University of Cyprus
Department of Psychology

Cognitive Function and Sport: Evaluation of the Cognitive Skills that Relate to Tennis Success

Demetra T. Theocharous

University of Cyprus, Nicosia

Thesis Defense

Supervisor: Prof. Marios Avraamides

30 May 2023

Acknowledgments

I would like to express my appreciation to my supervisors Professor Marios Avraamides and Dr. Andria Shimi for their support and cooperation to conduct my Thesis Project. I am pleased they provided me with their knowledge and guidance throughout the research process.

I am also thankful to Herodotou Tennis Academy, Charalambides Tennis Academy and all the people for voluntarily participating in the study.

I also thank my family and friends who supported me and believed in my abilities.

Contents

Abstract

The purpose of the study was to examine the relation between different cognitive skills and athletic performance in tennis players. Specifically, I aimed to investigate attention (alerting, orienting, executive control), reaction speed and visual search capacity, in tennis players and controls. The study consisted of 36 participants (boys and girls), aged 14-16 years, where 18 children were tennis players and 18 were non-players. They were classified into two groups, based on their engagement in tennis. They carried out 3 computerized tasks, each assessing different cognitive skills. The Attention Network Test (ANT) assessed the three networks of attention, namely alerting, orienting, and executive control. The Whack-a-Mole task evaluated inhibitory control of attention, by measuring performance in a classic Go/No-Go task and tapping on response inhibition. The Visual Search task examined reaction time performance as well as visual search processes. A Virtual Reality task (Reaction Speed Task) was also administered to evaluate reaction time. A Repeated Measures Analysis of Variance (ANOVA) revealed an interaction between group and the VR task's difficulty level, showing that although tennis players were faster than non-athletes at all task difficulty levels, the difference was larger at the easier level of 9 discs. Also, Independent Samples T-Tests showed that athletes exhibited lower reaction time to respond to targeted stimuli than non-athletes in the Whack-a-Mole task. Furthermore, the years of tennis experience was associated with the performance in the Whack-a-Mole task, the Reaction Speed task, and the Visual Search task (at set size 2). In addition, the frequency of tennis training was also correlated with the performance in the Whack-a-Mole task and in the Reaction Speed task. These findings support the idea that even from a young age athletes have more advanced cognitive skills than non-athletes.

Cognitive Function and Sport: Evaluation of the Cognitive Skills that Relate to Tennis Success

Physical exercise has important benefits for brain function, mental and physical health, as well as for psychological and social development (Diamond, 2013; Hernández-Mendo et al., 2019; Meijer et al., 2020). Therefore, popular sports like tennis attract scientists who are interested in understanding how the benefits of physical exercise come about.

Overall, children and adolescents who play tennis have been shown to have increased academic achievement, better health, and more advanced executive functions (EFs) (Davis et al., 2011; Hernández-Mendo et al., 2019; Meijer et al., 2020). The focus of the proposed study is to examine how cognitive skills, such as EFs, influence performance in tennis.

Tennis is an externally paced interceptive sport in which sharp reflexes and cognitive engagement (i.e., response accuracy to fast-paces shots, effortful problem solving, and inhibition of irrelevant actions and stimuli) are required (Jacobson & Matthaeus, 2014; Singer, 2000; Voss et al., 2010; Wang et al., 2013). Situations in a tennis match are often unpredictable as the environment is dynamic, and factors external to the performer (e.g., returning a serve) set the time of execution of particular actions. It relies much on rapid responses to unpredictable stimuli (Culpin, 2018) and requires flexibility in visual attention and hand-eye coordination (Jacobson & Matthaeus, 2014; Wang et al., 2013; Yu & Liu, 2020). Targeted tennis training, which includes the practice of unexpected situations that may occur in the tennis match, has been shown to help the development of skilled performance (Singer, 2000). In general, the literature on the involvement of cognitive functions to elite performance in tennis, suggests that three cognitive skills are of paramount importance: the inhibitory control of attention, reaction time and visual search.

Inhibitory control of attention is a core executive function that refers to the suppression of attention to irrelevant information while responding to stimuli that are central for achieving the desired goal (Diamond, 2013; Ishihara, Sugasawa, Matsuda, & Mizuno, 2017b; Jacobson & Matthaeus, 2014; Meijer et al., 2020). Past research supports that the inhibitory control of attention enables players to sufficiently cope, and in the appropriate manner, with the unpredictable and demanding requirements of a tennis match. Inhibitory control is considered an endogenous process requiring the top-down regulation of attention (Buck, Hillman, & Castelli, 2008; Diamond, 2013; Ishihara et al., 2017; Ishihara & Mizuno, 2018; Wang et al., 2013; Yu & Liu, 2020).

