on the distinctiveness of the reasoning processes (Goel, 2007; Goel, Buchel, Frith, & Dolan, 2000; Goel & Dolan, 2000; 2001).

Moreover, the findings of the present research suggest that inductive reasoning is a developmental factor for deductive reasoning. It contributes to rule formation and subsequently to the formation of rule hierarchies, a central process in developmental changes in executive function via the mechanism of rule reflection (Zelazo & Frye, 1997) and an important resource in deductive reasoning to the extent to which it is based on mental rules. Complex rule hierarchies allow for more flexible selections of rules according to the underlying condition that must be satisfied and it is imposed by the given premises. Age-related increases in individuals' metacognition, reflection and deliberate selection among mental rules, result in increased control over thought and action (Zelazo, Frye, & Rapus, 1996), a core process in deductive reasoning (Markovits & Barrouillet, 2002). Representational inflexibility (Zelazo, Qu, & Müller, 2005) and difficulty in inhibiting a prepotent response (Diamond, 1996), are observed when dissociations between knowledge and the ability to use that knowledge are not integrated into a more complex rule system. According to Frye, Zelazo and Palfai (1995) increases in control strongly affect children's reasoning. The level of rule complexity constrains the ability to control reasoning. Furthermore, rule reflection, rule assessment and rule employment are strongly associated with the functioning of working memory.

The proposed cascaded configuration of the processes closely reflects these relations proposed by Zelazo and his colleagues. Inhibitory control affects individual differences in working memory and inductive and deductive reasoning. Working memory is involved in rule construction, utilization and assessment, and limitations in its capacity have a direct effect on the efficiency of rule production, a process that is closely related to inductive reasoning. Finally, deductive reasoning is based on mental rules, at least during childhood and it reflects individual differences in all other processes involved in mental rule construction. It could also be argued that innate or early in life constructed rules via inductive reasoning processes, serve the needs of deductive reasoning. As individuals gain experience and as they mature in terms of processing efficiency parameters they are better able to construct mental models partly based on mental rules.

Third Hypothesis

During the age span studied here, it is expected that drastic developmental changes will occur in all processes. The profile of the age-related differences should suggest that a common mechanism underlies these changes. It is hypothesized that the processing efficiency parameters, namely the speed and control of processing, initiate and maintain changes in the representational processes, namely working memory and reasoning ability.

All processing efficiency parameters show significant developmental changes. Age-related changes account for large parts of the variance in each of these processes. Specifically, 30% of the variance in speed of processing, 50% of the variance in perceptual control and 40-50% of the variance in perceptual discrimination and conceptual control is accounted to age-related changes. Drastic changes occur during the whole age span studied indicating that childhood is a mostly crucial period where big developmental changes take place.

The role of the symbolic medium in processing efficiency was only possible to be examined in the perceptual control tests where verbal, numerical and figural stimuli were used. The result of the analysis suggests that as children grow older the difference between the three symbolic medium systems decreases. This can be attributed to the increasing mastery of control process which causes symbol dependent familiarity differences to disappear. Furthermore, as children grow older the effect of the verbal symbolic medium is minimized since children become efficient readers. Yet, despite this discrepancy in the effect of verbal symbolic medium on the inhibitory control process during early schooling, the verbal and the numerical symbolic media show common cognitive and developmental features. Although when the relevant to the task dimension is not the dominant one, a longer reaction time would have been expected as a normal outcome, this is the case only when the figural variant of the test is used. In the other two test variants, namely the verbal and the numerical, the mean reaction time relation is reversed, i.e. the mean reaction time is shorter when the relevant to the task dimension is the non-dominant one. This common feature of the verbal and the numerical tests can be attributed to the fact that children at these ages process letters and number symbols in the same way by activating the reading mechanism. Though the reading process is gradually automatized, children at these ages are still bounded to their reading protocol which confines their reading scope to the components of the stimulus – not the picture of it as in the gestalt meaning.

The similarities in the profiles of the verbal and the numerical variant of the test are further manifested in the interaction between the symbolic medium and the compatibility factor. Both test variants provide an almost identical profile in terms of how compatible and incompatible information is processed. It is suggested that the verbal and the numerical stimuli, as they were presented in the Stroop-like tests, are processed in a very similar way and thus they activate the control processes in a way that is to a great extent common. This finding also suggests that either test variant can be used in order to obtain the information on the functioning of the control processes.

Representational processes do not exhibit uniformity in their developmental profile as do processing efficiency parameters. This may reflect some kind of measurement weakness in identifying the exact developmental trace of the processes or even an inefficiency of the research design to adequately address a wide range of individual differences and cover the whole range of ages. Nevertheless, the present findings suggest that an important representational change occurs at around the age of 8 years old causing the system a transient drop of performance in information integration tasks. It could also be suggested that a strategy shift happens at this age. When the effect of speed on information integration performance is partialled out in order to examine whether the observed developmental changes are generated and maintained from the processing efficiency parameters, a total suppression of the effect of the symbolic medium is observed but only a slight decrease in the effect of age. The annihilation of the effect of the symbolic medium suggests that each test variant draws on speed and control resources differently, according to the specificities of each symbolic system. Furthermore, the fact that the effect of processing efficiency parameters on the development of the information integration is small, suggests that the developmental change occurring at the age of eight years does not originate from these processing efficiency factors. A plausible explanation of the U-shaped pattern of performance is that there may be a change in the strategy used to integrate information which is not well mastered at the beginning, thereby resulting in a temporal drop of performance.

Working memory capacity shows significant age-related changes. All tests used in the study tend to converge at the age of 11years to a working memory capacity of about five information units. This developmental trend is driven by changes in the condition of processing efficiency. Specifically, when the effect of speed of processing is controlled a decrease of the amount of the variance explained by age is observed, though it remains significant, indicating that speed of processing is a developmental and an individual differences factor. Once again, the imperative role of speed is manifested. Therefore, it is suggested that speed is a strong universal factor. Age-related changes in speed open the way for changes in other levels of the mind and differences in it within individuals of the same age signify individual differences in other levels of the mind. Another significant contributor to the observed changes in working memory is the control of processing. When its effect is statistically controlled the amount of the variance explained by age drops, though it remains significant, and the effect of the test type is significantly decreased indicating that control processes have a central role in the functioning of working memory, explaining individual and developmental differences in working memory capacity. An interesting finding emerges when the effect of both speed and control of processing is controlled. The effect of age, although less pronounced, is still significant suggesting that developmental changes in working memory are not fully dependent on speed and control processes. A significant part of developmental changes in working memory capacity is related to processes which are specific to the functioning of working memory as such. These processes may develop through experience and practice, through strategy planning, application, and evaluation, and through the changes in metacognitive representations. According to Frye, Zelazo, and Palfai (1995) metarepresentations emerge between the age of 3 and 5 years. Children are increasingly becoming more able to reflect on their rules and control any incompatibility residing during the processes of applying them. Increases in control strongly affect rule reflection, rule assessment and rule employment which are strongly associated with the functioning and the development of working memory. Halford, Wilson and Philips (1998) suggest that the systematic construction of increasingly complex relations is a major dimension of cognitive development.

An interesting finding emerged in regard to the different working memory tests used in the present study. When the variance due to both speed and control of processing is removed, the effect of the working memory tests is completely annihilated indicating that the difference between the various tests reflected in their developmental profile is due to their differential dependence on cognitive resources, namely speed and control of processing. When the effect of these cognitive resources is statistically controlled, the working memory tests appear similar, indicating that all four tests address the same mental ability with a common underlying mode.

Finally, age-related changes in both reasoning types are very strong. Performance on deductive reasoning was at all ages better than performance on inductive reasoning. This probably indicates that the underlying specificities in inductive and deductive reasoning in terms of cognitive resources' demands and in terms of mental rules application and mental models construction are differentiated during the age span of 6-to 11-years and it could also be suggested that this differentiation is an enduring aspect. Moreover, unlike other simpler processes, the effect of the symbolic medium of the tasks was significant and strong indicating that each symbolic medium carries a different load and it draws differently upon the cognitive resources. In general, the spatial reasoning tasks were more difficult to solve and the verbal tasks were the easiest to solve. This effect was more pronounced in inductive reasoning mechanisms. These findings on the differentiation of reasoning performance according to the symbolic medium of the premises offers further support to the thesis based on neurocognitive data (Goel, 2007) that inductive reasoning is conducted on an increasingly larger knowledge pool and therefore, absence of or limited knowledge in a domain affects inductive reasoning process. On the contrary, deductive reasoning can be conducted based on the syntactic and structural features of the premises, once individuals have mastered controlling knowledge and belief biases from intruding to the process.

The role of processing efficiency parameters and working memory capacity in the development of reasoning is differentiated. When the effect of speed of processing is statistically controlled, only a slight decrease of the variance explained by age is observed. This manipulation results in the annihilation of the effects of the reasoning type and the symbolic medium of the tasks. Therefore, it is suggested that speed of processing accounts for individual differences in reasoning performance among children of the same age. It is also suggested that the development of the reasoning process is not based on changes in speed of processing; rather, it involves other, more complex processes which are directly related to the manipulation of logical relations, to the mental rule application and to the mental models construction. When the effect of the control of processing is removed, there is a considerable decrease of the explained variance in reasoning performance and the effects of the reasoning type and the symbolic medium are annihilated, suggesting that the reasoning processes do draw on processing efficiency resources differently, according to the type and the domain of reasoning. These findings also suggest that control of processing is a developmental factor that drives age-related changes in reasoning throughout childhood. Unlike control of processing, working memory is not involved in age-related changes in reasoning. Working memory factor is a factor which affects individual differences in reasoning, but it does not contribute in the developmental course of reasoning. Moreover, the analyses indicate that each reasoning type has a different dependence on working memory. Conway, Cowan et al. (2002) argue that the factors that account for developmental differences in reasoning are not necessarily the same factors that account for individual differences in reasoning in young adults. Therefore, the findings of the present study in regard to the role of each cognitive process in the development of reasoning or in the observed individual differences may reflect the very specific age span studied here.

Fourth Hypothesis

Seen from a longitudinal perspective, it is expected that individual differences in the processes residing lower in the hierarchy determine, to a significant degree, the condition of the more general processes in subsequent points in time.

Structural equation modeling reveals that the various cognitive processes are intertwined in a way that changes in simple processes drive changes in more complex processes and it also shows the manner in which these changes occur within a year's interval. Speed of processing is an important developmental factor explaining a significant proportion of the variance in all processes after a year interval. Inhibitory control is also found to be a developmental factor for all processes except working memory. These findings suggest that both parameters of processing efficiency have a significant developmental role in the expansion of information processing and representational processes. An interesting finding is the relatively limited and not statistically significant role of working memory in the expansion of the functions ascribed to working memory per se. This finding suggests that changes in working memory features that are utterly freed from the effect of other cognitive processes need more time to have tangible results in the functioning of working memory as such. It should be noted that this same finding also emerged when the development of working memory was tested based on the two testing waves' data. Specifically, despite the strong effect of age, the effect of the testing waves was not significant suggesting that the rate of increase in working memory capacity is not fast and that any changes in the functioning of working memory are not directly detectable. The U-shape pattern of the differences from the first to the second testing wave in the mean working memory capacity indicates that a big representational change happens at around the age of 8 years which is manifested as a minimum change in the development of working memory capacity.

Working memory plays a significant role in the development of the inferential processes after a year's interval, explaining half of its variance. Inferential processes are therefore built on processing efficiency and on working memory. Reasoning capitalizes on these processes and the changes that occur to them are invested in the development of the inferential processes. The important role of working memory capacity as well as the significant contribution of the information processing parameters in the development of inferential processes, suggest that the best predictors of reasoning ability development are the parameters of processing efficiency and the capacity of working memory, as these had been identified earlier in time. As a consequence, it can be claimed that fostering inferential processes should be based on improving the speed and control processes and the functioning of working memory.

A careful examination of the pattern of significant regression coefficients suggests that any age-related changes of the cognitive processes are, to a significant extent, attributed to the original state of their simpler processes. Changes are expected to occur in more complex processes due to changes that have been already established in processes residing lower in the hierarchy. The only exception of this general conclusion is observed in the relation of the speed of processing at the second testing wave with the control of processing at the first testing wave suggesting that after a year's interval, changes can be identified in more simple processes due to changes that have been established in more complex processes. Such changes in more complex processes may result in the automation of some functions and in the establishment of routines which in turn enhance the expansion of more simple processes.

The importance of these findings from the longitudinal data of the present study is better understood when these are compared to the recent longitudinal evidence reported by Kail (2007) on the enhancement of children's reasoning by increases in processing speed and working memory. Kail proposes a longitudinal model according to which developmental changes in processing speed lead to greater working memory capacity, which is associated with better inductive reasoning. The model proposed by Kail provides strong evidence that working memory affects developmental change in inductive reasoning directly and processing speed indirectly. Nevertheless, Kail's model is not very informative as to the role of the cognitive processes in predicting reasoning ability since very few paths have been included in the model. The parsimonious longitudinal model proposed in the present study provides a more global view of the relations between the processes over time. Specifically, unlike Kail's model, it is suggested that processing speed has a direct effect on all processes after a one-year interval. The processes of inhibitory control and working memory also have a direct effect on reasoning after a year interval.

Finally, it is noted that developmental changes in working memory are only affected by speed of processing. This finding confirms the developmental nature of speed of processing but it also indicates the special relation between speed of processing and working memory capacity as it was discussed earlier.

Fifth Hypothesis

Reasoning ability develops in distinct stages and it should, at each of these, exhibit quantifiable and measurable characteristics. These characteristics constitute an absolute reflection of the cognitive processes. It is expected that each reasoning stage will be quite accurately described based on the processing efficiency parameters and the working memory capacity. Advancing to a higher reasoning stage should require changes in the cognitive processes.

The Rasch model was applied on both testing waves' data and on both types of reasoning. The resulting models suggest a three-level structure of each reasoning type. With respect to the cognitive demands and the mechanisms activated for addressing each task, the three-level organization is both cognitively and developmentally supported. The first level of inductive reasoning accommodates analogical reasoning that is based on many, concrete observations which are free of any non-relevant information. Children can formulate generalizations and identify patterns. Tracing a relation and applying it on a new case is feasible only if the relation is unidimensional, meaning that no more than one aspect may vary. Analogical reasoning calls upon retrieving primary knowledge from long-term memory, an action triggered by the information of the source and the relational schema it entails, that being an inter- or an intra- analogical relation, and applying it directly on the target. Syllogisms at this level are based on premises with constituent parts that are concrete. No abstraction and, therefore, no complex model construction are attainable. Syllogisms are strongly confined by the reasoner's experiences and specific knowledge, and thus, shortcomings in these areas cause knowledge and belief biases. Furthermore, these shortcomings act forcefully against any activation of the control processes. The executive functions of memory and the control processes of the system are not completely utilized by the reasoner.

The second level of inductive reasoning accommodates analogical reasoning which is based on *hidden* or *implied* relations that activate the retrieval of knowledge stored in long-term memory. Mapping out the hinted relation requires that non-relevant information lying in the premises or activated from the long-term memory is inhibited. The activation of the control processes prevents the overloading of working memory and therefore, the system can effectively identify the relational schema and effectively apply it in a new situation. Syllogisms, at this level, are confined by the syntactical characteristics of the premises, yet a primary abstraction level is achieved. Indirect relations can be processed within all symbolic media and no confinement of the premises in terms of their number and their specificity is imposed. The instructiveness of the premises calls for the activation of the control processes. Control processes help the system to stay in focus and capture the meaning of the premises, process it, and formulate generalizations. Further, the system can apply the extracted general rule to a specific situation.

Finally, the third level of inductive reasoning accommodates analogical reasoning based on complex relations which are not directly detectable and which often rely on very fine attributes. At this level analogies strongly demand a higher level of language expertise and a pool of detailed knowledge on various areas. Furthermore, individuals are capable of delineating and producing complex transformation applications. Syllogisms at this level are based on abstraction and theoretical supposition. Reasoning can be done on the basis of the existence of a possibility and it can also be placed in reality-or-belief contradicting context. Multiple relations can be manipulated and more than two parameters can be simultaneously considered. Generalizations can be extracted from an abstractive context and be applied on another context since they constitute mental rules that are inserted in the rule system of the individual. Inductive reasoning is considered as the function of the human mind that is closely related with intelligence.

In as far as the deductive reasoning is concerned, the three levels are defined in terms of the four inferential processes of Modus Ponens, Modus Tollens, Affirming the Consequent, and Denying the Antecedent, and in terms of the demand of each in cognitive resource. The first level of deductive reasoning accommodates Modus Ponens inferences in their simplest form, i.e. the constituent parts of the premises are given in an affirmative way. Higher in this level, some of the constituent parts of the premises in the MP inferential scheme are presented as negations, which adds some degree of complexity to the argument. The negation calls upon the activation of the control processes in order to secure that the meaning of the premises will be processed without the interference of non-relevant information and that no premature response will be given unless the alternatives in meaning emanating from the negation are taken under consideration. Constructing, or retrieving from memory, the complement of a negation calls upon further cognitive resources allocation. This finding conforms to Johnson-Laird's thesis that negative deductions are harder than affirmative deduction "because the negative deductions call for the detection of an inconsistency between elements of models" (Johnson-Laird & Byrne, 1991, p. 55).

The second level of deductive reasoning accommodates Modus Tollens inferences. This finding conforms to the thesis postulated by both the mental rule and the mental model theories on the comparison of the level of difficulty between Modus Ponens and Modus Tollens inferences. On the one hand, the mental rule theory postulates that the rule for Modus Ponens inferences is innate while the Modus Tollens rule has to be formulated. On the other hand, the mental model theory assumes that Modus Tollens inference demands fleshing out the first model and constructing a series of alternative models while the Modus Ponens inferences do not lead to any fleshing out procedure. Though our findings from the application of the Rasch model on deductive reasoning items are in accord with this thesis, they add some important information about the developmental aspect of reasoning. Mental rules and mental models theories base their assumptions on an algorithmic level. They both use a reductionist approach to explain the observed differences in the levels of success between the Modus Ponens and the Modus Tollens inferences: more examples needed to extract the Modus Tollens rule or more steps in fleshing out the original explicit model in the mental rules and mental models theories, respectively. Rasch model illuminates this difference in success from the cognitive development perspective. Succeeding in Modus Tollens inferences is an autonomous or distinct developmental stage which follows when the Modus Ponens stage is completed.

Developmentally speaking the scale of the deductive reasoning items according to their difficulties strongly suggests that success in Modus Tollens inferences must follow the completion of the Modus Ponens stage. Manipulating the information for a Modus Tollens inference is more complex when compared to the manipulation of Modus Ponens information, not only in computational terms but in cognitive terms. Development of the information processing system and the working memory capacity is a necessary step, a prerequisite, for moving from the Modus Ponens to the Modus Tollens inferences.

In the case of Modus Tollens inference (and of Denying the Antecedent inference at the next level), where a minor premise is given as a negation, the retrieval process and the outcome of the reasoning are affected by the kind of negation used (Handley et al., 2004). A negative premise can be given in an explicit and in an implicit manner. Explicit negations are stated in the form "not P" whereas implicit negations state the value of variable P in an affirmative way, without using the logical connector *not*. Implicit negation suggests that the variable has a complex semantic space and it can have many possible values. Explicit negation leads the reasoner to assume a dichotomization of the semantic space of the variable and process non-binary variables as binary ones. This, according to Barrouillet, Grosset, and Lecas (2000), results in a more frequent biconditional interpretation of the premises than when the negation is implicitly stated. In the design of the verbal deductive reasoning tasks care was taken as to use implicit negations. The context of these tasks was arbitrary and therefore, the semantic space of the variables used could be easily reduced to the minimum possible. Implicit negations helped reasoners avoid assuming dichotomization of the semantic space.

Towards the end of this stage the success in dealing with the Denying the Antecedent and Affirming the Consequence fallacies occurs in arguments where the setting is binary, i.e. the alternative to the negation of "p" was singular "not p". This is feasible because the alternative models are contained and the system can process them with less effort. Barrouillet and Lecas (1998) propose that activation of the complement instances of the values of P and Q as they are stated in the "if p then q" premise is easier than the activation of the complement instances when the variables P and Q can take more than two values each. Such inference is not possible at a lower stage because testing for the validity of alternatives, even if their number is small, calls upon higher reasoning functions which arise towards the end of the second stage when Modus Ponens and Modus Tollens are well established. These higher reasoning functions are a big step forward which leads the reasoner to break the limits of her thinking and see beyond the obvious. The binary nature of the elements proves to be of great importance in taking this step. Seen from the developmental perspective, during this stage the system is successfully coping with the Modus Tollens inferences and therefore is successfully dealing with the negation of the consequent and this ability is transformed or it is invested in situations where a fallacy is presented in a binary setting. Nevertheless, still at this level, the activation of the complement instances of the binary variables inhibits any further fleshing-out and searching for alternatives beyond the "p and q" and "not p and not q" leaving out the alternative “not p and q”, and results in a biconditional interpretation of the conditional premise (Barrouillet, et al., 2000; Markovits & Barrouillet, 2002).