A study with a sample of young adult tennis players of 18-24 years of age evaluated inhibition across high-skilled players, recreational athletes, and non-athletes (Jacobson & Matthaeus, 2014). Participants were administered the D-KEFS Color-Word Interference Test, a modified Stroop Task that assesses the inhibition of a salient verbal response to a stimulus. Additionally, participants responded to a vocabulary test that was used to control overall intelligence, a construct that correlates strongly with EF measures (Jacobson & Matthaeus, 2014). Results revealed that high-skilled players outperformed non-athletes in inhibitory control but did not score higher than recreational athletes. A possible explanation for this finding is that high-skilled and recreational athletes may not differ substantially in experience and in the hours they dedicate for training. They were grouped based on their athletic status (varsity or non-varsity athletes) which is a considerably limited indicator of sport level, according to the authors. In addition, it was not controlled whether participants were also engaged in any extracurricular activities, such as music and dance that are known to contribute to improvements in EFs.

A study by Wang et al. (2013) also examined the relationship between inhibitory control and the performance in tennis, in 18-22-year-old male players and sedentary non-athletic controls. The tennis players were members of the varsity tennis team with a mean experience of 5,5 years and participating in an ongoing training program of 3 hours per day for 3 or more days a week. The controls had no engagement in any sport. The participants' level of physical activity was evaluated through a 7-day physical activity recall questionnaire as well as by measuring their VO2max, an index of aerobic fitness. Both groups were also measured for their BMI (Body Mass Index) and they were administered the Stop Signal Task which assesses the ability to respond quickly to "go" trials and suppress a response to "no go" trials. Results showed that the tennis players exhibited greater inhibitory control compared to the control group, as indexed by shorter stop-signal reaction times (SSRTs). This was also the case even after controlling for potential confounding variables such as training experience, physical activity, and BMI, which is reported to be negatively associated with inhibitory control.

Overall, past results show that there is a performance advantage in inhibitory control, observed even in tasks, like the D-KEFS and the Stop Signal, which are not sport-specific. Indeed, it is suggested that sport-related enhancements in the inhibition of attention can still be observed out of the sport-specific context, depending on the sport type (Vaughan & Laborde, 2021; Wang et al., 2013). A meta-analysis by Voss et al. (2010) found an advantage in laboratory cognitive tests without employing sport-specific designs, especially for externally paced sports that require both physical and cognitive demands.

Supportive findings for the relation between aerobic fitness and inhibitory control are reported by a cross-sectional study done by Buck et al. (2008). In their study, 7–12-year-old non- athlete children completed a paper and pencil version of the Stroop Color Word Test, as the measure for inhibition. The FITNESSGRAM was used to assess different components of physical fitness (i.e. aerobic capacity through PACER test, muscle fitness, BMI score). IQ data were also collected as well as health and personal demographics, to take into consideration other factors that may influence the relationship between physical fitness and inhibitory control.

Results indicated that older children and those with higher IQ responded to more items correctly on each of the three conditions of the Stroop task (word, color, color–word). In addition, there was a positive correlation between aerobic fitness and performance on all the three Stroop conditions, regardless of the other variables. Specifically, children who ran more laps on the PACER test, showing better physical condition, read more stimuli successfully during the whole task than those children who ran fewer laps. Findings suggest that increased levels of physical fitness relate to better executive function, especially in preadolescence. Specifically, the children who were fitter demonstrated better performance in inhibitory control of attention, independently of the amount of executive function required. The literature indicates that inhibitory attentional control is related to performance in tennis, since the ability to inhibit prepotent actions is vital for attaining success. Consider a player who can suppress a response if the ball is going out of bounds and is generally able to avoid executing unnecessary or incorrect actions (Wang et al., 2013). Therefore, that player is in a position to commit fewer errors in the tennis match.

As it is apparent in the literature, the relation between exercise and cognition may change across the lifespan (Buck et al., 2008). Particularly in children, improvement in tasks requiring executive control has been associated with the development of the frontal lobe (Buck et al., 2008; Chaddock et al., 2011). That is why during adolescence children demonstrate difficulties in ignoring irrelevant stimuli due to their poor inhibitory control which is not fully developed until this time (Buck et al., 2008). Generally, physical exercise promotes neurocognitive processes and neural mechanisms that support performance and learning processes (Davis et al., 2011; Meijer et al., 2021). Enhanced white matter structures in the frontal lobes mediate the physical activity and the higher-level performance on EFs (Meijer et al., 2021). Nevertheless, not only physical exercise is involved in the cognitive function in childhood through neural integrity, but also conscious mental engagement and goal-oriented efforts from the children, are still important for cognitive development (Davis et al., 2011; Hillman et al., 2008).