Finally, the third level of deductive reasoning accommodates the fallacies of Denying the Antecedent and Affirming the Consequence. Obviously, this is the most demanding stage where the efficiency acquired from the other two stages is used in successfully dealing with the fallacies. This stage is not reached by preadolescents. The cognitive demands of successfully dealing with the fallacies are not met until later, in adolescence. Fallacies place a big cognitive load on the system. Many alternatives have to be retrieved from memory and be processed. Moreover, the nature of the outcome of this process makes this line of reasoning a very complex procedure. The extracted conclusion states that no conclusion can be reached. Seen from the developmental point of view, this stage is beyond the range of the cognitive abilities of the children in the age span studied here. Reasoning at this level demands that the reasoner acknowledges that not all arguments have a deterministic conclusion and that at some times uncertainty is the only certain conclusion. Children at the lower levels are not able to deal with the absence of an affirmative conclusion, so they are unable to ignore the inconsistencies caused by the fallacies. According to Barrouillet and his colleagues (Barrouillet & Lecas, 1998; Barrouillet, Grosset, & Lecas, 2000; Markovits & Barrouillet, 2002) a conditional interpretation of the premise “if p then q” and the activation of the alternative class of information beyond the complementary, is achieved when the cognitive capacity is increased later in adolescence and in early adulthood. Therefore, the third level of deductive reasoning is not reached, not even in late childhood.

Reasoners at each level of reasoning development present some cognitive characteristics that clearly differentiate them from reasoners in other levels. The three developmental stages of inductive reasoning ability significantly differ in terms of the processing efficiency parameters and simple storage and executive functions of working memory. Deep changes occur when moving from the first to the second inductive reasoning stage. These changes signify a representational shift which allows the reasoner to be engaged in more demanding situations and deal with more complex information in an efficient manner. Speed and control of processing significantly increase. Moreover, working memory capacity is also significantly increased. These findings support the thesis discussed in the analysis of the development of the various cognitive processes. Specifically, it was suggested that changes in speed and control of processing may act as the driving force for drastic changes in the reasoning processes. This synergy of changes is also evident when one moves from the second to the third stage. The only parameter that does not change significantly when one moves from the second to the third stage is speed of processing.

Deductive reasoning stages are also clearly differentiated in terms of their cognitive blueprint. The role of the parameters of processing efficiency is more vital during the first and second reasoning stages enabling the reasoner to reason based on the Modus Ponens and Modus Tollens inferential schemas. When the second stage completes its cycle, then the move to the third stage is driven by deep changes in working memory capacity. The reasoning processes of mental rule formulation and application and mental model construction are drawing on the memory resources. The efficiency in dealing with the fallacies is not a byproduct of drastic changes in speed and control of processing. Rather, it is a function of the organization and the repertoire of mental rules and knowledge in long-term memory and a function of their efficient retrieval and maintenance in working memory. It is suggested that the relation of working memory with reasoning ability is better delineated under conditions of complex reasoning tasks, as is the case with the logical fallacies.

Sixth Hypothesis

A proposed cognitive task analysis formula based on semantic, procedural, and mental constructs parameters should provide a reliable prediction of the individuals' reasoning ability. This is effected as a result of the calibration of the reasoning tasks' difficulty and the individuals' ability on a common imaginary metric provided by Rasch analysis. High correlation of the task distribution, based on their complexity analysis, with the obtained distribution from the Rasch analysis, would render the proposed task analysis formula both a predictor and an assessor of reasoning ability.

The proposed task complexity formula is a function of three parameters, namely the semantics embedded, the procedures applied, and the mental models constructed. Each of these parameters can be analyzed in more specific aspects some of which are implicitly present, and therefore cannot be quantified, whereas others are more tangible, and therefore a quantity measure can be assigned to them. Semantics (*S*) refer to the number, the meaning, the structure and the interrelations of the concepts included in the task. Semantics also refer to the existence of unknown "central meaning" words, and to the degree to which the reasoner feels committed and motivated throughout the task solving process. Procedure (*P*) refers to the processes (e.g. algorithms) and rules (e.g. logic rules) needed to be applied. It also refers to the degree of accessibility to information, the clarity of the problem definition, the external representations which are provided, time and other surrounding constraints. Mental Constructs (*M*) refer to the number of information bits simultaneously related to the process at hand, the number of constraints that need to be simultaneously complied with, and whether the outcome of each step is subject to variation. It also refers to the kind and the number of models to be constructed.

A numerical value (*Si, Pi, Mi*) is assigned to each parameter. This is the product of the values of the two quantifiable aspects of each parameter. Each parameter has a different weight (contribution) on the task complexity; therefore, unitary changes in parameters' modules cannot be equally weighted among the three parameters. *Semantics* is considered as the parameter which affects the complexity of a task less than the three of them, *Procedure* is considered a moderately affective parameter, and *Mental Constructs* is considered the most important contributor to task complexity. In order to make an accurate apodosis of this differentiation in the contribution of the parameters the natural logarithm *e* was chosen as the scaling factor. In order to regulate parameters with their relational weights, each parameter's absolute magnitude is multiplied by a power of the natural logarithm. *Semantics* is multiplied by 1 (e^0), *Procedure* is multiplied by e (e^1), and *Mental Constructs* is multiplied by e^2. It is assumed that the complexity of a task *(C)* is a function of the absolute magnitude of each of the three parameters multiplied by a weight condition: C=*f* (Si, ePi, e^2Mi).

It is assumed that the three parameters are independent and, therefore, orthogonal to each other and that any task can be represented on the three-dimensional space in terms of its parameters' values. Task complexity is defined as the area of the triangle whose apexes are the three points S (*Si, 0, 0*), P (*0, ePi, 0*), and M (*0, 0,* e^2*Mi*). Any change (increase or decrease) in any parameter's absolute value will directly cause a change (an increase or a decrease) of the complexity of the task, just as any change of the coordinates of any point on the three axes will alter the shape, and therefore the area, of the triangle. The resulted formula for the cognitive task complexity reflects the interaction of the three parameters and places emphasis on the interaction of the most critical parameter, namely the Mental Constructs parameter, with the second most critical parameter, namely the Procedure parameter. This pattern of interactions and the weight placed on them is derived directly from the exponential scaling applied on the constituent axes defining the task complexity vector.

A reliable way to evaluate the objectivity of the proposed complexity analysis and the accuracy of the complexity formula is to compare the relation between the Rasch logits of the items with their respective complexity level as this is derived from our complexity formula application. The comparison of the two scales reveals a very strong, positive correlation. Specifically, the correlation between the ranking of the reasoning items based on the Rasch logits with the ranking of the items based on their complexity values, for the whole set of reasoning items, is .84 (Spearman's rho). When the correlation of the two rankings resulting from these independent scales is calculated for the two reasoning types separately then the obtained Spearman's *rho*s are very high, reaching .97 and .84 for the inductive and the deductive items, respectively. These correlations are very indicative of the robustness of our suggested analysis and of the soundness of our proposed complexity formula. As Case (1985, p. 38) notes "it is one thing to explain two contrasting sets of data in a post hoc fashion, and quite another to use this sort of explanation to make predictions about new tasks". Unlike this, Piaget and Pascual-Leone first analyzed specific tasks on the basis of the performance of a group of individuals and then they assigned these tasks to their complexity level. Moreover, their analyses were addressed to specific tasks and therefore, their models are prone to mistakes and shortcomings. As a consequence, no abstraction is attainable and no formulation of a general task analysis model is possible. Assigning a task to its complexity level should be an autonomous procedure directed by the set of analysis rules as these were originally stated by the researcher. The proposed method of cognitive complexity analysis yields, a priori, an estimation of a task's complexity at parity in accuracy and objectivity with Rasch analysis. More importantly, this estimation is done without relating it on specific task performance and the specificity of the abilities of a group of test takers. This finding is crucially important in terms of designing reliable psychometric tests, evaluating school performance, and predicting academic or other performance. It is also a useful tool in terms of studying individual differences and theorizing on cognitive development.

The relation between the cognitive capacity of an individual, as it is measured in terms of speed and control of processing and in terms of the storage and executive functions of working memory, with the complexity of any reasoning task at which the individual succeeds or fails, reveals some important cognitive facts which allow for a proposal of a theoretical cognitive profile of an individual capable of meeting the challenges at each complexity level. Nevertheless, more intensive task analyses are necessary to determine exactly what task features lead to the need for specific process, such as controlled attention (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002) and what is the exact relation of each of the cognitive processes to the specific complexity parameters.

Two important findings emerge from the analyses on the relation of cognitive capacity and level of reasoning complexity. The first one refers to the identification of the specific parameters of the cognitive profile of individuals at each complexity level.

The second one refers to the difference in cognitive resources between individuals who succeed in one reasoning complexity level but fail at the next one. The similar pattern that emerges from all cognitive processes' difference distribution across the three transit phases from Complexity Level 1 to Complexity Level 4, indicates that as we move from the simpler to the most complex reasoning level the manifested incremental cognitive cost is reduced, suggesting that as complexity increases individual and developmental differences are attributed to the opulence of accumulated experience and specific knowledge, skills and strategies and the ability to capitalize on them.

The revealed asymptotic pattern may be a direct manifestation of Spearman's Law of Diminishing Returns on the relation of mental energy (or *g*) and the observable attributes of cognitive resources (Spearman, 1927). The successful leap from each less complex to the subsequent more complex level demands the dissipation of increased mental energy, a fact attested to by the progressively reduced portion of reasoners who achieve this. However, this increased energy dissipation yields diminishing marginal improvements on the measureable attributes of cognitive resources. Nevertheless, the value of these improvements should neither be overlooked nor be underestimated. Apparently, they posses the necessary and sufficient magnitudes and qualities to propel the reasoner to the next level. Vested into them, are presumably, besides the sheer improvement in measureable cognitive attributes, manifestations of underlying improvements in inferential processes per se.

In any case, the generalizability of these findings in regards to the relation of cognitive change and reasoning ability as well as the generalizability of the proposed complexity analysis should be tested in other test batteries.

Implications

In light of the finding that working memory is not as strongly correlated with reasoning processes as it is usually claimed in the literature, it is suggested that more *purified* working memory tests should be used. A *purified* test is one that would primarily activate working memory functions, laden off the effect of other aggravating processes which obscure the true relation of working memory to reasoning. Tapping simple storage or executive functions of working memory per se is not easily attained. As it was evident in the analyses conducted to study the effect of processing efficiency parameters on the working memory performance, when the variance due to speed and control of processing was removed the effect of all the working memory tests used was completely annihilated. This indicates that the difference between the various tests reflected their differentiated dependence on these cognitive resources, and that all tests address exactly the same memory function. Therefore, no additional information is provided by the use of the various tests. It is suggested that other executive function measures should complement working memory tests. By applying the same technique as it was already presented in the cascade models, where each subsequent factor is regressed on the simplest factor and the residuals of the factors that reside lower than it in the hierarchy, one can decompose each process into its constituent parts and obtain a more accurate picture of the dynamic interplay between the processes. Additionally, information integration should cover a broader complexity span in order to better reflect variability in other processes embedded in it. The role of working memory functions in the information integration test needs to be more discernible. This will allow for a more precise organization of the processes in the hierarchical cascaded structure. Such tests need to be more complex in terms of the control and the planning and decision making processes involved, but less demanding in terms of the mechanics (time for completion) of each task. As it is suggested by the present study, the relation of working memory with reasoning ability is better delineated under conditions of complex reasoning tasks, as is the case with the logical fallacies. Logical fallacies need to be tested under various different conditions. The role of working memory and other cognitive resources in the inferential processes that successfully deal with logical fallacies need to be clarified. This will allow for deciphering the cognitive and the developmental stages in reasoning successfully when faced with fallacies.

Future Research

Future research may focus on studying the functions of information processing and the representational processes in both their dynamic interplay and their developmental trajectories in a broader age span. Ideally, this should cover from preschool ages through early adulthood. The design would be a combination of cross-sectional and longitudinal study. Ultimately, data from microgenetic research would allow the researcher to test the accumulated knowledge in a time scale emulating near real-time observations. This would possibly foster existing beliefs, test or dismiss others and provide totally new perspectives.

An interesting area for research would be the study of the relation of reasoning with long-term memory and knowledge. Research has been confined in studying the relation of reasoning with working memory, despite the fact that the functioning of working memory is to a great extent depended on the contents and the structure of long-term memory. Such a research would permit the differentiation of working memory from long-term memory both theoretically and statistically.

Cognitive task analysis needs to be applied on a greater range of reasoning tasks. Complexity defining parameters need to be further analyzed. Their role in determining the complexity of a task needs to be better calibrated by manipulating their values. This would allow for establishing the predicting power of the analysis and its reliability as a means of assessing reasoning processes and general intelligence.

Summary

Human intelligence is reflected in a complicated configuration of dynamic relations between various mental processes. Researchers have focused on different aspects of this multidimensional pattern of relations and have experimentally approached them in multiple ways. The general intelligence landscape still needs to be demystified. The role of each of these processes in the structure of intelligence and the way the maturational changes during the critical period of 6-to-11 years of age alter the processes' interplay with general intelligence, comprise the main research questions of this study. The central role of some processes in the architecture of the mind as developmental factors or as factors explaining individual differences in other more complex processes is revealed based on structural and developmental evidence. In addition, the identification of developmental stages of logical reasoning and the role of cognitive processes in the advancement from one stage to the other are examined. Finally, a proposed formula of cognitive task analysis is validated and it is used in identifying levels of reasoning complexity. These levels are analyzed in respect to the processing efficiency and working memory profile of the individuals accommodated in each complexity level.

Six working hypotheses were tested. The first one refers to the organization of the mental processes' architecture. The study confirmed that the cognitive processes are hierarchically structured in such a way that a general factor residing at the apex of the hierarchy accounts for the individual differences encountered both in age-peered populations as well as developmentally. This general factor reflects general intelligence

and it maps strongly onto other general, albeit less so, factors residing lower in the hierarchy, such as processing efficiency, working memory and reasoning ability. Each of these less general factors stand in their own right as complete autonomous process, while maintaining its own specificities. Reasoning ability is an almost perfect reflection of the general intelligence factor whereas only half of the variance of processing efficiency parameters is explained by general intelligence, a finding that is in accord with the fundamental thesis that *g* reflects the mental complexity of a test. The findings on the relation of working memory with the general intelligence factor suggest that there are processes attributed to working memory which are not included in what is conceived as general intelligence. Presumably, these are processes that are closely based on mnemonic strategies knowledge and application and on any kind of knowledge that is acquired via educational and cultural means and is not reflected in the *g* factor. Further analysis of the second level factors reveals an underlying hierarchy comprising more specific processes, such as sheer speed of processing, inhibitory control, working memory, and inductive and deductive reasoning

The second hypothesis assumes an interrelation of the processes in a cascaded fashion. The resulted models confirm that each of the specific cognitive processes is related with the other mental processes in such a way that the more fundamental processes are embedded in the more complex ones and that two broad levels of processes, namely the encoding and selection, and the representational level exist. A dynamic interplay among the cognitive processes emerged, suggesting a cascaded arrangement of the processes. This cascaded configuration amplifies the gained benefit from improvements in the less *g*-loaded process and carries it over to the most *g*-loaded processes. Speed of processing is a strong developmental factor driving changes in the representational processes while inhibitory control is a factor that strongly defines individual differences in these processes. The most important finding emanating from the cascade models refers to the fine differences in the functioning of the simple storage and the executive feature of working memory. When the system is merely memorizing information without any processing on it, it draws on the speed and control resources in order to store as many bits of information as the capacity limitations allow. The role of both processes in the efficient simple storage functioning of working memory is of great importance. High speed of processing prevents the loss of information due to the decay of its mnemonic trace and perceptual control protects the working memory from overloading with non-relevant processing. Due to the working memory capacity limitations it is important for the system to make good use of its processing efficiency resources in order to facilitate the efficient storage of information. Working memory is a factor describing individual differences in reasoning ability.

The third hypothesis refers to the developmental trajectories of the processes and to the existence of a common mechanism that drives these changes. The analyses revealed that age-related changes in speed open the way for changes in other levels of the mind and differences in it within ages signify differences between persons in other levels of the mind. Control processes have a central role in the functioning of working memory, explaining individual and developmental differences in working memory capacity. A significant part of developmental changes in working memory capacity is related to processes which are specific to the functioning of working memory as such. Age-related changes in both reasoning types are very strong. Developmental changes in reasoning process involve complex processes which are directly related to the manipulation of logical relations, to the mental rule application and to the mental models construction. Moreover, processing efficiency parameters drive age-related changes in reasoning throughout childhood. Working memory is a factor which affects individual differences in reasoning.

The fourth hypothesis refers to the developmental changes that occur in cognitive processes examined from a longitudinal perspective. Speed of processing is verified as an important developmental factor explaining a significant proportion of the variance in all processes after a year interval. Inhibitory control is also found to be a developmental factor for all processes, but the working memory. These findings suggest that both parameters of processing efficiency have a significant developmental role in the expansion of information processing and representational processes. An interesting finding is the relatively limited and not statistically significant role of working memory in the expansion of the functions ascribed to working memory per se. This finding suggests that changes in working memory features that are utterly freed from the effect of other cognitive processes need more time to have tangible results in the functioning of working memory as such. Working memory plays a significant role in the development of the inferential processes after a year interval, explaining half of its variance. Inferential processes are therefore built on processing efficiency and on working memory. Reasoning capitalizes on these processes and the changes that occur to them are invested in the development of the inferential processes. The important role of working memory capacity as well as the significant contribution of the information processing parameters in the development of inferential processes suggest that the best predictors of reasoning ability development are the parameters of processing efficiency and the capacity of working memory, as these have been identified earlier in time.

The fifth hypothesis refers to the stage-wise development of reasoning ability. At each stage quantifiable and measurable characteristics are exhibited. These characteristics constitute an absolute reflection of the cognitive processes. Each reasoning stage is described based on the processing efficiency parameters and the working memory capacity. Advancing to a higher reasoning stage requires changes in the cognitive processes. Three developmental stages are identified at each type of reasoning. These stages are clearly differentiated from each other in terms of the cognitive characteristics of the reasoners at each level of reasoning development. The three developmental stages of inductive reasoning ability significantly differ in terms of the processing efficiency parameters and simple storage and executive functions of working memory. Deep changes occur when moving from the first to the second inductive reasoning stage. These changes signify a representational shift which allows the reasoner to be engaged in more demanding situations and deal with more complex information in an efficient manner. Speed and control of processing significantly increase. Moreover, working memory capacity is also significantly increased. These findings support the thesis discussed in the analysis of the development of the various cognitive processes. Specifically, it was suggested that changes in speed and control of processing may act as the driving force for drastic changes in the reasoning processes. This synergy of changes is also evident when one moves from the second to the third stage. The only parameter that does not change significantly when one moves from the second to the third stage is speed of processing. Deductive reasoning stages are also clearly differentiated in terms of their cognitive blueprint. The role of the parameters of processing efficiency is more vital during the first and second reasoning stages enabling the reasoner to reason based on the Modus Ponens and Modus Tollens inferential schemas. When the second stage completes its cycle, then the move to the third stage is driven by deep changes in working memory capacity. The reasoning processes of mental rule formulation and application and mental model construction are drawing on the memory resources. The efficiency in dealing with the fallacies is not a byproduct of drastic changes in speed and control of processing. Rather, it is a function of the organization and the repertoire of mental rules and knowledge in long-term memory and a function of their efficient retrieval and maintenance in working memory. It is suggested that the relation of working memory with reasoning ability is better delineated under conditions of complex reasoning tasks, as is the case with the logical fallacies.

Finally, the sixth hypothesis refers to the proposed cognitive task analysis formula that is based on semantic, procedural, and mental constructs parameters. This formula provides a reliable prediction of the individuals' reasoning ability. This is effected as a result of the calibration of the reasoning tasks' difficulty and the individuals' ability on a common imaginary metric provided by Rasch analysis. The high correlation of the task distribution, based on their complexity analysis, with the obtained distribution from the Rasch analysis, renders the proposed task analysis formula both a predictor and an assessor of reasoning ability. The analyses on the relation of cognitive capacity and level of reasoning complexity provide two significant results. The first one refers to the difference in cognitive resources between individuals who succeed in one reasoning complexity level but fail at the next one. Such differences indicate what the cost is, in terms of speed, control and working memory resources, when moving from one level to the next one. A similar pattern emerges from all cognitive processes' difference distribution across the three transit phases from Complexity Level 1 to Complexity Level 4. This pattern indicates that as we move from the simpler to the most complex reasoning level the cognitive cost is decreased, suggesting that as complexity increases individual and developmental differences are attributed to the opulence in experience and specific knowledge, skills and strategies and the ability to capitalize on them. The second important finding that emerges from the study of the relation between cognitive capacity and reasoning complexity level is the identification of the specific parameters of the cognitive profile of individuals at each complexity level. The relations of the four cognitive resources with the levels of reasoning complexity present a common exponential pattern of change which indicates that big changes take place during the age span studied here and that these changes get increasingly less salient. As reasoning gets more complex success is based on reasoning processes per se.