Another cognitive process that has been shown to relate to performance in tennis is working memory (Diamond, 2013; Furley & Memmert, 2010). Working memory is also a core executive function that refers to the temporary storage of information in connection with the performance of other cognitive tasks such as learning, problem-solving or reading (Baddeley, 2008). It According to Logie & Baddeley (1999), working memory comprises multiple specialized components of cognition that allow humans to comprehend and mentally represent their immediate environment, to retain information about their recent experience, to support the acquisition of new knowledge, to solve problems, and to formulate, relate, and act on current goals.

Ishihara et al. (2017) examined the relation between cognitively engaging activities (coordination and game-based exercises), executive functions (inhibitory control, working memory) and levels of physical fitness in 6–12-year-old children. Prior to the study, the children regularly participated in tennis lessons (once a week, mean ± SD = 2.55 ± 1.61 years). Physical fitness was evaluated by using the Tennis Field Test which measures performance on the tennis court. Inhibitory control was assessed by the Stroop Color and Word Test and working memory with the 2-back task. Also, participants followed instructional activities/tennis lessons, including coordination training, game-based exercise, rallying, and non-physical exercise that included instructions and breaks. An observer recorded the duration of time spent in each of the activities while heart rate was measured using an HR monitor.

Specifically, game-based exercise consisted of cognitively engaging gaming, such as following and playing using one side stroke (only forehand or backhand). Coordination training consisted of unautomated skills requiring top-down cognitive processes, such as following, self-rallying with the nondominant hand, self-rallying behind the back or under the leg, and playing catch using 2 balls. Rallying contained many restrictions (e.g., using only forehand or backhand) and the player continually aimed at the permitted side to keep up the rallying. Therefore, rallying required less cognitive engagement than gaming.

The findings showed that the duration of game-based exercise was positively correlated with inhibitory control and physical fitness, where coordination training was associated with better working memory. The non-physical exercise was negatively associated with working memory, inhibitory control, and physical fitness. Again, it is suggested that the participation in game-based tennis lessons results in improvements on inhibition and in physical condition levels, as well as the longer duration of involvement with coordination training leads to improved working memory. Both game-based exercise and coordination training facilitated executive function more than the other types of training. In summary, results indicated that shortened non-physical activity time within a sports setting is associated with improvements in EFs and physical fitness (Ishihara et al., 2017).

Past research supports that physical activity that involves high cognitive engagement and high physical exertion (e.g., team games, coordinative exercise) lead to greater improvement in cognitive skills, than engagement with sports that rely less on cognition (e.g. circuit training, aerobic exercise) (Budde, Voelcker-Rehage, Pietraßyk-Kendziorra, Ribeiro & Tidow, 2008; Schmidt, Jäger, Egger, Roebers & Conzelmann, 2015). The cognitive skills that tennis requires from the player to manage the game, such as to be able to move effectively across the court and hit the ball accurately (e.g., strategic behavior, superior anticipation, decision-making capacities) may contribute to improved inhibitory control and working memory (Ishihara et al., 2017; Lineweaver et al., 2020). It is worth noting that these executive functions are more sensitive to the effects of physical exercise than other cognitive functions are, according to Best (2010) and Hillman et al. (2014). From the findings of the literature reviewed by Best (2010), who focused on the relationship between executive function and exercise type, it can be assumed that strategic play in team games, coordinative exercise, and non-automatized exercise, involve similar cognitive processes of those engaged in executive function tasks.

In another study, a tennis training program was adopted to assess its effect on executive functions and the relationships of daily moderate-to-vigorous physical activity (MVPA), physical competence, and enjoyment of playing tennis to executive functions in 6–11-year-old children (Ishihara & Mizuno, 2018). Participants had previous tennis experience once a week (mean ± SD = 3 ± 2 years) and they were randomly assigned to 2 groups, based on the frequency of physical activity they would follow in the program. The "low dose" group received training for 1 time per week while the "high dose" group for 4 times. The intervention lasted for 12 months. Specifically, researchers examined inhibitory control of attention by using a modified Stroop task, working memory with the 2-back Task, and attention shifting, which is an aspect of cognitive flexibility, with the Local Global Task-switching condition. LGT measures the ability to either identify the global features of a stimulus or concentrate on the specific details, to engage in attentional switching (Navon, 1977). Children's daily MVPA including tennis play was assessed using triaxial accelerometers while their physical competence and enjoyment of tennis play were assessed through questionnaires. All measurements were collected before and after the intervention.