The proposed method of cognitive complexity analysis yields, a priori, an estimation of a task's complexity at parity in accuracy and objectivity with Rasch analysis. More importantly, this estimation is done without relating it on specific task performance and the specificity of the abilities of a group of test takers. This finding is crucially important in terms of designing reliable psychometric tests, evaluating school performance, and predicting academic or other performance. It is also a useful tool in terms of studying individual differences and theorizing on cognitive development.

REFERENCES

Ackerman, P. L., & Beier, M. E. (2006). Determinants of domain knowledge and independent study learning in an adult sample. *Journal of Educational Psychology, 98*, 2, 366-381.

Ackerman, P. L., Beier, M. E., & Boyle, M. O. (2002). Individual differences in working memory within a nomological network of cognitive and perceptual speed abilities. *Journal of Experimental Psychology: General*, *131*, 567-589.

Ackerman, P. L., Beier, M. E., & Boyle M. O. (2005). Working Memory and Intelligence: The Same or Different Constructs? *Psychological Bulletin*, *131*, 1, 30–60.

Ackerman, P.L. & Schneider, W. (1985). Individual differences in automatic and controlled information processing. In R. Dillon (Ed.), Individual differences in cognition , (Vol. 2). New York: Academic.

Adams, A.-M., & Gathercole, S. E. (1995). Phonological working memory and speech production in preschool children. *Journal of Speech and Hearing Research, 38*, 403-414.

Adams, A.-M., & Gathercole, S. E. (1996). Phonological working memory and spoken language development in young children. *Quarterly Journal of Experimental Psychology, 49A*, 216-233.

Alderton, D. L., Goldman, S. R., & Pellegrino, J. W. (1985). Individual differences in process
outcomes for verbal analogy and classification solution. *Intelligence*, *9*, 69-85.

Alderton, D. L. & Larson, G. E. (1994). Cross-task consistency in strategy use and the relationship with intelligence. *Intelligence*, *18*, 47-76.

Anderson, M, (1992). *Intelligence and development: A cognitive theory*, Cambridge, MA: Blackwell.

Annett, J., Duncan, K. D., Stammers, R. B., & Gray, M. J. (1971). *Task analysis*. London: HMSO.

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences*, *8*, 4, 170–177.

Atkinson, R. C., & Shiffrin, R. M. (1968). Human Memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds). The psychology of learning and motivation (Vol. 2). New York: Academic Press.

Awh, E. and Jonides, J. (2001). Overlapping mechanisms of attention and spatial working memory. *Trends in Cognitive Sciences*, *5*, 3, 119-126.

Babcock, R. L. (2002). Analysis of age differences in types of errors on the Raven's advanced progressive matrices, *Intelligence*, *30*, 485–503.

Baddeley, A. D. (1966). Short-term memory for word sequences as a function of acoustic, semantic, and formal similarity. *Quarterly Journal of Experimental Psychology, 18,* 362-365.

Baddeley, A. D. (1986). *Working Memory*. Oxford University Press, New York.

Baddeley, A. D. (1992). Working Memory. *Science*, *255,* 556-559.

Baddeley, A. D. (1996). Exploring the central executive [special issue]. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *49*, 5-28.

Baddeley, A.D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, *4*, 417-423.

Baddeley, A. D., Emslie, H., Kolodny, J., & Duncan, J. (1998). Random generation and the executive control of working memory. *Quarterly Journal of ExperimentalPsychology,51*, 4, 819-852.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G.A. Bower (Ed.), The psychology of learning and motivation (pp. 47-89). Academic Press.

Baddeley, A. D., Lewis, V. J., & Vallar, G. (1984). Exploring the articulatory loop. *Quarterly Journal of Experimental Psychology*, *36*, 233-252.

Baddeley, A. D., & Logie, R. H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (Eds.), Models of Working Memory: Mechanisms of active maintenance and executive control (pp. 28–61). Cambridge, UK: Cambridge University Press.

Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of verbal learning and verbal behavior*, *14*, 575-589.

Baker, K., Segalowitz, S. J., & Ferlisi, M. C. (2001). The effect of differing scoring methods for the Tower of London task on developmental patterns of performance. *Clinical Neuropsychologist*, *15*, 3, 309–313.

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*, *133,* 83-100.

Barrouillet, P., Grosset, N., & Lecas, J. F. (2000). Conditional reasoning by mental models: Chronometric and developmental evidences. *Cognition*, *75*, 237-266.

Barrouillet, P., & Lecas, J. F. (1998). How can mental models account for content effects in conditional reasoning: A developmental perspective. *Cognition*, *67*, 209-253.

Beier, M. E., & Ackerman, P. L. (2005). Age, ability, and the role of prior knowledge on the acquisition of new domain knowledge. *Psychology and Aging*, *20*, 341-355.

Bejar, I.I, Chaffin, R., & Embretson, S. (1991). Cognitive and psychometric analysis of analogical problem solving. New York: Springer-Verlag.

Bell, J. A. & Livesey, P. J. (1985). Cue significance and response regulation in 3- to 6-year-old children's learning of multiple choice discrimination tasks. *Developmental Psychobiology*, *18*, 229–245.

Belmont, J. M. & Mitchell, D. W. (1987). The general strategies hypothesis as applied to cognitive theory in mental retardation. *Intelligence*, *11*, 91-105.

Bentler, P. M. (1995). *EQS structural equations program manual*. Encino, CA: Multivariate Software Inc.

Beth, E. W. & Piaget, J.: 1961, ʻEpistémologie Mathématique et Psychologie, *Et. Ep. Génét.*, vol.XIV, Paris.

Bettell-Fox, C. E., Lohman, D. F., & Snow, R. E. (1984). Adaptive reasoning: Componential and eye movement analysis of geometric analogy performance. *Intelligence*, *8*, 205-238.

Bickhard, M. H., & Campbell, R. L. (1996). Developmental aspects of expertise: Rationality and generalization. *Journal of Experimental and Theoretical Artificial Intelligence*, *8*, 399 –417.

Birney, D.P., Halford, G.S. & Andrews, G. (2006). Measuring the influence of complexity on relational reasoning: The development of the Latin Square Task. Educational and Psychological Measurement, 66, 146-171.

Bjorklund, D. F., & Harnishfeger, K. (1995). The evolution of inhibition mechanisms and their role in human cognition and behavior. In F. N. Dempster & C. J. Brainerd (Eds.), Interference and inhibition in cognition (pp. 141–173). San Diego: Academic Press.

Braine, M. D. S. (1978). On the relation between the natural logic of reasoning and standard logic. *Psychological Review*, *85*, 1-21.

Braine, M. D. S. & O'Brien, D. P. (1991). A theory of if. A lexical entry, reasoning program, and pragmatic principles. *Psychological Review*, *98*, 182-203.

Braine, M. D. S., & O'Brien, D. P. (Eds.). (1998). Mental logic. Mahwah, NJ: Lawrence Erlbaum Associates Inc.

Briars, D., & Siegler, R. S. (1984). A featural analysis of preschoolers' counting knowledge. *Developmental Psychology*, *20*, 607-618.

Brocki, K. C., & Bohlin, G. (2004). Executive functions in children aged 6 to 13: A dimensional and developmental study. *Developmental Neuropsychology*, 26, 2, 571–593.

Brown, G. D. A., & Hulme, C. (1992). Cognitive psychology and second-language processing: The role of short-term memory. In R. J. Harris (Ed.), *Cognitive approaches to bilingualism* (pp. 105-122). Amsterdam: Elsevier Science Publishers.

Buck, G., Van Essen, T., Tatsuoka, K., Kostin, I., Lutz, D., & Phelps, M. (1998). *Development, selection and validation of a set of cognitive and linguistic attributes for* *the SAT I Verbal: Sentence Completion section*. (Research Report 98-23). Princeton, NJ: Educational Testing Service.

Burgess, P. W. (1997). Theory and methodology in executive function research. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 81–116). Hove, UK: Psychology Press.

Byrne, R. M. J. (1989). Suppressing valid inferences with conditionals. *Cognition*, *31*, 61-83.

Carlson, S. M., & Moses, L. J. (2001). Individual differences in inhibitory control and theory of mind. *Child Development*, *72*, 1032-1053.

Carlson, S. M., Moses, L. J., & Hix, H. R. (1998). The role of inhibitory processes in young children's difficulties with deception and false belief. *Child Development*, *69*, 672-691.

Carlstedt, B., Gustafsson, J.- E., & Ullstadius, E. (2000). Item sequencing effects on the measurement of fluid intelligence. *Intelligence*, 28, 145-160.

Carpenter, P. A., Just, M. A., Shell, P. (1990). What one intelligence test measures: a theoretical account of the processing in the Raven Progressive Matrices test. *Psychological Review*, *97*, 404-431.

Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analytic studies*. New York: Cambridge University Press.

Case, R. (1985). *Intellectual Development*. *Birth to adulthood*. New York: Academic Press.

Case, R. (1992). *The mind's staircase: Exploring the conceptual underpinnings of children's thought and knowledge*. Hillsdale, NJ: Erlbaum.

Case, R., Kurland, M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology*, 33, 386-404.

Case, R., Okamoto, Y., Griffin, S., MacKeough, A., Bleiker, C., Henderson, B., & Stephenson, K. M. (1996). The role of conceptual structures in the development of children's thought. *Monographs of the Society for Research in Child Development*, *61*, 246.

Casey, B. J., Davidson, M. C., Hara, Y., Thomas, K. M., Martinez, A., Galvan, A., Halperin, J. M., Rodriguez-Aranda, C. E., & Tottenham, N. (2004). Early development of subcortical regions involved in non-cued attention switching. *Developmental Science*, *7*, 534–542.

Cattell, R. B. (1971). *Abilities: Their structure, growth and action*. Boston: Houghton Mifflin.

Ceci, S. J. (1996). *On intelligence: A bioecological treatise on intellectual development* (Expanded Edition). Cambridge, MA: Harvard University Press.

Cepeda, N. J., Kramer, A. F., & Gonzalez de Sather, J. C. (2001). Changes in executive control across the life span: Examination of task-switching performance. *Developmental Psychology, 37*, 715–730.

Cerella, J. and Hale, S. (1994). The rise and fall in information-processing rates over the life span. *Acta Psychologica*, *86*, 109-197.

Cheng, P. W., & Holyoak, K. J. (1985). Pragmatic reasoning schemas. *Cognitive Psychology, 17*, 391-416.

Chi, M. T. H. and Ceci, S. J. (1987). Content knowledge: Its role, representation and restructuring in memory development. In: H.W. Reese (Ed.), *Advances in child development and behavior,* Vol. 17 (pp. 91-142). New York: Academic Press.

Christ, S. F., White, D. A., Mandernach, T. & Keys, B. A. (2001). Inhibitory control across the life-span. *Developmental Neuropsychology, 20*, 653–669.

Cohen, J. D., Dunbar, K., & McCelland, J. L. (1990). On the control of automatic processes: a parallel distributed processing account of the Stroop effect. *Psychological Review, 97*, 332–361.

Cohen, R. L., & Sandberg, T. (1980). Intelligence and short-term memory: A clandestine relationship. *Intelligence, 4,* 319-331.

Colom, R., Rebollo, I., Palacios, A., Juan-Espinosa, M., & Kyllonen, P. C. (2004). Working memory is (almost) perfectly predicted by g. *Intelligence*, *32,* 277-296.

Commons, M. L., Richards, F. A., & Armon, C. (Eds.). (1984). *Beyond formal operations: Vol. 1. Late adolescent and adult cognitive development*. New York: Praeger.

Commons, M. L., Trudeau, E. J., Stein, S. A., Richards, F. A., & Krause, S. R. (1998). The existence of developmental stages as shown by the hierarchical complexity of tasks. *Developmental Review*, *8*, 237-278.

Conlin, J. A., Gathercole, S. E., & Adams, J. W. (2005). Children's working memory: Investigating performance limitations in complex span tasks. *Journal of Experimental Child Psychology*, *90*, 303-317.

Conrad, R. (1964). Acoustic confusions in immediate memory. *British Journal of Psychology, 55,* 75-84.

Conway, A. R. A., Cowan, N, & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychonomic Bulleting & Review*, *8*, 331-335.

Conway, A. R. A., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychonomic Bulletin & Review, 8*, 331-335.

Conway, A. R. A., Cowan, N., Bunting, M. F., Therriault, D. J., & Minkoff. S. R. B. (2002). A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. *Intelligence*, 30, 163-183.

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review & user's guide. *Psychonomic Bulletin & Review*, 112, 5, 769-786.

Cornoldi, C. (2006). The contribution of cognitive psychology to the study of human intelligence. *European Journal of Cognitive Psychology, 18,* 1, 1-17.

Cornoldi, C., Vecchia, R. D., & Tressoldi, P. E. (1995). Visuo-spatial working memory limitations in low visuospatial high verbal intelligence children. *Journal of Child Psychology and Psychiatry, 36*, 1053-1064.

Coull, J. T. (1998). Neural correlates of attention and arousal: Insights from electrophysiology, functional neuroimaging and psychopharmacology. *Progress in Neurobiology, 55*, 343–361.

Cowan, N. (1992). Verbal memory span and the timing of spoken recall. *Journal of Memory and Language, 33*, 234-250.

Cowan, N. (1995). *Attention and memory: An integrated framework*. New York: Oxford University Press.

Cowan N. (1997). *The Development of Memory in Childhood* . Psychology Press, East Sussex, U.K.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*, 1.

Cowan, N., Elliott, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., & Conway, A. R. A. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology*, *51*, 42-100.

Cowan, N., Keller, T., Hulme, C., Roodenrys, S., McDougall, S., & Rack, J. (1994). Verbal memory span in children: Speech timing clues to the mechanisms underlying age and word length effects. *Journal of Memory and Language*, *33,* 234–250.

Cowan, N., Morey, C. C., Chen, Z., & Bunting M. F. (2007). What Do Estimates of Working Memory Capacity Tell Us? In Naoyuki Osaka, Robert Logie, and Mark D'Esposito (eds.)*, Working Memory: Behavioural & Neural Correlates*.

Cowan, N., Wood, N. L., Wood, P. K., Keller, T. A., Nugent, L. D.,& Keller, C. V. (1998). Two separate verbal processing rates contributing to short-term memory span. *Journal of Experimental Psychology: General*, *127*, 141–160.

Craik, F. I. M., & Bialystock, E. (2006). Cognition through the lifespan: mechanisms of change. *Trends in Cognitive Sciences*, *10,* 3, 131-138.

Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of verbal learning and verbal behavior*, *11*, 671-684.

Crone, E. A., Bunge, S. A., van der Molen, M. W., & Ridderinkhof, K. R. (2006). Switching between tasks and responses: a developmental study. *Developmental Science*, *9*, 3, 278–287.

Crone, E. A., Wendelken, C., Donohue, S. E., & Bunge, S. A. (2005). Neural evidence for dissociable components of task-switching. *Cerebral Cortex*, *15*, 2003 - 2012.

Crone, E. A., Wendelken, C., Donohue, S., van Leijenhorst, L., & Bunge, S. A. (2006). Neurocognitive development of the ability to manipulate information in working memory. *PNAS*, *103*, 9315-9320.

Cummins, D. D. (1995). Naïve theories and causal deduction. *Memory & Cognition*, *23*, 646-658.

Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: Meta-Analysis. *Psychonomic Bulletin & Review*, *3*, 422-433.

Davidson, M. C., Amso, D., Anderson, L. C., Diamond, A., (2006). Development of cognitive control and executive functions from 4 to 13 years: evidence from manipulations of memory, inhibition and task switching. *Neuropsychologia*, *44*, 2037–2078.

Davidson, J. E., & Dowing, C. L. (2000). Contemporary models of Intelligence. In R. J. Sternberg (Ed.), *Handbook of Intelligence*, 34-49. New York: Cambridge University Press.

Deary, I. J. (2000). Simple information processing and Intelligence. In R. J. Sternberg (Ed.), *Handbook of Intelligence* (pp. 267-284). New York: Cambridge University Press.

Dehaene, S. (1997). *The number sense: How the mind creates mathematics*. New York: Oxford University Press.

De Jong, P. F., & Das-Small, E. A. (1995). Attention and intelligence: The validity of the star counting test. *Journal of Educational Psychology*, *87*, 80–92.

Della Sala, S., Gray, C., Baddeley, A. D., Allemano, N. & Wilson, L. (1999). Pattern span: A tool for unwielding visuo-spatial memory. *Neuropsychologia, 37*, 1189-1199.

Demetriou, A. (1998). Cognitive development. In A. Demetriou, W. Doise, K. F. M. van Lieshout (Eds.), *Life-span developmental psychology* (pp 179-269). London: Wiley.

Demetriou, A., (2000). Organization and development of self-understanding and self-regulation: Toward a general theory. In M. Boekaerts, P. R. Pintrich, & M. Zeidner (Eds.), *Handbook of self-regulation* (pp. 209-251). Academic Press.

Demetriou, A. (2003). Self-formations: Toward a life-span model of the developing mind and self. *Jounal of Adult Development, 17*, 151-171.

Demetriou, A., Christou, C., Spanoudis, G., & Platsidou, M. (2002). The development of mental processing: Efficiency, working memory, and thinking. *Monographs of the Society of Research in Child Development, 67,* 268.

Demetriou, A., Christou, C., Spanoudis, G., & Platsidou, M. (2002b). Modeling the Stroop phenomenon: Processes, processing flow, and development. *Cognitive Development, 16,* 4, 987-1005.

Demetriou, A., & Efklides, A. (1985). Structure and sequence of formal and postformal thought: General patterns and individual differences. *Child Development, 56*, 1062-1091.

Demetriou A., & Efklides, A. (1989). The person's conception of the structures of developing intellect: Early adolescence to middle age. *Genetic, Social, and General Psychology Monographs, 115,* 371-423.

Demetriou, A., Efklides, A., & Platsidou, M. (1993) The architecture and dynamics of developing mind: Experiential structuralism as a frame for unifying cognitive developmental theories. *Monographs of the Society for Research in Child Development, 58,* 234, 5-6.

Demetriou, A. & Kazi, S. (2001). *Unity and modularity in the mind and the self: Studies on the relationships between self-awareness, personality, and intellectual development from childhood to adolescence*. London: Routledge.

Demetriou, A., & Kazi, S. (2006). Self-awareness in g (with processing efficiency and reasoning). *Intelligence, 34,* 297-317.

Demetriou, A., Pachaury, A., Metallidou, Y., & Kazi. S. (1996). Universal and specificities in the structure and development of quantitative-relational thought: A cross-cultural study in Greece and India. *International Journal of Behavioral Development, 19,* 255-290.

Demetriou, A., Platsidou, M., Efklides A., Metallidou, Y., & Shayer, M. (1991). Structure and sequence of the quantitative-relational abilities and processing potential from childhood and adolescence. *Learning and Instruction: The Journal of the European Association for Research on Learning and Instruction, 1,* 19-44.

Demetriou, A., & Raftopoulos, A. (1999). Modeling the developing mind: From structure to change. *Developmental Review, 19,* 319-368.

Demetriou, A., Raftopoulos, A., & Kargopoulos, P. (1999). Interactions, computations, and experience: Interleaved Springboards of Cognitive Emergence, *Developmental Review, 19,* 389-414.

Dempster, F. N. (1981). Memory span: Sources of individual and development differences. *Psychological Bulletin, 89,* 63-100.

Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: toward a unified theory of cognitive development and aging. *Developmental Review,* 12, 45-75.

Dempster, F. N. (1993). Resistance to interference: Developmental changes in a basic processing mechanism. In M. L. Howe & R. Pasnak (Eds.), Emerging themes in cognitive development, Vol.1:Foundations (pp. 3–27). New York: Springer.

Denckla, M. B. & Reiss, A. L. (1997). Prefreontal-subcortical circuits in developmental disorders. In N. A. Krasnegor, G. R. Lyon, & P. S. Goldman-Rakic (Eds.), Development of the prefrontal Cortex: Evolution, neurobiology, and behavior (pp. 283-293). Baltimore, MD: Paul Publishing.

Detterman, D. K. (1987). Theoretical notions of intelligence and mental retardation. *American Journal of Mental Deficiency*, *92,* 2-11.

Diamond, A. (1990). The development and neural bases of memory functions as indexed by the AB and delayed response tasks in human infants and infant monkeys. In A. Diamond (Ed.), The development and neural bases of higher cognitive functions. Annals of the New York Academy of Sciences: 608 (pp. 239–266). New York: New York Academy of Sciences.

Diamond, A., (1990). Developmental time course in human infants and infant monkeys, and the neural bases, of inhibitory control in reaching. In: Diamond, A. (Ed.), The Development and Neural Bases of Higher Cognitive Functions. Annals of the New York Academy of Sciences, New York, pp.394–426.

Donald, M. (1991). *Origins of the modern mind.* Harvard University Press.

Diamond, A. (1991). Neuropsychological insights into the meaning of object concept development. In S. Carey & R. Gelman (Eds.), The epigenesis of mind: Essays on biology and cognition (pp. 67-110). Hillsdale, NJ: Erlbaum.

Diamond, A. (1996). Evidence for the importance of dopamine for prefrontal cortex functions early in life. *Philosophical Transcripts of the Royal Society of London, 351*, 1346, 1483-1493.

Diamond, A. (2002). Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. In D. Diamond, A., Zola-Morgan, S., & Squire, L. (1989). Successful performance by monkeys with lesions of the hippocampal formation on AB and object retrieval, two tasks that mark developmental changes in human infants. Behavioral Neuroscience, 103, 526–537.

Diones, R., Bejar, I., & Chaffin, R. (1996). *The dimensionality of responses to SAT analogy items*. (Research Report 96-1). Princeton, NJ: Educational Testing Service.

Dougherty, T. M., & Haith, M. M. (1997). Infant expectations and reaction time as predictors of childhood speed of processing and IQ. *Developmental Psychology, 33*, 146–155.

Dowsett, S. M. & Livesey, D. J. (2000). The Development of Inhibitory Control in Preschool Children: Effects of “Executive Skills” Training. *Developmental Psychobiology*, *36*, 161-174.

Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organization of goal-directed behavior. *Cognitive Psychology*, *30*, 257-303.

Duncan-Johnson C.C. & Kopell, B.S. (1980). The locus of interference in the Stroop task: when you read ‘blue’, do you see ‘red’?. *Psychophysiology*, *17,* 3, 308–309.

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science, 11*, 19-23.

Engle, R.W. (2001). What is working memory capacity? In Roediger H. L., Nairne, J. S., Neath, I., & Surprenant, A. M. (Eds.), The nature of remembering: Essays in honor of Robert G. Crowder. Washington, DC: American Psychological Association.

Engle, R. W. (2002). Working Memory Capacity as Executive Attention. *Current Directions in Psychological Science, 11*, 1, 19-23.

Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 102-134). Cambridge, UK: Cambridge University Press.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General*, *128*, 309–331.

Ericsson, K. A., & Delaney, P. F. (1999). Long-term working memory as an alternative to capacity models of working memory in everyday skilled performance. In: A. Miyake, & P. Shah (Eds.), Models of working memory: mechanisms of active maintenance and executive control (pp. 257–297). New York: Cambridge University Press.

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review*, *102*, 211–245.

Evans, J. St. B.T., Newstead, S. E. & Byrne, R. M. J. (1993). *Human reasoning: The psychology of deduction*. Hove, UK: Lawrence Erlbaum.

Farah, M. J., Hamond, K. M., Levine, D. L., & Calvanio, R. (1988). Visual and spatial mental imagery: Dissociable systems of representation. *Cognitive Psychology*, *20*, 439-462.

Fias, W., & Fischer, M. H. (2005). Spatial representation of numbers. In J. Campbell (Ed.), Handbook of mathematical cognition (pp. 43–54). New York: Psychology Press.

Flach, J. M. (2000). Discovering situated meaning: an ecological approach to task analysis. In J. M. Schraagen, S. F. Chipman, and V. L. Shalin (Eds). *Cognitive task analysis*. London: Lawrence Erlbaum Associates.

Ford, S., & Silber, K. P. (1994). Working memory in children: A developmental approach to the phonological coding of pictorial material. *British Journal of Developmental Psychology*, *12*, 165-175.

Frege, G. (1884/1974). *The foundations of arithmetic*. Oxford: Basil Blackwell.

Friedman, N. P., Miyake, A., Corley, R. P., Young, S.E., DeFries, J. C., & Hewitt, J. K. (In press). Not All Executive Functions Are Related to Intelligence. *Psychological Science*.

Fry, A., & Hale, S. (1996). Processing speed, working memory, and fluid intelligence. *Psychological Science*, *7*, 237-241.

Frye, D., Zelazo, P. D., & Palfai, T. (1995). Theory of mind and rule-based reasoning. Cognitive Development, 10, 483-527.

Gardner, H. (1983). Frames of mind: The theory of multiple intelligences. New York: Basic.

Gardner, H. (1993). Multiple intelligences: The theory in practice. New York: Basic Books.

Gathercole, S. E. (1995). Is nonword repetition a test of phonological memory or long-term knowledge? It all depends on the nonwords. *Memory and Cognition*, *23*, 83-94.

Gathercole, S. E. (1998). The Development of Memory. *Journal of Child Psychology and Psychiatry*, *39*, 1, 3-27.

Gathercole, S. E., & Adams, A. (1993). Phonological working memory in very young children. *Developmental Psychology*, *29*, 770-778.

Gathercole, S. E., & Adams, A. (1994). Children's phonological working memory: Contributions of long-term knowledge and rehearsal. *Journal of Memory and Language*, *33*, 672-688.

Gathercole, S. E., Adams, A.-M., & Hitch, G. J. (1994). Do young children rehearse? An individual-differences' analysis. *Memory and Cognition*, *22*, 201-207.

Gathercole, S. E., & Baddeley, A. D. (1989). Evaluation of the role of phonological STM in the development of vocabulary in children: A longitudinal study. *Journal of Memory and Language*, *28*, 200-213.

Gathercole, S. E. & Baddeley, A. (1993). *Working Memory and Language*. Erlbaum, Hillsdale, NJ.

Gathercole, S. E., & Hitch, G. J. (1993). Developmental changes in short-term memory: A revised working memory perspective. In A. Collins, S. E. Gathercole, M. A. Conway, & P. E. Morris (Eds.), *Theories of memory* (pp. 189-210).

Gathercole, S. E., & Martin, A. J. (1996). Interactive processes in phonological memory. In S. E. Gathercole (Ed.), *Models of short-term memory* (pp. 73-100). Hove, U.K.: Psychology Press.

Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology, 40*, 2, 177–190.

Gathercole, S. E., Willis, C., Emslie, H., & Baddeley, A. D. (1991). The influences of syllables and wordlikeness on children's repetition of nonwords. *Applied Psycholinguistics, 12*, 349-367.

Gathercole, S. E., Willis, C., Emslie, H., & Baddeley, A. D. (1992). Phonological memory and vocabulary development during the early school years: A longitudinal study. *Developmental Psychology*, *28*, 887-898.

Gelman, S. A. & Coley, J. D. (1990). The importance of knowing dodo is a bird: Categories and inferences in 2-year-old children. *Developmental Psychology*, *26*, 796-804.

Gelman, S. A. & Markman, E. M. (1986). Categories and induction in young children. *Cognition*, *23*, 183-209.

Gentner, D. & Toupin, C. (1986). Systematicity and surface similarity in the development of analogy. *Cognitive Science*, *10*, 277-300.

Gitomer, D. H., Curtis, M. E., Glacer, R., & Lensky, D. B. (1987). Processing differences as a function of item difficulty in verbal analogy performance. *Journal of Educational Psychology*, *79*, 212-219.

Goel, V. (2007). The Anatomy of Deductive Reasoning. *Trends in Cognitive Sciences*, *11*, 435-441.

Goel, V., Buchel, C., Frith, C., & Dolan, R. J. (2000). Dissociation of mechanisms underlying syllogistic reasoning. *NeuroImage*, 12, 504-514.

Goel, V., & Dolan, R. J. (2000). Anatomical Segregation of Component Processes in an Inductive Inference Task. *Journal of Cognitive Neuroscience*, *12*, 1-10.

Goel, V., & Dolan, R. J. (2001). Functional Neuroanatomy of Three-Term Relational Reasoning. *Neuropsychologia*, *39*, 901-909.

Goel, V., Gold, B., Kapur, S., & Houle, S. (1997). The Seats of Reason: A Localization Study of Deductive & Inductive Reasoning using PET (O15) Blood Flow Technique. *NeuroReport*, *8*, 1305-1310.

Goswami, U. & Brown, A. L. (1989). Melting chocolate and melting snowmen: Analogical reasoning and causal relations. *Cognition*, *35*, 69-95.

Goswami, U. & Brown, A. L. (1990). Higher-order structure and relational reasoning: Contrasting analogical and thematic relations. *Cognition*, *36*, 207-226.

Goswami, U. (2002). Inductive and Deductive Reasoning. In U. Gowsami (Ed.), *Handbook of Child Cognitive Development* (pp. 282-302). Oxford, UK: Blackwell.

Grafman J. (1994). Alternative frameworks for the conceptualization of prefrontal lobe functions. In Boller, F. and Grafman, J. (Eds.), Handbook of Neuropsychology, *Vol. 9*, (pp 187–202). Amsterdam: Elsevier.

Groot, A. S., De Sonneville, L. M. J., Stins, J. F., Boomsma, D. I., 2004. Familial influences on sustained attention and inhibition in preschoolers. *Journal of Child Psychology & Psychiatry, 45,* 306–314.

Gruber, O. & Goschke, T. (2004). Executive control emerging from dynamic interactions between brain systems mediating language, working memory and attentional processes. *Acta Psychologica*, *115*, 2-3, 105-121.

Gustafsson, J.-E. (1988). Hierarchical models of individual differences in cognitive abilities. In R. J. Sternberg, *Advances in the psychology of human intelligence. Vol. 4,* (pp. 35-71). Hillsdale, New Jersey: Lawrence Erlbaum Associates, Inc.

Gustafsson, J-E., & Carlstedt, B. (2006). Abilities and grades as predictors of achievement: The Encapsulation theory. Paper presented at the annual meeting of the American Psychological Association, New Orleans, August 10-13.

Gutheil, G. & Gelman, S. A. (1997). Children’s use of sample size and diversity information within basic-level categories. *Journal of Experimental Child Psychology*, *64*, 159-174.

Hale, S. (1990). A global developmental trend in cognitive processing speed. *Child Development*, *61*, 653-663.

Hale, S., Myerson, J., Rhee, S. H., Weiss, C. S., Abrams, R. A. (1996). Selective interference with the maintenance of location in working memory. *Neuropsychology*, *10*, 228-240.

Halford, G. S. (1993). *Children’s understanding: The development of mental models*. Hilsdale, NJ: Lawrence Erlbaum.

Halford, G. S. (2002). Information-processing models of cognitive development. In U. Gowsami (Ed.), *Handbook of Child Cognitive Development* (pp. 556-574). Oxford, UK: Blackwell.

Halford, G. S. & Andrews, G. (2004). The development of deductive reasoning: How important is complexity? *Thinking & Reasoning*, *10*, 123-145.

Halford G. S., Andrews G. (2006). Reasoning and problem solving. In D. Kuhn and R. Siegler (Eds). Handbook of Child Psychology: Volume 2, Cognitive, Language and Perceptual Development, (pp. 557-608) 6th edition.

Halford, G. S., Cowan, N., & Andrews, G. (2007). Separating cognitive capacity from knowledge: a new hypothesis. *Trends in Cognitive Sciences*, *11*, 6, 236-242

Halford, G. S., Maybery, M. T., O’ Hare, A. W., & Grant, P. (1994). The development of memory and processing capacity. *Child Development*, *65*, 1338-1356.

Halford, G. S., Wilson, W. H., & Philips, S. (1998). Processing capacity defined by relational complexity: Implications for comparative, developmental, and cognitive psychology. *Behavioral and Brain Sciences, 21*, 803-864.

Handley, S. J., Capon, A., Beveridge, M., Dennis, I., Evans, J. St. B. T. (2004). Working memory, inhibitory control and the development of children's reasoning. *Thinking & reasoning*, *10*, 2, 175-195.

Hanley, J. R., Young, A. W., & Pearson, N. A. (1991). Impairment of the visuospatial sketchpad. *Quarterly Journal of Experimental Psychology*, *43A*, 101-126.

Hengsteler & B. Sodian (Eds.), *Young children's cognitive development*. New Jersey: Lawrence Erlbaum Associates, Publishers.

Henry, L. A. (1994). The relationship between speech rate and memory span in children. *International Journal of Behavioral Development, 17*, 37-56.

Henry, L. A., & Millar, S. (1991). Memory span increase with age: A test of two hypotheses. *Journal of Experimental Child Psychology, 51*, 459-484.

Hitch, G. J. & Halliday, M. S. (1983). *Working memory in children. Philosophical Transactions of the Royal Society*. London B, 302, 325-340.

Hitch, G. J., Halliday, M. S., & Littler, J. E. (1989). Item identification time and rehearsal rate as predictors of memory span in children. *Quarterly Journal of Experimental Psychology*, *41A*, 321-328.

Hitch, G. J., Halliday, M. S., Schaafstal, A. M., & Schraagen, J. M. C. (1988). Visual working memory in young children. *Memory and Cognition*, *16*, 120-132.

Hitch, G. J., Towse, J. N., & Hutton, U. (2001). What limits children's working memory span? Theoretical accounts and applications for scholastic development. *Journal of Experimental Psychology: General*, *130*, 184–198.

Hommel, B., & Prinz, W. (Eds). (1997). *Theoretical issues in stimulus-response compatibility*. Amsterdam: North Holland.

Horn, J. L. (1972). The structure of intellect: primary abilities. In R. M. Dreger (Ed.), *Multivariate personality research*. Baton Rouge, LA: Claitor.

Huizinga , M., Dolan, C. V., & van der Molen, M. W. (2006). Age-related change in executive function: Developmental trends and a latent variable analysis. *Neuropsychologia*, *44*, 2017–2036.

Hulme, C., Maughan, S., & Brown, G. D. A. (1991). Memory for familiar and unfamiliar words: Evidence for a long-term memory contribution to short-term memory span. *Journal of Memory and Language*, *30*, 685-701.

Hummel, J. E., & Holyoak, K. J. (1997). Distributed representations of structure: A theory of analogical access and mapping. *Psychological Review, 104*, 427-466.

Humphreys, L.G. (1994). Intelligence from the standpoint of a (pragmatic) behaviorist. *Psychological Inquiry, 5*, 179–192.

Hunt, E. B. (1980). Intelligence as an information-processing concept. *British Journal of Psychology, 71*, 449-474.

Hunt, R. R., & McDaniel, M. A. (1993). The enigma of organization and distinctiveness. *Journal of memory and language*, *32*, 421-445.

Hutton, U., Wilding, J., & Hudson, R (1997). The role of attention in the relationship between inspection time and IQ in children. *Intelligence*, *24*, 445-460.

Hyde, T.S., & Jenkins, J.J. (1973). Recall of words as a function of semantic, graphic, and syntactic orienting tasks. *Journal of verbal learning and verbal behavior, 12*, 471-480.

Inhelder, B., & Piaget, J. (1958). The growth of logical thinking from childhood to adolescence. New York: Basic Books.

Isaacs, E. B., & Vargha-Khadem, F. (1989). Differential course of development of spatial and verbal memory span: Anormative study. *British Journal of Developmental Psychology, 7*, 377-380.

Janveau-Brennan, G., & Markovits, H. (1999). The development of reasoning with causal conditionals. *Developmental Psychology*, *35*, 904-911.

Jenkinson, J. C. (1983). Is speed of information processing related to fluid or to crystallized intelligence? *Intelligence*, *7*, 91-106.

Jensen, A. J. (1998). *The g factor. The science of mental ability*. New York: Praeger.

Jensen, A. J. & Weng, L-J. (1994). What is a good g? *Intelligence*, *18*, 231-258.

Johnson-Laird, P. N. (1983). *Mental Models*. Cambridge, MA: Harvard University Press.

Johnson-Laird, P. N., & Byrne, R. M. J. (1991). *Deduction*. Hove, UK: Lawrence Erlbaum Associates Ltd.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: individual differences in working memory. *Psychological Review, 99*, 122-149.

Kail, R. (1991). Processing time declines exponentially during childhood and adolescence. *Developmental Psychology*, *27*, 2, 259-266.

Kail, R. (1992). Processing speed, speech rate, and memory. *Developmental Psychology*, *28*, 899-904.

Kail, R. (1993). Processing time decreases globally at an exponential rate during childhood and adolescence. *Journal of Experimental Child Psychology*, *56*, 254-265.

Kail, R. (2000). Speed of information processing: Developmental change and links to intelligence. *Journal of School Psychology*, *38*, 51-61.

Kail, R., (2007). Longitudinal evidence that increases in processing speed and working memory enhance children's reasoning. *Psychological Science, 4,* 312- 313.

Kail, R. & Salthouse, T. A. (1994). Processing speed as a mental capacity. *Acta Psychologica*, *86*, 199-225.

Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General*, *130*, 169-183.

Kane, M. J. & Engle, R. W. (2003) Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology General*, *132*, 47.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. E. (2004). The generality of working-memory capacity: A latent-variable approach to verbal and visuo-spatial memory span and reasoning. *Journal of Experimental Psychology: General*, *133*, 189-217.

Kargopoulos, P., & Demetriou, A. (1998). What, why, and whence logic? A response to the commentators. *New Ideas in Psychology*, *16*, 125-139.

Karmiloff-Smith, A. (1992). Beyond modularity: A Developmental Perspective on Cognitive Science. Massachusetts: The MIT Press.

Kerr, B., Davidson, J., Nelson, J., & Haley, S. (1982). Stimulus and response contributions to the children's reaction-time repetition effect. *Journal of Experimental Child Psychology*, *34*, 526-542.

Kipp, K. (2005). A developmental perspective on the measurement of cognitive deficits in attention-deficit/hyperactivity disorder. *Biological Psychiatry*, *57*, 1256-1260.

Kirkham, N. Z., Cruess, L. M., & Diamond, A. (2003). Helping children apply their knowledge to their behavior on a dimensions witching task. *Developmental Science*, *6*, 449-467.

Klaczynski, P. A., Gordon, D. H., & Fauth, J. (1997). Goal-oriented reasoning and individual differences in critical reasoning biases. *Journal of Educational Psychology*, *89*, 470-485.

Klaczynski, P. A., & Narasimham, G. (1998). Representations as mediators of adolescent deductive reasoning. *Developmental Psychology*, *5*, 865-881.

Klaczynski, P. A., & Robinson, B. (2000). Personal theories, intellectual ability, and epistemological beliefs: Adult age differences in everyday reasoning biases. *Psychology and Aging*, *15*, 400-416.

Klahr, D., & Chen, Z. (2003). Overcoming the positive-capture strategy in young children: Learning about indeterminacy. *Child Development*, *74*, 1275 – 1296.

Klenberg, L., Korkman, M., & Lahti Nuuttila, P. (2001). Differential development of attention and executive functions in 3- to 12-year-old Finnish children. *Developmental Neuropsychology, 20,* 1, 407–428.

Kline, R. T. (1998). *Principles and practice of structural equation modeling*. New York: Guilford.

Klingberg, T., Forssberg, H., & Westerberg, H. (2002). Increased Brain Activity in Frontal and Parietal Cortex Underlies the Development of Visuospatial Working Memory Capacity during Childhood. *Journal of Cognitive Neuroscience, 14,* 1, 1- 10.

Kray, J., Eber, J., & Lindenberger, U. (2004). Age differences in executive functioning across the lifespan: The role of verbalization in task preparation. *Acta Psychologica, 115,* 143-165.

Kuhn, D. (1989). Children and adults as intuitive scientists. *Psychological Review, 96,* 674-689.

Kuhn, D. (1995). Microgenetic study of change: What has it told us? *Psychological Science, 6,* 133-139.

Kuhn, D. (2000). Theory of mind, metacognition, and reasoning: A life-span perspective. In P. Mitchell & K. J. Riggs (Eds.), *Children's reasoning and the mind* (pp. 301-326). Hove, UK: Psychology Press.

Kuhn, D. & Franklin, S. (2006). The Second Decade: What Develops (and how). In W. Damon (Ed.), Handbook of Child Psychology, Set, 6th Edition.

Kuhn, D., Garcia-Mila, M., Zohar, A., & Anderson, C. (1995). Strategies of knowledge acquisition. *Monographs of the Society for Research in Child Development, 60,* 245.

Kuhn, D., & Pease, M. (2006). Do children and adults learn differently? *Journal of Cognition and Development*, 7, 279-293.

Kwon, H., Reiss, A. L. & Menon, V. (2002) *Proc. Natl. Acad. Sci. USA, 99***,** 13336–13341.

Kyllonen, P. C. (1996). Is working memory capacity Spearman's g? In: I. Dennis, & P. Tapsfield (Eds.), Human abilities: their nature and measurement (pp. 49-75). Mahwah, NJ: Erlbaum.

Kyllonen, P., & Christal, R. E. (1990). Reasoning ability is (little more than) working memory capacity? *Intelligence, 14,* 389-433.

Lachman, R., Lachman, J. L., & Butterfield, E. C. (1979). *Cognitive psychology and information processing: An introduction.* Hillsdale, NJ: Erlbaum.

Larson, G. E., Merritt, C. R. & Williams, S. E. (1988). Information processing and intelligence: some implications of task complexity. *Intelligence, 12,* 131-147.

Larson, G. E., Succuzzo, D. P. & Brown, J. (1994). Motivation: Cause or confound in information processing / intelligence correlations? *Acta Psychologica*, *85,* 25-37.

Lawrence, B. M., Myerson, J., Abrams, R. A. (2004). Interference with spatial working memory: An eye movement is more than a shift of attention. *Psychon Bulletin Review*, *11,* 488-494.

Lawrence, B. M., Myerson, J., Oonk, H. M., Abrams, R. A. (2001). The effects of eye and limb movements on working memory. *Memory*, *9*, 433–444.

Leather, C. V., Henry, L. A. (1994). Working memory span and phonological awareness tasks as predictors of early reading ability. *Journal of Experimental Child Psychology*, *58,* 88-111.

Lehto, J. H., Juujaervi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *British Journal of Developmental Psychology*, *21*, 59-80.

Lépine, R., Barrouillet, P., & Camos, V. (2005). What makes working memory spans so predictive of high level cognition ? *Psychonomic Bulletin & Review, 12*, 165-170.

Lindsay, D. S. & Jacoby, L. L. (1994). Stroop process dissociations: the relationship between facilitation and interference. *Journal of Experimental Psychology, Human Perception and Performance*, *20*, 219–234.

Liu, X., Wang, H., Corbly,C. R., Zhang,J., & Joseph, J. E. (2006). The Involvement of the Inferior Parietal Cortex in the Numerical Stroop Effect and the Distance Effect in a Two-digit Number Comparison Task. *Journal of Cognitive Neuroscience*, *18*, 9, 1518-1530.

Livesey, D. J., & Morgan, G. A. (1991). The development of response inhibition in 4- and 5-year-old children. *Australian Journal of Psychology, 43*, 133–137.

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review, 95*, 492-527.

Logie, R. H. (1995). Visuo-spatial working memory. Hove, England: Erlbaum.

Lohman, D. F. (2000). Complex information Processing and Intelligence. In R. J. Sternberg (Ed.), *Handbook of Intelligence* (pp. 285-340). New York: Cambridge University Press.

Lohman, D. (2004). Aptitude for college: The importance of reasoning tests for minority admissions. In R. Zwick (Ed.). *Rethinking the SAT. The future of standardized testing in university admissions*, (pp. 41-56). New York and London: RoutledgeFalmer.

Longoni, A. M., & Scalisi, T. G. (1994). Developmental aspects of phonemic and visual similarity effects: Further evidence in Italian children. *International Journal of Behavioural Development*, *17*, 57-71.

Los, S. A. (1996). On the origin of mixing costs: exploring information processing in pure and mixed blocks of trials. *Acta Psychologica*, *94*, 145–188.

Luna, B., Garver, K. E., Urban, T. A., Lazar, N. A., & Sweeney, J. A. (2004). Maturation of Cognitive Processes From Late Childhood to Adulthood. *Child Development, 75,* 1357-1372.

Luria, A. R. (1966). *Higher cortical functions in man (2nd Ed.)*. New York: Basic Books. (Original work published in 1962).

Luria, A. R. (1973). *The working brain: An introduction to neuropsychology* (B. Haigh, Trans.). New York: Basic Books.

MacDonald, A. W., Cohen, J. D., Stenger, V. A. & Carter, C. S. (2000). Dissociating the role of dorsolateral, prefrontal and anterior cingulated cortex in cognitive control. *Science*, *288*, 1835-1838.

MacLeod, C. M. (1991). Half a century research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*, 163-203.

Macnamara, J. (1986). *A border dispute: The place of logic in psychology*. Cambridge, MA:Bradford Books, MIT Press.

Markovits, H. (1984). Awareness of the 'possible' as a mediator of formal thinking in conditional reasoning problems. *British Journal of Psychology*, *75*, 367-376.

Markovits, H. (2000). A mental model analysis of young children's conditional reasoning with meaningful premises. *Thinking and Reasoning*, *6*, 1-14.

Markovits, H. & Barrouillet, P. (2002). The development of conditional reasoning: A mental model account. *Developmental Review*, *22,* 5-36.

Markovits, H. & Barrouillet, P. (2004). Why is understanding the development of reasoning important? *Thinking & Reasoning*, *10*, 113-121.

Mathews, N. N., Hunt, E. B., & MacLeod, C. M. (1980). Strategy choice and strategy training in sentence–picture verification. *Journal of Verbal Learning and Verbal Behavior*, *19*, 531–548.

Mattson, A. J., Harward, H., Ringholz, G., Ewing-Cobbs, L., & Fletcher, J. M. (1991). Developmental changes in performance on tests of purported frontal lobe functioning. *Developmental Neuropsychology*, *7*, 377–395.

Mayr, U., & Kliegl, R. (2000). Task-set switching and long term memory retrieval. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *26*, 1124–1140.

McConnell, J. & Quinn, J.G. (2000). Interference in visual working memory. *Quarterly Journal of Experimental Psychology*, *53*, 53–67.

McConnell, J. & Quinn, J.G. (2004). Cognitive mechanisms of visual memories and visual images. *Cognitive Personality*, *23*, 201–207.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *22*, 1423–1442.

Meiran, N. (2000). Reconfiguration of stimulus task sets and response task sets during task switching. In S. Monsell & J. Driver (Eds.), *Attention and performance XVIII: Control of cognitive performance*. Cambridge, MA: MIT Press.

Meredith, W. (1993). Measurement invariance, factor-analysis and factorial invariance. *Psychometrika*, *58*, 525-543.

Michas, I. C., & Henry, L. A. (1994). The link between phonological memory and vocabulary acquisition. *British Journal of Developmental Psychology*, *12*, 147-164.

Miles, C., Morgan, M. J., Milne, A. B., & Morris, E. D. M. (1996). Developmental and individual differences in visual memory span. *Current Psychology*, *15*, 53-67.

Miller, G.A. (1956). The magical number seven plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*, 81-97.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*, 167–202.

Miller, S. A., Custer, W. L., & Nassau, G. (2000). Children's understanding of the necessity of logically necessary truths. *Cognitive Development*, *15*, 383 – 403.

Miller, S. A., Hardin, C. A., & Montgomery, D. E. (2003). Young children's understanding of the conditions for knowledge acquisition. *Journal of Cognition and Development*, *4*, 325-356.

Miller, L. T., & Vernon, P. A. (1992). The general factor in short-term memory, intelligence and reaction time. *Intelligence*, *16*, 5-29.

Miller, L. T., & Vernon, P. A. (1996). Intelligence, reaction time, and working memory in 4- to 6-year-ols children. *Intelligence*, *22*, 155-190.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49–100.

Miyake, A., & Shah, P. (1999). *Models of working memory: Mechanisms of active maintenance and executive control*. Cambridge: Cambridge University Press.

Morra, S. (1994). Issues in working memory measurement: Testing for M capacity. *International Journal of Behavioral Development*, *17*, 143–159.

Morris, A. K. (2000). Development of logical reasoning: Children's ability to verbally explain the nature of the distinction between logical and nonlogical forms of argument. *Developmental Psychology*, *36*, 741-758.

Morris, C.. D., Bransford, J. D., & Franks, J. J. (1977). Levels of processing versus transfer appropriate processing. *Journal of verbal learning and verbal behavior, 16*, 519-533.

Morris, B. J., & Sloutsky, V. (2001). Children's solutions of logical versus empirical problems: What's missing and what develops? *Cognitive Development, 16*, 907 – 928.

Moshman, D. (1990). The development of metalogical understanding. In W. F. Overton (Ed.), Reasoning, necessity and logic: Developmental perspectives (pp. 205-225). Hillsdale, NJ: Erlbaum.

Moshman, D. (1994). Reason, reasons, and reasoning: A constructivist account of human rationality. *Theory & Psychology*, *4*, 245 – 260.

Moshman, D. (2004). From inference to reasoning: The construction of rationality. *Thinking & Reasoning*, *10*, 221-239.

Moshman, D. (in press). The development of rationality. In H. Siegel (Ed.), *Oxford handbook of philosophy of education*. Oxford, UK: Oxford University Press.

Moshman, D., & Franks, B. A. (1986). Development of the concept of inferential validity. *Child Development*, *57*, 153-165.

Mulholland, T. M., Pellegrino, J. W., & Glaser, R. (1980). Components of geometric analogy solution. *Cognitive Psychology*, *12*, 252-284.

Murray, D.J. (1967). The role of speech responses in short-term memory. Canadian *Journal of Psychology*, *21*, 263-276.

Narayanan, N. S., Prabhakaran, V., Bunge, S. A., Christoff, K., Fine, E. M., & Gabrieli, J. D. E. (2005). The role of the prefrontal cortex in the maintenance of verbal working memory: An event-related fMRI analysis. *Neuropsychology*, *19*, 223–232.

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology*, *9*, 353-383.

Neath, I., & Surprenant, A. M. (2003). *Human memory. (2nd edition)*. Belmont: Wadsworth.

Neubauer, A. C. & Freudenthaler, H. H. (1994). Reaction Times in a Sentence-Picture Veification Test and Intelligence: Individual Strategies and Effects of Extended Practice. *Intelligence, 19,* 193-218

Neumann, O. (1996). Theories of attention. In O. Neumann, & A. F. Sanders (Eds.), *Handbook of perception and action* (pp.389–446). San Diego: Academic Press.

Neumann, O. (1992). Theorien der Aufmerksamkeit: Von Metaphern zu Mechanismen [Theories of attention. From metaphors to mechanisms]. *Psychologische Rundschau*, *43*, 83–101.

Nuerk, H.-C., Weger, U., Willmes, K., (2001). Decade breaks in the mental number line? Putting the tens and units back in different bins. *Cognition*, *82*, B25– B33.

Oberauer, K., Schulze, R., Wilhelm, O., & Süß, H-M. (2005). Working Memory and Intelligence. Their Correlation and Their Relation: Comment on Ackerman, Beier, and Boyle. *Psychological Bulletin*, *131*, 61–65.

Oberauer, K., Süß, H.-M., Schulze, R., Wilhelm, O., & Wittmann, W. W. (2000). Working memory capacity. Facets of a cognitive ability construct. *Personality and Individual Differences, 29*, 1017–1045.

Oh, S., Kim, M. (2004). The role of spatial working memory in visual search efficiency. *Psychon Bull Rev*, *11*, 275–281.

Paivio, A. (1975). Perceptual comparisons through the mind's eye. *Memory and Cognition, 3*, 635-647.

Pascual-Leone, J. (1970). A mathematical model for the transition rule in Piaget's developmental stages. *Acta Psychologica*, *32*, 301-345.

Pascual-Leone, J., & Goodman, D. (1979). Intelligence and experience: a neo-Piagetian approach . *Instructional Science*, *8*, 301-367.

Pearson, D. G, Logie, R. H., Gilhooly, K. (1999). Verbal representations and spatial manipulation during mental synthesis. *European Journal of Cognitive Psychology*, *11*, 295–314.

Pearson, D. G., Sahraie, A. (2003). Oculomotor control and the maintenance of spatially and temporally distributed events in visuo-spatial working memory. *Quarterly Journal of Experimental Psychology*, *56*, 1089–1111.

Pellegrino, J. W. & Glaser, R. (1982). Components of inductive reasoning. In R. E. Snow, P. A. Federico, & W. E. Montaque (Eds.), *Aptitude, learning, and instruction: Vol.1. Cognitive process analyses of aptitude* (pp. 177-218). Hillsdale, NJ: Erlbaum.

Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *37*, 51-87.

Perner, J. (1991). *Understanding the representational mind*. Cambridge, MA: MIT Press.

Perner, J., Stummer, S., & Lang, B. (1999). Executive functions and theory of mind: Continue complexity or functional dependence? In P. D. Zelazo, J. W. Astington, & D. R. Olson (Eds.), *Developing theories of intention: Social understanding and self-control* (pp. 133-152). Mahwah, NJ: Lawrence Erlbaum Associates.

Phillips, L. H. (1997). Do ''frontal tests'' measure executive function? Issues of assessment and evidence from fluency tests. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 191–213). Hove, UK: Psychology Press.

Piaget, J. (1978). *The development of thought*. Oxford, UK: Blackwell.

Pickering, S.J., Gathercole, S.E., Hall, M., & Lloyd, S.A. (2001). Development of memory for pattern and path: further evidence for the fractionation of visuo-spatial memory. *Quarterly Journal of Experimental Psychology*, *54*, 397–420.

Pillow, B. H. (1999). Children’s understanding of inferential knowledge. *Journal of Genetic Psychology*, *160*, 419 – 428.

Pillow, B. H. (2002). Children’s and adults’ evaluation of the certainty of deductive inferences, inductive inferences, and guesses. *Child Development*, *73*, 779 – 792.

Pillow, B. H., Hill, V., Boyce, A., & Stein, C. (2000). Understanding inference as a source of knowledge: Children’s ability to evaluate the certainty of deduction, perception, and guessing. *Developmental Psychology*, *36*, 169 – 179.

Polderman, T.J.C., Stins, J.F., Posthuma, D., Gosso, M.F., Verhulst, F.C., Boomsma, D.I. (2006). The phenotypic and genotypic relation between working memory speed and capacity. Intelligence 34, 549–560.

Polderman, T. J. C., Posthuma, D., De Sonneville, L. M. J., Stins, J. F. Verhulst, F. C., & Boomsma, D. I. (2007). Genetic analyses of the stability of executive functioning during childhood. *Biological Psychology*, *76*, 11–20.

Polya, G. (1968). *Mathematics and Plausible Reasoning*. Princeton, New Jersey: Princeton University Press.

Posner, M. I., & Rothbart, M. K. (1998). Summary and commentary: Developing attentional skills. In J. E. Richards (Ed), *Cognitive neuroscience of attention: A developmental perspective* (pp. 317-323). Mahwah, NJ: Lawrence Erlbaum Associates.

Posner, M.I. & Snyder, C.R.R. (1975). Attention and cognitive control. In: R.L. Solso, (Ed.), *Information Processing and Cognition: the Loyola Symposium*, (pp. 55–85). NJ: Erlbaum, Hillsdale.

Rebai, M., Bernard, C., & Lannou, J. (1997). The Stroop’s test evokes a negative brain potential, the N400. *International Journal of Neuroscience*, *91*, 85–94.

Prabhakaran, V., Narayanan, K., Zhao, Z., Gabrieli, J. D. (2000). Integration of diverse information in working memory within the frontal lobe. *Nat Neurosci*, *3*, 85–89.

Rabbitt, P. (1997). Introduction: Methodologies and models in the study of executive function. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 1–38). Hove, UK: Psychology Press.

Rasch, G. (1980). *Probabilistic Models for some intelligence and attainment tests*. Chicago: University of Chicago Press.

Reitan, R. M., & Wolfson, D. (1994). A selective and critical review of neuropsychological deficits and the frontal lobes. *Neuropsychology Review*, *4*, 161–197.

Repovš, G. & Baddeley, A. (2006). The multi-component model of working memory: explorations in experimental cognitive psychology. *Neuroscience*, *139*, 5–21.

Ridderinkhof, K. R., Band, G. P. H., & Logan, G. D. (1999). A study of adaptive behavior: Effects of age and irrelevant information on the ability to inhibit one's actions. *Acta Psychologica, 101*, 315–337.

Riesbeck, C. K. & Schank, R. C. (1989). *Inside case-based reasoning*. Hillsdale, NJ: Erlbaum.

Rips, L. J. (1983). Cognitive Processes in propositional reasoning. *Psychological Review*, *90*, 38-71.

Rips, L. J. (1994). The Psychology of Proof: Deductive Reasoning in Human Thinking. Cambridge, MA: MIT Press.

Roberts, R. D., Beh, H. C., Spilsbury, G., & Stankov, L. (1991). Evidence for an attentional model of human intelligence using the competing task paradigm. *Personality and Individual Differences*, *12*, 445–455.

Roberts, A. C., & Wallis, J. D. (2000). Inhibitory control and affective processing in the prefrontal cortex: Neuropsychological studies in the common marmoset. *Cerebral Cortex*, *10*, 252–262.

Rogers, W. A., Hertzog, C., & Fisk, A. D. (2000). An individual differences analysis of ability and strategy influences: age-related differences in associative learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*, 359–394.

Roodenrys, S., Hulme, C., & Brown, G. (1993). The development of short-term memory span: Separable effects of speech rate and long-term memory. *Journal of Experimental Child Psychology*, *56*, 431-442.

Rougier, N. P., Noelle, D. C., Braver, T. S., Cohen, J. D., and O'Reilly R. C. (2005). Prefrontal cortex and flexible cognitive control: Rules without symbols. *PNAS*, *102*, 20, 7338–7343.

Rousselet, G. A., Thorpe, S. J., & Fabre-Thorpe, M. (2004). How parallel is visual processing in the ventral pathway? *Trends in Cognitive Sciences*, *8,* 8, 363-370.

Rumain, B., Connell, J., and Braine, M. D. S. (1983). Conversational comprehension processes are responsible for reasoning fallacies in children as well as adults. *Developmental Psychology*, *19*, 471-481.

Rushworth, M., Walton, M., Kennerley, S., & Bannerman, D. (2004). The role of medial frontal cortex in making decisions and changing tasks. *International Journal of Psychology*, *39*, 514, 5–6.

Salthouse, T.A. (1992). What do adult age differences in the Digit Symbol Substitution Test reflect? *Journal of Gerontology: Psychological Sciences*, *47*, 121-128.

Salthouse, T.A. (1993). Speed mediation of adult age differences in cognition. Developmental Psychology. *Developmental Psychology*, *29*, 722-738.

Salthouse, T. A. (1996). The processing - speed theory of adult age differences in cognition. *Psychological Review*, *103*, 403-428.

Salthouse, T. A. (2000). Aging and measures of processing speed. *Biological Psychology, 54*, 35–54.

Schachar, R. J., & Logan, G. D. (1990). Impulsivity and inhibitory control in normal development and childhood psychopathology. *Developmental Psychology, 26,* 710–720.

Schmidt-Atzert, L., & Bühner, M. (2000). Aufmerksamkeit und intelligenz [Attention and intelligence]. In K. Schweizer (Ed.), Intelligenz und kognition (pp. 125–151). Landau: Verlag Empirische Pädagogik.

Schneider, W., Lockl, K., & Fernadez, O. (2005). Interrelationships among theory of mind, executive control, language development, and working memory in young children: A longitudinal analysis. In W. Schneider, R. Schumann-Hengsteler & B. Sodian (Eds.), *Young children's cognitive development*. New Jersey: Lawrence Erlbaum Associates, Publishers.

Schweickert, R., Guentert, L., & Hersberger, L. (1990). Phonological similarity, pronunciation rate, and memory span. *Psychological Science*, *1*, 74-77.

Schweizer, K. (2001). Preattentive processes and cognitive ability. *Intelligence*, *29*, 169–186.

Schweizer, K., & Koch, W. (2003). Perceptual processes and cognitive ability. *Intelligence*, *31*, 211–235.

Schweizer, K., & Moosbrugger, H. (2004). Attention and working memory as predictors of intelligence. *Intelligence*, *32*, 329–347.

Schweizer, K., Moosbrugger, H., & Goldhammer, F. (2005). The structure of the relationship between attention and intelligence. *Intelligence, 33,* 589–611.

Schweizer, K., Zimmermann, P., & Koch, W. (2000). Sustained attention, intelligence and the crucial role of perceptual processes. *Learning and Individual Differences*, *12*, 271–286.

Shah, P., & Miyake, A. (1997). The separability of working memory resources for spatial thinking and language processing: an individual differences approach. *Journal of Experimental Psychology: General*, *125*, 4–27.

Shaw, R. M., Helmes, E., & Mitchell, D. (2006). Age-related change in visual, spatial and verbal memory. *Australasian Journal on Ageing*, *25*, 1, 14 –19.

Shayer, M., Demetriou, A., & Pervez, M. (1988). The structure and scaling of concrete operational thought: Three studies in four countries. *Genetic, Social, and General Psychology Monographs, 114*, 307-376.

Siegel, L.S. (1994). Working memory and reading: a life-span perspective. *International Journal of Behavioral Development*, *17*, 109-124.

Siegler, R. S. (1981). Developmental sequences within and between concepts. *Monographs of the Society for Research in Child Development*, *46*, 1-84.

Siegler, R. S. (1995). How does change occur: A microgenetic study of number conservation. *Cognitive Psychology*, *28*, 225-273.

Siegler, R. S., & Crowley, K. (1991). The microgenetic method: A direct means for studying cognitive development. *American Psychologist*, *46*, 606-620.

Simoneau, M., & Markovits, H. (2003). Reasoning with premises that are not empirically true: Evidence for the role of inhibition and retrieval. *Developmental Psychology*, *39*, 964-975.

Smith, E. E., & Jonides, J. (1999). Neuroscience-Storage and executive processes in the frontal lobes. *Science*, *283*, 1657–1661.

Smulders, S. F. A., Notebaert, W., Meijer, M., Crone, E. A., van der Molen, M. W., & Soetens, E. (2005). Sequential effects on speeded information processing: a developmental study. *Journal of Experimental Child Psychology*, *90*, 208–234.

Smyth, M. M. (1996). Interference with rehearsal in spatial working memory in the absence of eye movements. *Quarterly Journal of Experimental Psychology*, *49*, 940–949.

Sodian, B., & Wimmer, H. (1987). Children’s understanding of inference as a source of knowledge. *Child Development*, *58*, 424 – 433.

Soetens, E., & Hueting, J. E. (1992). Age influence on sequential effects in serial two-choice reaction time. In H. Bouma & J. A. M. Graafmans (Eds.), *Gerontology* (pp. 237–243). Amsterdam: IOS Press.

Spearman, C. E. (1904). 'General intelligence ' objectively determined and measured. *American Journal of Psychology, 15*, 201-293.

Sperber, D., Cara, F., & Girotto, V. (1995). Relevance theory explains the selection task. *Cognition*, *57*, 31-95.

Stankov, L., & Roberts, R. D. (1997). Mental speed is not the ‘basic’ process of intelligence. *Personality and Individual Differences*, *22*, 69-84.

Staudenmayer, H. (1975). Understanding conditional reasoning with meaningful propositions. In R. J. Flamagne (Ed.), *Reasoning: Representation and process in children and adults*. Hillsdale, NJ: Erlbaum.

Sternberg, R. J. (1984). Mechanisms of cognitive development: A componential approach. In R. J. Sternberg (Ed.), Mechanisms of cognitive development (pp. 163-186). New York: W.H. Freeman.

Sternberg, R. J. (1984). Towards a triarchic theory of human intelligence. *Behavioral and brain Sciences*, *7*, 269-315.

Sternberg, R. J. (1985). *Beyond IQ: A triarchic theory of mental intelligence*. New York: Cambridge University Press.

Sternberg, R. J. (1997). The concept of intelligence and its role in lifelong learning and success. *American Psychologist, 52*, 1030-1037.

Stankov, L., Roberts, R., & Spilsbury, G. (1994). Attention and speed of test-taking in intelligence and aging. *Personality and Individual Differences*, *17*, 273–284.

Stins, J. F., De Sonneville, L. M. J., Groot, A. S., Polderman, T. J. C., Van Baal, C. G. C. M., Boomsma, D. I. (2005). Heritability of selective attention and working memory in preschoolers. *Behavior Genetics*, *35*, 407–416.

Stough, C., Brebner, J., Nettelbeck, T., Cooper, C. J., Bates, T., & Mangan, G. L. (1996). The relationship between intelligence, personality and inspection time. *British Journal of Psychology*, *81*, 255-268.

Stroop, J. R. (1935). Studies of inference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643-662.

Sturm, W., & Zimmermann, P. (2000). Aufmerksamkeitssto¨rungen [Attention disorders]. In W. Sturm, M. Herrmann, & C. -W. Wallesch (Eds.), Lehrbuch der klinischen Neuropsychologie (pp. 345–365). Lisse7 Swets and Zeitlinger.

Stuss, D. T. (1992). Biological and psychological development of executive functions. *Brain and Cognition*, *20*, 8–23.

Stuss T. & Knight R. T. (Eds.), *Principles of frontal lobe function* (pp. 466–503). London, UK: Oxford University Press.

Stuss, D. T., Shallice, T., Alexander, M. P., & Picton, T. W. (1995). A multidisciplinary approach to anterior attentional functions. In J. Grafman & K. J. Holyoak (Eds.), *Structure and functions of the human prefrontal cortex. Annals of the New York Academy of Sciences* (pp. 191–211). New York, NY: Academy of Sciences.

Thompson, P.M., Giedd, J. N.,Woods, R. P., MacDonald, D., Evans, A. C., Toga, A. W., 2000. Growth patterns in the developping brain detected by using continuum mechanical tensor maps. *Nature*, *404*, 190–193.

Thomson, G. (1951). *The factorial analysis of human ability (5th ed.)*. London: University of London Press.

Thorndike, E.L. (1927). *The Measurement of Intelligence*. New York: Teachers College.

Thorndike, R.L. (1987). Stability of factor loadings. *Personality and Individual Differences, 8*, 585-586.

Thurstone, L. L. (1938). *Primary mental abilities.* Chicago, IL: University of Chicago Press.

Townsend, J. T., & Fific, M. (2004). Parallel Versus Serial Processing and Individual Differences in High-Speed Search in Human Memory. *Perception and Psychophysics*, *66*, 953-962.

Tulving, E. (1983). *Elements of episodic memory*. New York: Oxford University Press.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, *28*, 127–154.

Unsworth, N. & Engle, R.W. (2005). Working memory capacity and fluid abilities: Examining the correlation between Operation Span and Raven. *Intelligence*, *33*, 67–81.

Van den Wildenberg, W. P. M., & van der Molen, M. W. (2003). Developmental trends in simple and selective inhibition of compatible and incompatible responses. *Journal of Experimental Child Psychology*, *87*, 201–220.

Van den Wildenberg, W. P. M., & van der Molen, M. W. (2004). Developmental trends in simple and selective inhibition of compatible and incompatible responses. *Journal of Experimental Child Psychology*, *87*, 201-220.

Verguts, T., & De Boeck, P. (2002). On the correlation between working memory capacity and performance on intelligence tests. *Learning & Individual Differences*, *13*, 37-55.

Vernon, P.A. (1983). Speed of information processing and general intelligence. *Intelligence*, *7*, 53-70.

Vernon, P.A. (1989). The generality of g. *Personality and Individual Differences*, *10*, 803-804.

Vernon, P. A., & Mori, M. (1992). Intelligence, reaction times, and peripheral nerve conduction velocity. *Intelligence*, *16*, 273-288.

Wagar, B. M., Dixon, M. J. (2005). Past experience influences object representation in working memory. *Brain Cognition*, *57*, 248–256.

West, R. & Alain, C. (1999). Event-related neural activity associated with the Stroop task. *Cognitive Brain Research*, *8*, 157–164.

West, R., & Alain, C. (2000). Age-related decline in inhibitory control contributes to the increased Stroop effect in older adults. *Psychophysiology*, *37*, 179-189.

Welsh, M. C., Pennington, B. F., & Groisser, D. B. (1991). A normative developmental study of executive function: A window on prefrontal function in children. *Developmental Neuropsychology*, *7*, 131–149.

Wickelgren, W. A. (1965). Short-term memory for phonemically similar lists. *American Journal of Psychology*, *78*, 567-574.

Wickens, C. D. (1980). The structure of attentional resources. In R. S. Nickerson (Ed.), Attention and performance VIII. Hillsdale, NJ7 Erlbaum.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomic Science*, *3*, 159–177.

Wilhelm, O. & Schulze, R. (2002). The relation of speeded and unspeeded reasoning with mental speed. *Intelligence*, *30*, 537-554.

Williams, B. R., Ponesse, J. S., Schacher, R. J., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the life span. *DevelopmentalPsychology*, *35*, 205-213.

Wilson, J. T. L., Scott, J. H., & Power, K. G. (1987). Developmental differences in the span of visual memory for pattern. *British Journal of Developmental Psychology*, *5*, 249-255.

Woodman, G. F, Luck, S. J. (2004). Visual search is slowed when visuospatial working memory is occupied. *Psychonomy Bulletin Review*, *11*, 269–274.

Woodman, G. F., Vecera, S. P., Luck, S. J. (2003). Perceptual organization influences visual working memory. *Psychonomy Bulletin Review*, *10*, 80–87.

Xu, Y. (2002). Encoding color and shape from different parts of an object in visual short-term memory. *Percept Psychophys*, *64*, 1260–1280.

Zelazo, P. D. (2004). The development of conscious control in childhood. *Trends in Cognitive Sciences*, *8*, 12-17.

Zelazo, P. D., Carter, A., Reznick, J. S., & Frye, D. (1997). Early development of executive function: A problem-solving framework. *Review of General Psychology*, *1*, 1-29.

Zelazo, P. D., Craik, F. I. M., & Booth, L. (2004). Executive function across the life span. *Acta Psychologica*, *115*, 167-183.

Zelazo, P. D., & Frye, D. (1997). Cognitive complexity and control: A theory of the development of deliberate reasoning and intentional action. In M. Stamenov (Ed.), Language structure, discourse, and the access to consciousness (pp. 113-153). Amsterdam: John Benjamins.

Zelazo, P. D., Frye, D., & Rapus, T. (1996). An age-related dissociation between knowing rules and using them. *Cognitive Development*, *11*, 37-63.

Zelazo, P. D., Müller, U., Frye, D., & Marcovitch, S. (2003). The development of executive function in early childhood. *Monographs of the Society for Research in Child Development*, *68*, 3, Serial No. 274.

Zelazo, P. D., Qu, L., & Müller, U. (2005). Hot and cool aspects of executive function: Relations with early development. In W. Schneider, R. Schumann-Zelazo, P. D. & Müller, U. (2002). Executive function in typical and atypical development. In U. Gowsami (Ed.), *Handbook of Child Cognitive Development* (445-469). Oxford, UK: Blackwell.

Zelazo, P. D., & Reznick, J. S. (1991). Age-related asynchrony of knowledge and action. *Child Development*, *62*, 719–735.

Zelazo, P. D., Reznick, J. S., & Pinon, D. E. (1995). Response control and the execution of verbal rules. *Developmental Psychology*, *31*, 508–517.

Zomeren, A. H. Van, & Brouwer, W. H. (1994). Clinical *neuropsychology of attention*. New York: Oxford University Press.

APPENDIX

APPENDIX A

Reasoning Tasks

Inductive Reasoning – Verbal – Syllogisms

Pi, Yi and Xi are all Chinese.

Pi likes rice.
Yi likes rice.
Xi likes rice.

Andreas is not Chinese.

- Do you think Andreas likes rice? **$IVLc_1$**
    - o Definitely Yes
    - o Definitely No
    - o May be yes, may be no

Li doesn't like rice.

- Do you think Li is Chinese? **$IVLc_2$**
    - o Definitely Yes
    - o Definitely No
    - o May be yes, may be no

What do you think?

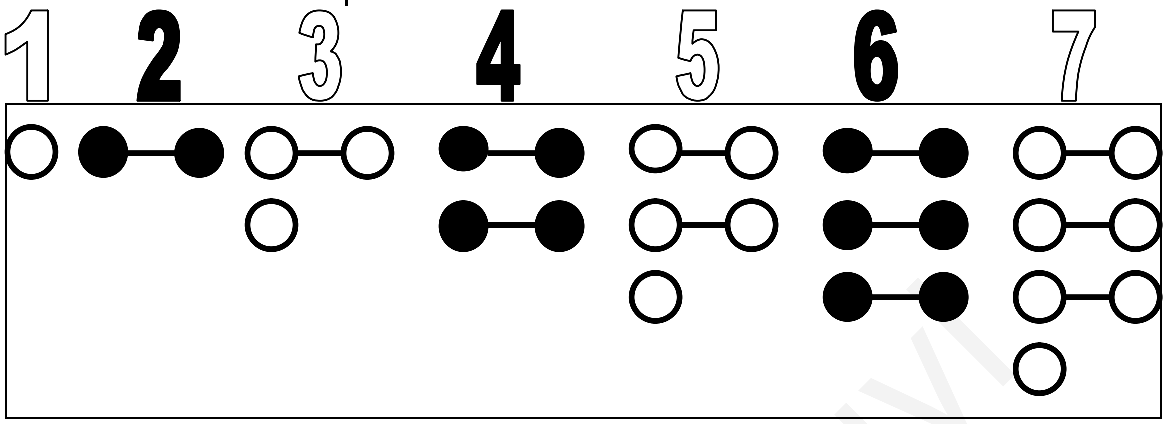
- Is it possible that there is a Chinese who does not like rice? **$IVLc_3$**
    - o Definitely Yes
    - o Definitely No
    - o May be yes, may be no

Inductive Reasoning – Verbal – Analogies

car : street :: ship : ________	sailors anchor trip sea	**IVAc$_1$**
speech : ________ :: water : fire	silence tongue audience peace	**IVAc$_2$**
leaf : ________ :: page : book	forest tree branch garden	
flour : ________ :: verse : music	bread cook water wheat	

Inductive Reasoning – Numerical – Syllogisms

Under each number you can see the balls that can fit to it.
The balls are drawn in pairs.



1, 3, 5, 7 and 9 are white numbers.
2, **4**, **6** and **8** are black numbers.

Underneath 3 one ball is left over.
Underneath 5 one ball is left over.
Underneath 7 one ball is left over.

What do you think?

- Is it possible to put together the balls of two black numbers and have a ball left over?
    - o Yes
    - o No
    - o May be yes, may be not **$IMLc_1$**

We have put together the ball of two numbers. They were places in couples and there was one ball left over. Do you think that the two numbers were white?

- o Yes
- o No
- o May be yes, may be not **$IMLc_2$**

In the equations below the numbers on the left are even, while the numbers on the right are prime numbers.

Prime number is any number that can be divided just by 1 and itself.

Number 4 is an even number and it can be written as a sum of two prime numbers
4=2+2

Number 6 is an even number and it can be written as a sum of two prime numbers
6=3+3

Number 8 is an even number and it can be written as a sum of two prime numbers
8=5+3

20 is an even number.

- Do you think it can be written as a sum of two prime numbers?
    - Yes
    - No
    - May be yes, may be not **$IMLc_3$**

There is a number which is impossible to write as a sum of two prime numbers.

- Do you think that this number can be an even number?
    - Yes
    - No
    - May be yes, may be not **$IMLc_4$**

Inductive Reasoning – Numerical – Analogies

In each row the number on the left has the same relation with the number on the right. Fill in the square the correct number.

1	3
3	9
5	15
4	□

IMAC₁

These numbers are connected in a different way.

2	5
4	9
5	11
6	□

IMAC₂

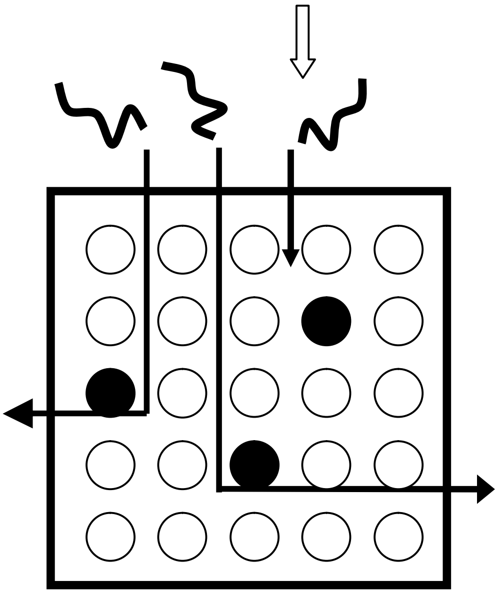
These numbers are connected in a different way.

16	7
20	9
8	3
10	□

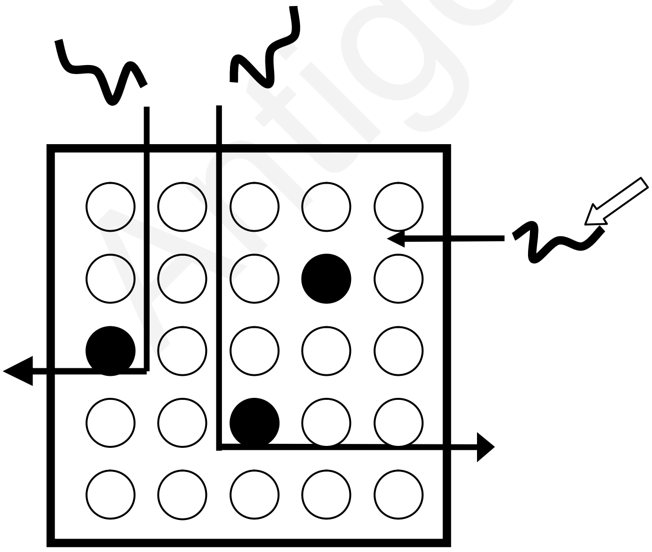
IMAC₃

Inductive Reasoning – Spatial – Syllogisms

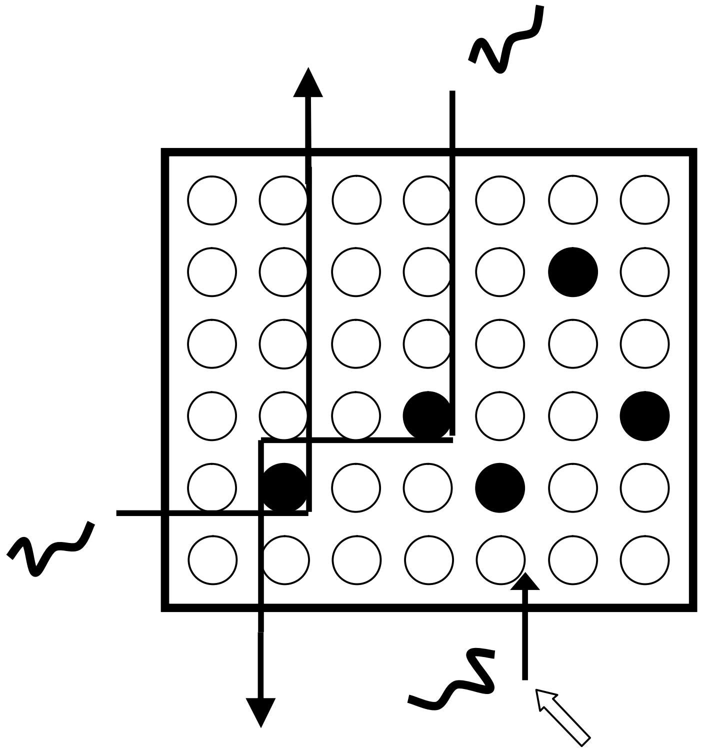
The worms are walking in the garden. In the garden there are some white and some black stones. Worms walk among the stones in a way of their own. Can you figure out the way they are walking so that you can help the worm pointed by the white arrow to enter the garden, walk in it and get out? Draw lines to show to the worm the way it must follow.



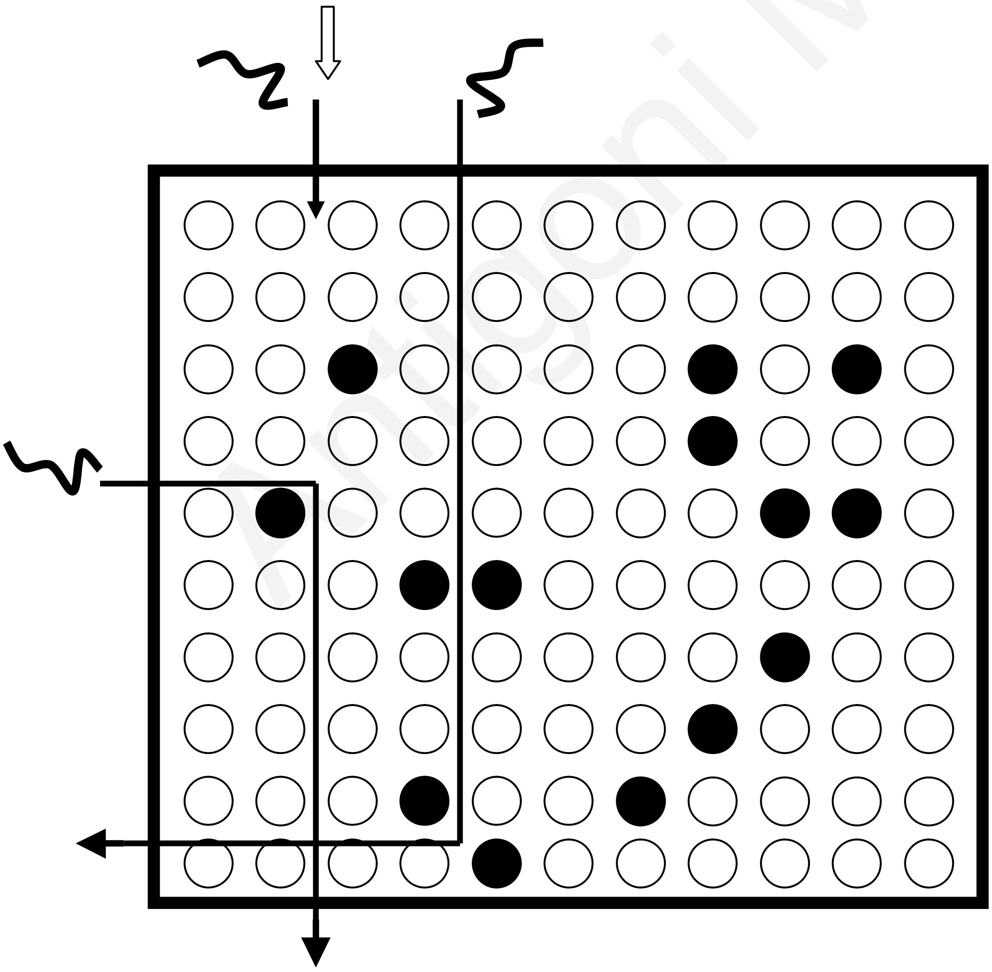
ISLc$_1$



ISLc$_2$

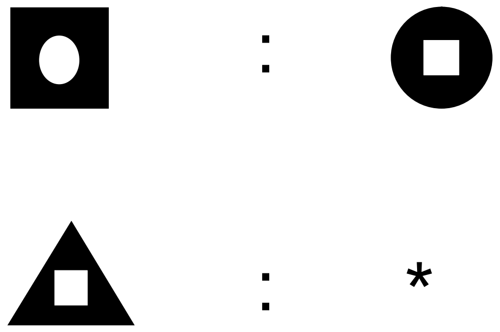


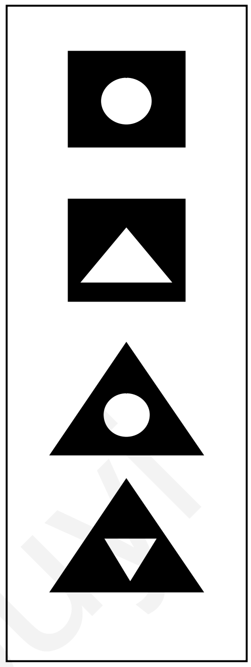
ISLc$_3$



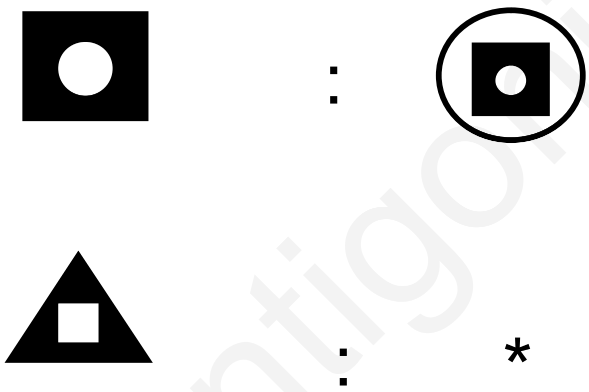
ISLc$_4$

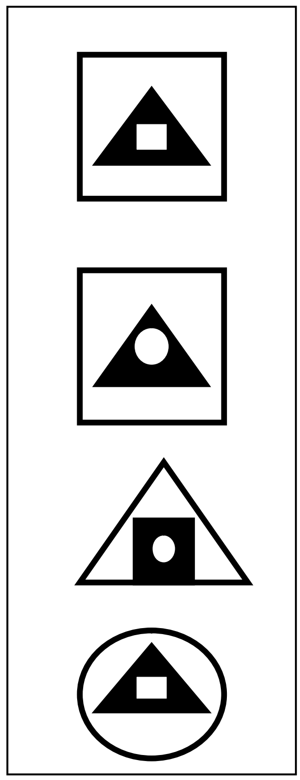
Inductive Reasoning – Spatial – Analogies



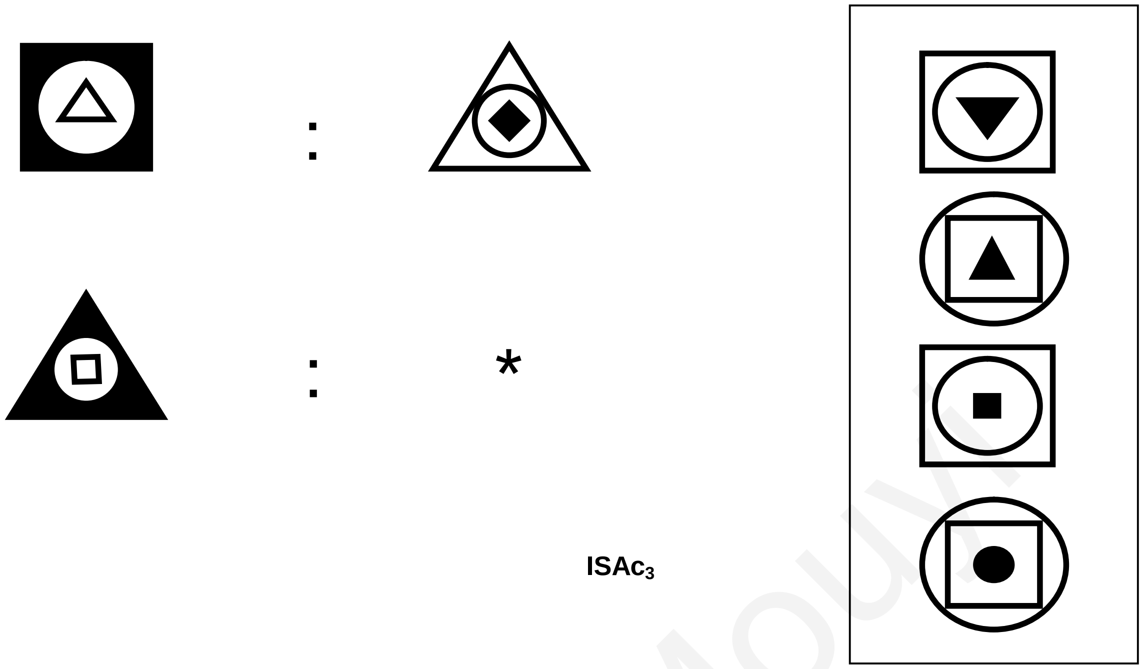


ISAc$_1$





ISAc$_2$



ISAc$_3$

Deductive Reasoning – Verbal – Syllogisms

A group of aliens lives on **thee** different planets, the **red**, the **purple** and the **blue** planet. These aliens, called Paff, have weird shape heads. Some are **triangles**, some are **squares** and some are **circles**. Their names sound like the letters in the Greek alphabet.

1. If a Paff has a triangular head, then it lives on the blue planet.
   Hta has a circular head.
   ___
   Hta does not live on the blue planet.

○ Definitely Correct **DVLc1**
○ Definitely Wrong
○ I cannot decide for sure based on the information I get

2. If a Paff has a triangular head, then it lives on the purple planet.
   Psi lives on the blue planet.
   ___
   Psi has a triangular head.

○ Definitely Correct **DVLc2**
○ Definitely Wrong
○ I cannot decide for sure based on the information I get

3. If a Paff has a triangular head, then it lives on the purple planet.
   Omega lives on the red planet.
   ___
   Omega has a squared head.

○ Definitely Correct **DVLc3**
○ Definitely Wrong
○ I cannot decide for sure based on the information I get

Some other group of aliens lives on **two** different planets, the **yellow** and the **green** planet. These aliens, called Zan, have **triangular** or **squared** heads. Zans do not have names. Instead they have numbers.

1. If a Zan lives on the yellow planet then it has a triangular head.

   Four lives on the yellow planet.

   Four has a triangular head.

○ Definitely Correct DVLc4

○ Definitely Wrong

○ I cannot decide for sure based on the information I get

2. If a Zan lives on the green planet then it has a triangular head.

   Six does not have a triangular head.

   Six does not live on the green planet.

○ Definitely Correct DVLc5

○ Definitely Wrong

○ I cannot decide for sure based on the information I get

3. If a Zan lives on the green planet then it has a triangular head.

   Eight has a squared head.

   Eight lives on the yellow planet.

○ Definitely Correct DVLc6

○ Definitely Wrong

○ I cannot decide for sure based on the information I get

Deductive Reasoning – Numerical – Syllogisms

The information below will help you figure out the hidden number in each square. You can use one of the numbers 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9, in each square.

1st	2nd	3rd

DMLc$_1$

- The third number is number 1.
- If the third number is the smallest one of the three numbers, then the first one is number 4.
- There is no number 0.
- The second number is either the smallest or the biggest number we can use.
- No number is written twice.

- -

1st	2nd	3rd	4th

DMLc$_2$

- If the second number is the biggest one-digit even number we can use, then the fourth number is the smallest odd number.
- If the first number is 3, then the third number is 2.
- If the sum of the third and fourth number is equal with the first number, then the second number is 8.
- If the sum of the third and fourth number is equal to 2, then the first number is 3.
- If the second number is odd, then the first number is 3.
- The first number is 3.
- The second number is not an odd number.
- The second number is either 5 or 8.

$DMLc_3$

1st	2nd	3rd	4th

- There is no even number.
- No number is written twice.
- If the second number is the smallest, then the fourth number is the biggest of all one-digit numbers.
- The second number is either 1 or 3.
- If the second number is 1, then the third number is either 5 or 7.
- The third number is either 5 or 7.
- If the third number is 7, then the smallest number used is 1.
- The smallest number used is 3.
- If the difference between the first and the second number is equal to 4, then the difference between the third and the fourth number is equal to 4 and if the difference between the third and the fourth number is equal to 4, then the difference between the first and the second number is equal to 4.

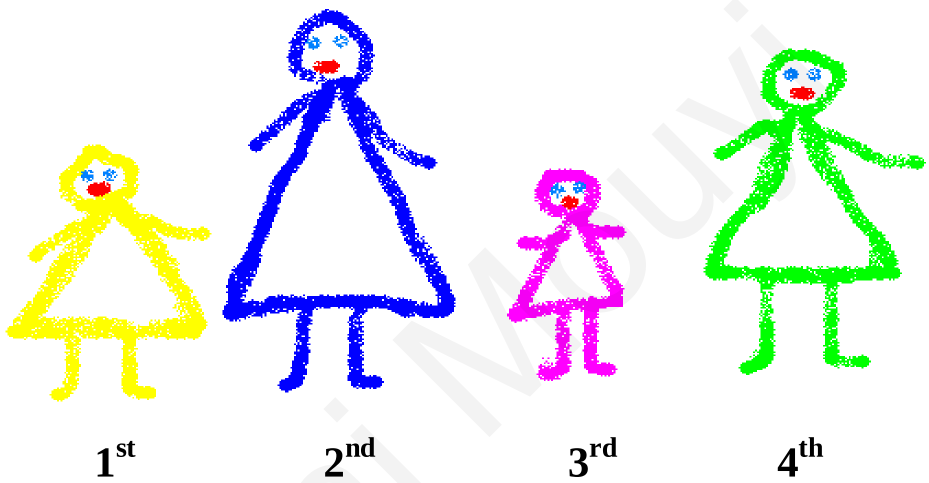
Deductive Reasoning – Spatial – Syllogisms

1. Four girlfriends, Maria, Catherine, Alice and Lena, stood up on a line.

Alice: If Lena stands fourth then I am the shortest. **DSLc$_1$**

Maria: I am either standing first or I am the shortest.

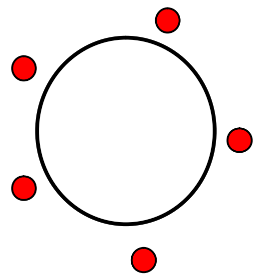
Lena: I am not the tallest and I am standing next to the shortest.



2. Five friends, Antony, Vicky, John, Demetra and Helen, sat at a round table.

- Antony did not sit next to Demetra or next to John.
- If Helen sat next to John, then she sat next to Vicky.

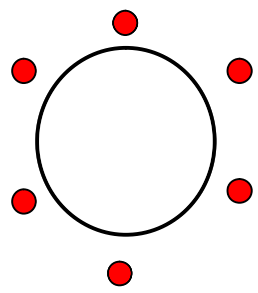
Can you place the five friends at their places? **DSLc$_2$**



3. Six friends, Stelios, Vasilis, Demetris, George, Costas and Alexis, are going to sit at a round table.

   - George wants to sit as far as possible from Stelios.
   - Alexis will either sit next to Demetris or next to Vasilis, but not both.
   - If Alexis sits next to Demetris, then George will sit next to Stelios.
   - If Alexis sits next to Vasilis, then Stelios will sit in between Alexis and Costas. Vasilis and Demetris are not sitting next to each other.

Can you place the six friends at their places? **$DSLc_3$**



APPENDIX B

Table B1a. Reliability coefficients for all tasks used (first wave).

		Speeded Performance Measures (1st wave)										
Class		**SP left**	**SP right**	**PD conceptual relation**	**PD part-whole**	**PD resemblance**	**PC verbal**	**PC figural**	**PC numeical**	**CC conceptual relation**	**CC part-whole**	**CC resemblance**
Year 1	**Mean**	749.949	760.980	1693.981	1789.006	1770.512	1638.026	1887.914	2098.718	2765.191	2588.557	2114.043
	N	20	20	21	21	21	20	19	20	21	21	21
	SD	83.202	79.648	333.715	401.084	284.291	456.385	439.690	271.493	700.595	534.802	486.005
Year 2	**Mean**	674.051	682.999	1345.813	1377.647	1333.197	1427.785	1678.580	1803.133	2208.125	2275.398	1775.814
	N	21	21	20	21	20	21	21	21	21	21	21
	SD	83.013	80.289	298.969	336.094	298.720	505.740	353.410	380.285	674.786	509.372	402.758
Year 3	**Mean**	605.553	601.039	1287.372	1285.585	1247.943	1579.856	1471.327	1535.231	1895.570	1959.805	1624.586
	N	20	20	20	20	20	20	20	20	20	20	20
	SD	88.928	117.676	315.875	290.959	264.603	729.572	320.629	270.711	459.630	556.962	445.116
Year 4	**Mean**	593.733	615.200	1302.161	1358.493	1311.274	1491.380	1419.679	1433.252	1867.879	1691.074	1526.704
	N	21	21	21	21	21	19	20	21	21	21	21
	SD	107.768	106.945	306.702	338.044	309.647	417.298	428.808	291.511	446.359	352.822	325.619
Year 5	**Mean**	617.180	608.153	1135.435	1061.262	1122.253	1272.554	1375.217	1349.770	1789.426	1553.153	1435.053
	N	21	21	21	21	21	20	21	21	21	21	21
	SD	94.940	79.931	262.703	253.422	256.896	284.035	273.105	290.410	368.975	389.761	377.554
Year 6	**Mean**	573.709	581.235	1041.431	1039.354	1107.717	1195.174	1076.183	1149.124	1854.340	1802.236	1384.255
	N	21	21	21	21	21	21	21	21	21	21	21
	SD	83.784	87.762	178.796	169.493	235.605	508.747	185.293	197.320	543.118	498.245	302.679
Total	**Mean**	635.017	640.965	1300.781	1318.822	1315.885	1431.629	1478.853	1557.418	2064.765	1978.519	1643.560
	N	124	124	124	125	124	121	122	124	125	125	125
	SD	106.973	110.124	349.213	391.781	350.684	516.960	419.778	420.202	636.187	589.947	459.411
Corrected Item-Total Correlation		0.714	0.715	0.776	0.781	0.766	0.398	0.670	0.720	0.725	0.639	0.698
Cronbach's alpha		0.893										

Class		WM storage1 figure ACC	WM storage2 CAP	WM executive control1 CAP	WM executive control2 CAP	Information Integration number ACC	Information Integration word ACC	Information Integration pictures ACC	Induction-Verbal	Induction-Math	Induction-Spatial	Deduction-Verbal	Deduction-Math	Deduction-Spatial
		Information Integration, Working Memory and Reasoning Measures (1st wave)												
Year 1	**Mean**	2.857	4.136	1.713	1.488	5.136	4.000	4.136	0.370	0.261	0.298	0.356	0.267	0.149
	N	21	22	20	20	22	22	22	23	23	23	23	23	23
	SD	1.797	1.406	1.989	1.463	1.457	1.234	1.207	0.146	0.128	0.110	0.112	0.174	0.091
Year 2	**Mean**	3.526	4.430	2.514	1.400	5.087	4.261	3.957	0.369	0.336	0.259	0.305	0.232	0.274
	N	19	24	18	20	23	23	23	24	24	24	24	24	24
	SD	1.264	1.057	2.268	1.494	1.311	1.356	1.296	0.178	0.167	0.203	0.093	0.226	0.188
Year 3	**Mean**	3.500	4.317	2.250	2.000	4.300	3.550	3.550	0.448	0.428	0.239	0.364	0.286	0.331
	N	20	20	16	17	20	20	20	22	22	22	22	22	22
	SD	2.236	1.547	2.275	2.037	1.593	1.099	1.146	0.155	0.155	0.137	0.117	0.202	0.135
Year 4	**Mean**	4.571	4.968	2.766	3.528	6.158	4.579	4.368	0.575	0.451	0.297	0.301	0.429	0.415
	N	21	21	16	18	19	19	19	21	21	21	21	21	21
	SD	0.926	0.146	2.044	1.923	1.167	1.427	1.606	0.181	0.154	0.120	0.145	0.212	0.285
Year 5	**Mean**	4.476	4.933	2.330	3.452	5.810	4.524	4.429	0.743	0.603	0.451	0.443	0.543	0.617
	N	21	25	22	21	21	21	21	25	25	25	25	25	25
	SD	0.928	0.236	1.943	2.001	1.209	1.030	1.028	0.146	0.160	0.236	0.078	0.251	0.192
Year 6	**Mean**	4.952	4.930	4.125	4.409	6.294	4.765	4.471	0.737	0.580	0.434	0.445	0.549	0.629
	N	21	24	24	22	17	17	17	25	25	25	25	25	25
	SD	0.865	0.241	2.042	1.711	1.649	0.970	1.179	0.229	0.207	0.259	0.121	0.263	0.202
Total	**Mean**	3.992	4.630	2.672	2.752	5.426	4.262	4.139	0.545	0.447	0.334	0.371	0.388	0.408
	N	123	136	116	118	122	122	122	140	140	140	140	140	140
	SD	1.581	0.985	2.193	2.095	1.532	1.245	1.268	0.235	0.204	0.205	0.125	0.257	0.259
Corrected Item-Total Correlation		0.392	0.431	0.405	0.452	0.397	0.422	0.307	0.697	0.689	0.637	0.463	0.707	0.735
Cronbach's alpha		0.672							0.857					

Table B1b. Reliability coefficients for all tasks used (second wave).

		Speeded Performance Measures (2nd wave)										
Class		**SP left**	**SP right**	**PD conceptual relation**	**PD part-whole**	**PD resemblance**	**PC verbal**	**PC figural**	**PC numeical**	**CC conceptual relation**	**CC part-whole**	**CC resemblance**
Year 1	**Mean**	696.722	701.445	1584.581	1580.046	1626.531	1971.802	1999.823	2236.288	2134.306	2195.547	1679.563
	N	61	62	61	62	62	55	57	57	62	62	62
	SD	98.253	103.698	468.685	468.784	544.416	711.714	351.803	501.221	739.643	663.131	529.094
Year 2	**Mean**	634.263	646.347	1491.609	1508.993	1582.147	1744.866	1754.988	1856.673	2131.857	2060.851	1723.853
	N	61	61	62	61	62	61	59	62	62	62	62
	SD	97.282	105.059	349.674	367.917	371.464	427.251	365.087	516.732	490.387	573.805	433.506
Year 3	**Mean**	588.014	591.095	1320.183	1267.906	1286.129	1528.300	1528.224	1514.355	1914.132	1689.513	1576.361
	N	74	73	74	74	74	71	73	74	74	74	74
	SD	102.552	93.412	339.588	304.808	285.990	435.279	376.697	335.192	495.053	442.027	392.959
Year 4	**Mean**	566.640	570.300	1155.688	1169.670	1194.016	1438.482	1404.700	1462.350	1645.212	1511.450	1383.609
	N	68	68	68	68	68	65	66	68	68	68	68
	SD	83.651	85.766	259.600	264.848	290.649	408.263	349.600	312.027	441.891	422.204	364.103
Year 5	**Mean**	531.426	537.906	1061.864	1099.153	1059.745	1420.559	1341.681	1454.474	1715.501	1484.684	1370.091
	N	54	54	54	54	54	54	53	54	54	54	54
	SD	80.020	78.204	231.773	258.276	208.705	408.497	369.084	326.084	411.181	392.846	317.495
Year 6	**Mean**	519.017	520.413	966.586	956.370	947.940	1185.979	1081.400	1159.150	1411.616	1282.738	1204.403
	N	72	72	73	73	72	73	73	73	73	73	73
	SD	70.444	68.632	262.294	224.172	237.980	299.554	228.861	233.316	394.704	363.688	356.971
Total	**Mean**	587.951	593.241	1258.472	1256.488	1277.507	1530.827	1500.934	1590.834	1816.049	1693.415	1485.126
	N	390	390	392	392	392	379	381	388	393	393	393
	SD	107.237	108.497	393.479	388.376	418.938	516.713	448.772	505.595	568.829	579.713	442.839
Corrected Item-Total Correlation		0.660	0.664	0.781	0.780	0.793	0.472	0.661	0.677	0.683	0.753	0.638
Cronbach's alpha		0.899										

Information Integration, Working Memory and Reasoning Measures (2nd wave)

Class		WM storage2 CAP	WM executive control1 CAP	WM executive control2 CAP	Information Integration number ACC	induction-verbal	induction-math	induction-spatial	deduction-verbal	deduction-math	deduction-spatial
Year 1	Mean	3.984	2.101	1.871	4.700	0.194	0.078	0.199	0.380	0.071	0.159
	N	62	62	62	61	62	62	61	61	61	61
	SD	1.365	2.219	1.752	1.333	0.172	0.096	0.115	0.164	0.138	0.168
Year 2	Mean	4.409	2.508	1.899	4.730	0.356	0.225	0.246	0.421	0.148	0.235
	N	62	62	62	62	61	61	61	61	61	61
	SD	1.112	2.391	2.037	1.611	0.149	0.170	0.165	0.210	0.232	0.214
Year 3	Mean	4.649	3.160	2.617	5.860	0.375	0.479	0.378	0.502	0.366	0.460
	N	75	75	75	74	71	71	71	71	71	71
	SD	0.968	2.464	2.315	1.338	0.160	0.211	0.209	0.177	0.277	0.266
Year 4	Mean	4.770	2.882	2.592	5.250	0.462	0.567	0.314	0.508	0.475	0.490
	N	68	68	68	67	66	66	66	66	66	66
	SD	0.891	2.495	2.331	1.352	0.173	0.211	0.153	0.199	0.315	0.299
Year 5	Mean	4.716	3.810	3.088	5.750	0.513	0.615	0.394	0.569	0.560	0.516
	N	54	54	54	53	53	53	53	53	53	53
	SD	0.910	2.517	2.104	1.343	0.196	0.230	0.198	0.225	0.338	0.266
Year 6	Mean	4.838	4.149	3.750	6.240	0.595	0.671	0.454	0.601	0.694	0.639
	N	74	74	74	71	73	73	73	73	73	73
	SD	0.811	2.481	2.073	1.152	0.189	0.213	0.250	0.198	0.282	0.259
Total	Mean	4.572	3.118	2.660	5.450	0.418	0.445	0.334	0.499	0.392	0.423
	N	395	395	395	388	386	386	385	385	385	385
	SD	1.052	2.517	2.209	1.468	0.215	0.288	0.208	0.209	0.348	0.299
Corrected Item-Total Correlation		0.215	0.460	0.462	0.392	0.526	0.687	0.541	0.470	0.677	0.659
Cronbach's alpha		0.582				0.819					

Table B2a. Correlations between indicators (first wave).

	age	S1	S2	PD1	PD2	PD3	PC1	PC2	PC3	CC1	CC2	CC3	WMs1	WMs2	WMe1	WMe2	II1	II2	II3
age	1																		
S1	-0.50**	1																	
S2	-0.50**	0.92**	1																
PD1	-0.56**	0.60**	0.63**	1															
PD2	-0.60**	0.59**	0.63**	0.85**	1														
PD3	-0.56**	0.57**	0.61**	0.81**	0.82**	1													
PC1	-0.29**	0.30**	0.30**	0.33**	0.37**	0.32**	1												
PC2	-0.58**	0.51**	0.52**	0.57**	0.63**	0.57**	0.44**	1											
PC3	-0.71**	0.55**	0.55**	0.58**	0.63**	0.63**	0.43**	0.67**	1										
CC1	-0.47**	0.58**	0.57**	0.54**	0.50**	0.55**	0.28**	0.41**	0.51**	1									
CC2	-0.53**	0.56**	0.58**	0.53**	0.48**	0.45**	0.14	0.36**	0.45**	0.72**	1								
CC3	-0.52**	0.55**	0.54**	0.53**	0.49**	0.54**	0.20	0.39**	0.51**	0.72**	0.70**	1							
WMs1	0.43**	-0.28**	-0.31**	-0.25**	-0.28**	-0.28**	-0.08	-0.25**	-0.34**	-0.27**	-0.27**	-0.27**	1						
WMs2	0.30**	-0.28**	-0.36**	-0.23*	-0.26**	-0.22*	-0.14	-0.19*	-0.32**	-0.23*	-0.25**	-0.26**	0.41**	1					
WMe1	0.29v	-0.14	-0.12	-0.15	-0.15	-0.21*	-0.17	-0.34**	-0.29**	-0.08	-0.07	-0.05	0.33**	0.23*	1				
WMe2	0.54**	-0.36**	-0.33**	-0.38**	-0.33**	-0.31**	-0.22*	-0.36**	-0.39**	-0.25**	-0.33**	-0.30**	0.21*	0.15	0.31*	1			
II1	0.22*	-0.13	-0.15	-0.08	-0.05	-0.13	-0.32**	-0.19*	-0.24**	-0.17	-0.16	-0.09	0.17	0.18*	0.25**	0.33**	1		
II2	0.29**	-0.15	-0.12	-0.10	-0.10	-0.12	-0.14	-0.15	-0.18	-0.09	-0.12	-0.12	0.23*	0.25**	0.25*	0.19	0.47**	1	
II3	0.12	0.02	-0.04	-0.06	-0.08	-0.04	-0.08	-0.15	-0.15	0.03	-0.02	-0.05	0.13	0.25**	0.13	0.15	0.26**	0.37**	1
IV	0.67**	-0.21*	-0.26**	-0.34**	-0.42**	-0.33**	-0.34**	-0.44**	-0.51**	-0.32**	-0.34**	-0.25**	0.22*	0.25**	0.22*	0.45**	0.35**	0.22*	0.16
IM	0.60**	-0.39**	-0.42**	-0.39**	-0.39**	-0.36**	-0.30**	-0.44**	-0.47**	-0.26**	-0.32**	-0.25**	0.27**	0.37**	0.40**	0.47**	0.32**	0.29**	0.22**
IS	0.33**	-0.13	-0.17	-0.19*	-0.21*	-0.22	-0.28**	-0.34**	-0.30**	-0.13	-0.14	-0.13	0.21*	0.26**	0.33**	0.35**	0.37**	0.38**	0.17
DV	0.32**	-0.10	-0.15	-0.20*	-0.29**	-0.16	-0.11	-0.22*	-0.19*	-0.04	-0.16	-0.03	0.02	0.01	0.05	0.24**	0.08	0.03	0.01
DM	0.49**	-0.13	-0.18	-0.25**	-0.29**	-0.32**	-0.30**	-0.36**	-0.41**	-013	-0.17	-0.10	0.19*	0.26**	0.21**	0.40*	0.42**	0.26**	0.25**
DS	0.67**	-0.36**	-0.38**	-0.48**	-0.49**	-0.49**	-0.26**	-0.48**	-0.59**	-0.31**	-0.35**	-0.32**	0.27**	0.32**	0.27**	0.34**	0.37**	0.21	0.16

	IV	IM	IS	DV	DM	DS
IV	1					
IM	0.59**	1				
IS	0.48**	0.52**	1			
DV	0.43**	0.36**	0.42**	1		
DM	0.58**	0.55**	0.53**	0.32**	1	
DS	0.59**	0.59**	0.53**	0.39**	0.66**	1

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

Table B2b. Correlations between indicators (second wave).

	age	S1	S2	PD1	PD2	PD3	PC1	PC2	PC3	CC1	CC2	CC3	WMs2	WMe1	WMe2	II2	IV	IM	IS
age	1																		
S1	-0.55**	1																	
S2	-0.55**	0.87**	1																
PD1	-0.57**	0.59**	0.58**	1															
PD2	-0.56**	0.49**	0.53**	0.79**	1														
PD3	-0.59**	0.56**	0.56**	0.77**	0.78**	1													
PC1	-0.47**	0.32**	0.38**	0.39**	0.38**	0.37**	1												
PC2	-0.64**	0.53**	0.52**	0.53**	0.49**	0.54**	0.46**	1											
PC3	-0.63**	0.47**	0.48**	0.49**	0.51**	0.51**	0.49**	0.68**	1										
CC1	-0.45**	0.44**	0.46**	0.57**	0.61**	0.59**	0.28**	0.42**	0.45**	1									
CC2	-0.55**	0.58**	0.59**	0.62**	0.66**	0.65**	0.35**	0.52**	0.53**	0.63**	1								
CC3	-0.41**	0.44**	0.43**	0.58**	0.57**	0.58**	0.21**	0.38**	0.35**	0.68**	0.58**	1							
WMs2	0.24**	-0.18**	-0.15**	-0.22**	-0.18**	-0.21**	-0.21**	-0.21**	-0.23**	-0.16**	-0.18**	-0.09	1						
WMe1	0.26**	-0.20**	-0.19**	-0.11*	-0.10*	-0.10	-0.22**	-0.18**	-0.29**	-0.07	-0.20**	-0.08	0.16**	1					
WMe2	0.28**	-0.22**	-0.20**	-0.15**	-0.16**	-0.17**	-0.23**	-0.21**	-0.23**	-0.15**	-0.25**	-0.13*	0.12*	0.44**	1				
II2	0.33**	-0.20**	-0.21**	-0.20**	-0.20**	-0.21**	-0.29**	-0.26**	-0.28**	-0.15**	-0.23**	-0.10*	0.23**	0.30**	0.32**	1			
IV	0.58**	-0.31**	-0.33**	-0.39**	-0.38**	-0.38**	-0.37**	-0.42**	-0.44**	-0.31**	-0.40**	-0.26**	0.27**	0.26**	0.27**	0.26**	1		
IM	0.71**	-0.45**	-0.45**	-0.42**	-0.44**	-0.44**	-0.43**	-0.51**	-0.54**	-0.30**	-0.43**	-0.26**	0.26**	0.28**	0.32**	0.37**	0.50**	1	
IS	0.38**	-0.27**	-0.26**	-0.25**	-0.23**	-0.24**	-0.29**	-0.35**	-0.34**	-0.20**	-0.28**	-0.09	0.23**	0.25**	0.20**	0.34**	0.36**	0.42**	1
DV	0.36**	-0.26**	-0.26**	-0.26**	-0.22**	-0.25**	-0.25**	-0.35**	-0.27**	-0.21**	-0.24**	-0.16**	0.12*	0.24**	0.23**	0.19**	0.29**	0.35**	0.31**
DM	0.63**	-0.38**	-0.40**	-0.37**	-0.37**	-0.41**	-0.31**	-0.46**	-0.47**	-0.32**	-0.41**	-0.25**	0.28**	0.29**	0.28**	0.36**	0.42**	0.61**	0.47**
DS	0.53**	-0.33**	-0.32**	-0.35**	-0.37**	-0.38**	-0.33**	-0.48**	-0.48**	-0.30**	-0.42**	-0.25**	0.25**	0.29**	0.24**	0.32**	0.39**	0.56**	0.45**

	DV	DM	DS
DV	1		
DM	0.38**	1	
DS	0.43**	0.54**	1

**Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed).

Table B3a. Correlations between indicators (first wave).

	SP	PD	PC	CC	WMs	WMe	II	IND	DED
SP	1								
PD	0.66**	1							
PC	0.53**	0.63**	1						
CC	0.64**	0.60**	0.46**	1					
WMs	-0.31**	-0.33**	-0.41**	-0.26**	1				
WMe	-0.28**	-0.33**	-0.40**	-0.23*	0.94**	1			
II	-0.13	-0.11	-0.27**	-0.13	0.37**	0.35**	1		
IND	-0.32**	-0.41**	-0.53**	-0.32**	0.45**	0.53**	0.44**	1	
DED	-0.29**	-0.46**	-0.51**	-0.27**	0.36**	0.37**	0.38**	0.77**	1

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

Table B3b. Correlations between indicators (second wave).

	SP	PD	PC	CC	WMs	WMe	II	IND	DED
SP	1								
PD	0.62**	1							
PC	0.54**	0.60**	1						
CC	0.59**	0.75**	0.53**	1					
WMs	-0.26**	-0.21**	-0.36**	-0.23**	1				
WMe	-0.24**	-0.17**	-0.32**	-0.20**	0.97**	1			
II	-0.20**	-0.22**	-0.33**	-0.19**	0.39**	0.36**	1		
IND	-0.46**	-0.49**	-0.63**	-0.43**	0.45**	0.40**	0.41**	1	
DED	-0.43**	-0.46**	-0.57**	-0.43**	0.43**	0.39**	0.38**	0.71**	1

**Correlation is significant at the 0.01 level (2-tailed).

APPENDIX C

Table C1. Analysis of the reasoning tasks based on three parameters: Semantics, Procedure and Mental Constructs.

Item	Rasch Item Estimate	Number of Concepts	Linearity	Mental Rules	Number of Constraints Imposed	Number of Constraints Simultaneously Mastered	Mental Models	Complexity Value	Complexity Level
IVLc$_1$	-1.48	3	1	1	2	3	2	137.89	1
IVLc$_2$	0.29	3	1	2	2	3	2	250.56	2
IVLc$_3$	1.27	3	1	4	2	3	4	973.78	3
IVAc$_1$	-1.53	3	1	1	1	2	2	59.97	1
IVAc$_2$	-1.48	3	1	1	1	2	2	59.97	1
IMLc$_1$	-1.82	3	1	2	2	2	1	84.92	1
IMLc$_2$	0.40	3	1	2	3	3	3	551.95	3
IMLc$_3$	-0.50	3	1	2	3	3	2	368.42	2
IMLc$_4$	0.62	4	1	2	4	3	2	492.07	3
IMAc$_1$	-1.25	2	2	1	3	3	1	101.99	1
IMAc$_2$	-0.59	2	2	2	3	3	2	373.68	2
IMAc$_3$	0.25	2	2	3	3	3	2	551.68	3
ISLc$_1$	-2.19	2	2	2	2	2	1	88.33	1
ISLc$_2$	1.79	2	2	2	3	3	4	745.22	3
ISLc$_3$	2.20	2	2	2	4	3	4	981.24	3
ISLc$_4$	2.02	2	2	2	4	3	5	1226.12	4
ISAc$_1$	-1.12	2	1	2	3	3	1	182.85	2
ISAc$_2$	-0.46	2	1	2	4	3	1	243.02	2
ISAc$_3$	0.58	3	2	2	4	4	1	339.70	2
DVLc$_1$	0.74	2	1	3	2	4	3	728.68	3
DVLc$_2$	-0.64	2	1	2	2	4	3	490.26	3
DVLc$_3$	-0.25	2	1	2	2	4	3	490.26	3
DVLc$_4$	-1.25	2	1	2	2	4	3	490.26	3
DVLc$_5$	-0.31	2	1	2	2	4	4	653.61	3
DVLc$_6$	0.24	2	1	2	2	4	4	653.61	3
DMLc$_1$	-0.32	2	1	2	2	3	2	245.31	2
DMLc$_2$	-0.07	3	1	7	3	2	5	2113.63	4
DMLc$_3$	1.38	4	1	9	3	2	6	3261.99	4
DSLc$_1$	-1.64	2	1	3	4	2	1	243.67	2
DSLc$_2$	0.67	2	1	2	7	2	2	564.46	3
DSLc$_3$	1.45	2	1	4	7	2	3	1689.48	4

An example of a deductive reasoning task analysis

1st	2nd	3rd	4th

- There is no even number.
- No number is written twice.
- If the second number is the smallest, then the fourth number is the biggest of all one-digit numbers.
- The second number is either 1 or 3.
- If the second number is 1, then the third number is either 5 or 7.
- The third number is either 5 or 7.
- If the third number is 7, then the smallest number used is 1.
- The smallest number used is 3.
- If the difference between the first and the second number is equal to 4, then the difference between the third and the fourth number is equal to 4 and if the difference between the third and the fourth number is equal to 4, then the difference between the first and the second number is equal to 4.

Each of the 3 parameters (Semantics, Procedure and Mental Constructs) analyzed in 2 aspects (Sa, Sb, Pa, Pb, Ma, Mb)

How values are assigned to each parameter's aspects:
Sa: value = the number of concepts
Sb: value = 1 if the relationship between the concepts is linear
value = 2 if non-linear relationship
Pa: value = the sum of weighted values assigned to the rules (non-reiterating)
value = 1 for negation or conjunction or disjunction
value = 2 for Modus Ponens or Modus Tollens
value = 3 for Affirming the Consequent or Denying the Antecedent
Pb: value = maximum number of constraints originally imposed from the premises
number or premises which explicitly give information are not accounted
Ma: value = number of logical constraints simultaneously mastered
Mb: value = number of models constructed (or autonomous logical steps taken)

Semantics: the product of Sa and Sb values
Procedure: the product of Pa and Pb values
Mental Constructs: the product of Ma and Mb values

Semantics:

Sa: Number of Concepts-Variables – Dimensions: 4
(One-digit numbers (0-9), number comparison (bigger, smaller number), odd and even number, difference)

Sb: Relation between concepts: 1
Linear relation

Procedure:

Pa: Logic rules to be applied: 9
Negation: 1
Disjunction: 1
Modus Ponens: 2
Modus Tollens: 2
Affirming the Consequent (avoiding fallacies): 3

Pb: Maximum number of constraints originally imposed: 3
P3: If the second number is the smallest, then the fourth number is the biggest of all one-digit numbers.
P5: If the second number is 1, then the third number is either 5 or 7.
P9: If the difference between the first and the second number is equal to 4, then the difference between the third and the fourth number is equal to 4 and if the difference between the third and the fourth number is equal to 4, then the difference between the first and the second number is equal to 4.

Mental Constructs:

Ma: number of constraints simultaneously mastered: 2
(a disjunction and a negation)

Mb: Deductive Models to be constructed based on the Premises (P1 – P9): 6

1st model (reading-scanning the premises)
P1: There is no even number
P2: No number is written twice
P3: If the second number is the smallest, then the fourth number is the biggest of all one-digit numbers
P4: The second number is either 1 or 3
P5: If the second number is 1, then the third number is either 5 or 7
P6: The third number is either 5 or 7
P7: If the third number is 7, then the smallest number used is 1
P8: The smallest number used is 3
P9: If the difference between the first and the second number is equal to 4, then the difference between the third and the fourth number is equal to 4 and if the difference between the third and the fourth number is equal to 4, then the difference between the first and the second number is equal to 4
P1 and P2 set general constraints that will be imposed on all subsequent models
P1: There is no even number
P2: No number is written twice

2nd model (reading-scanning the premises not used yet)
P3: If the second number is the smallest, then the fourth number is the biggest of all one-digit numbers
P4: The second number is either 1 or 3
P5: If the second number is 1, then the third number is either 5 or 7
P6: The third number is either 5 or 7
P7: If the third number is 7, then the smallest number used is 1
P8: The smallest number used is 3
P9: If the difference between the first and the second number is equal to 4, then the difference between the third and the fourth number is equal to 4 and if the difference between the third and the fourth number is equal to 4, then the difference between the first and the second number is equal to 4

P8: The smallest number used is 3
P4: The second number is either 1 or 3
So, the second number is 3

	3		

3rd model (reading-scanning the premises not used yet)
P3: If the second number is the smallest, then the fourth number is the biggest of all one-digit numbers
P5: If the second number is 1, then the third number is either 5 or 7
P6: The third number is either 5 or 7
P7: If the third number is 7, then the smallest number used is 1
P9: If the difference between the first and the second number is equal to 4, then the difference between the third and the fourth number is equal to 4 and if the difference between the third and the fourth number is equal to 4, then the difference between the first and the second number is equal to 4

P7: “If the third number is 7, then the smallest number used is 1”
The P8 premise (P8: The smallest number used is 3) states that the consequent of the conditional in P7 is false (since the smallest number used is 3), so, based on Modus Tollens inference, the antecedent is also false.
Outcome: “The third number is not 7”

4th model (reading-scanning the premises not used yet)
P3: If the second number is the smallest, then the fourth number is the biggest of all one-digit numbers
P5: If the second number is 1, then the third number is either 5 or 7
P6: The third number is either 5 or 7
P9: If the difference between the first and the second number is equal to 4, then the difference between the third and the fourth number is equal to 4 and if the difference between the third and the fourth number is equal to 4, then the difference between the first and the second number is equal to 4

Based on the outcome of the previous model, “The third number is not 7”, P6 is used to extract which is the third number.
P6: The third number is either 5 or 7
So, the third number is 5

	3	5	

5*th model (reading-scanning the premises not used yet)*
P3: If the second number is the smallest, then the fourth number is the biggest of all one-digit numbers
P5: If the second number is 1, then the third number is either 5 or 7

P9: If the difference between the first and the second number is equal to 4, then the difference between the third and the fourth number is equal to 4 and if the difference between the third and the fourth number is equal to 4, then the difference between the first and the second number is equal to 4

P3: If the second number is the smallest, then the fourth number is the biggest of all one-digit numbers
This conditional has its antecedent true since it is stated in P8 that "The smallest number used is 3" and it was extracted in the 2nd model that the second number is number 3.
So, based on the Modus Ponens inference, since the antecedent is true the consequence is true too. Thus, the fourth number is the biggest of all one-digit numbers, i.e. number 9 (an outcome that agrees with the constraint P1: There is no even number)

	3	5	9

6th *model (reading-scanning the premises not used yet)*
P5: If the second number is 1, then the third number is either 5 or 7
P9: If the difference between the first and the second number is equal to 4, then the difference between the third and the fourth number is equal to 4 and if the difference between the third and the fourth number is equal to 4, then the difference between the first and the second number is equal to 4

P9: If the difference between the first and the second number is equal to 4, then the difference between the third and the fourth number is equal to 4 and if the difference between the third and the fourth number is equal to 4, then the difference between the first and the second number is equal to 4
Based on the biconditional in P9, the following outcome is produced:
Outcome: The difference between the third and the fourth number is equal to 4, so the difference between the first and the second number is equal to 4. Since the second number is number 3, it is concluded that the first number is number 7.

7	3	5	9

Note: The premise P5 "If the second number is 1, then the third number is either 5 or 7" is not used since it is a fallacy (Affirming the Consequent)