Results demonstrate greater improvement in working memory (faster reaction time in the n-back) for the "high dose" group as it was evaluated from the measures at baseline and post-intervention. While there were no significant differences in reaction time at baseline between the groups, at post-intervention the "high dose" children performed faster in the task compared both to their "low-dose" peers and to their own baseline measures. Also, there was an improvement in cognitive flexibility measures. That is, a change in reaction time on the Local Global Task-switching condition as the daily MVPA levels increased. That is, increases in overall MVPA in daily life, including greater tennis experience, were associated with better cognitive flexibility. Results also showed that a positive change in perceived physical competence was associated with reduction in reaction time on the 2-back Task, and with an increase in accurate responses on the Local-global Task- switching condition. Likewise, enjoyment correlated positively with accuracy on the Stroop task-incongruent condition, showing that greater physical competence and enjoyment of the tennis activity was associated with improvements in inhibitory control, working memory and cognitive flexibility. To summarize the findings, longer sessions and intense physical activity are associated with benefits on executive functions.

In addition to these findings, Ishihara et al. (2017) claim that, even physically active children should increase the frequency of exercise to expect enhancement and development in EFs. At the same time, higher enjoyment and physical competence are linked to positive emotions during tennis play which alongside with regular engagement in exercise, have the potential to improve executive functions in children. Therefore, a suggestion is that future training programs should also focus on enhancing (positive) emotional, social, and physical needs that can support the development of those core cognitive components. Higher physical competence and enjoyment are related to fun, confidence and sociality during tennis play that can contribute in EFs development, whilst negative emotions (stress, loneliness, sadness) are known to impair their development (Diamond & Lee, 2011).

Hillman et al. (2014) examined a 9-month physical activity intervention program on preadolescent children (8-9 years) to assess the effect of the intervention on brain and behavioral indices of executive function. Participants were randomly assigned to the intervention condition or to the wait-list group. Aerobic fitness was assessed using a test that evaluates maximal oxygen consumption. By using a modified Flanker Task, researchers collected data regarding attentional inhibition and by using a Color-Shape Switch Task they assessed cognitive flexibility. In addition, EEG activity was recorded during the cognitive tasks. The afterschool intervention program focused on the improvement of aerobic fitness through involvement in interesting physical activities for the children.

The children participated in 70 minutes of MVPA, of which 30-40 minutes included physical activities, and then played games focusing on motor skill development. The activities were aerobically demanding but also practiced motor skills. Results showed that there was a greater improvement in fitness in the intervention group than the control, from pretest to posttest measures. Likewise, a beneficial effect was observed in the intervention group in both inhibition and cognitive flexibility, compared to controls. Brain function during task performance (inhibition, cognitive flexibility) was also improved and correlated positively with intervention attendance. The researchers argued that those findings provide evidence of a causal effect of physical activity training programs on EFs, and that future work should emphasize improving childhood cognition though physical training.

A study by Wang et al. (2016) investigated differences in alerting, orienting and executive network in table tennis athletes and non-athlete college students, by using the

ANT. The ANT provides scores for the alerting network which refers to the maintenance of arousal and sustained vigilance, for the orienting network which relates to the selection of information from multiple sensory inputs, and for the executive control network that is related to the ability to monitor and resolve conflict (Fan et al., 2002). In essence, the executive network measures the inhibitory control of attention, which in previous studies was evaluated with different measurements and tasks. Results showed a positive correlation between executive control and athletic ability, suggesting that the table tennis players have enhanced executive control of attention; however, no relationship was found between athletic ability and either alerting or orienting. A possible explanation for the positive relationship, may be due to the cognitive effects of physical exercise while at the same time the involvement in cognitively demanding environments (table tennis and tennis training) serve a superior advantage to induce neural and cognitive benefits, rather that exercise alone.

A selective positive effect of physical exercise on the executive network was also evident in the work of Pérez et al. (2014). The purpose of the study was to examine whether chronic physical activity improves attentional control in young healthy adults. Participants were categorized in physically active v. inactive groups based on a self-reported questionnaire about their physical exercise level. A difference was only observed between the active and inactive groups for the executive network, whilst no differences were found for the alerting and the orientation network.

Research in primary school-aged children revealed useful findings about cardiovascular fitness and executive function (Meijer et al., 2021). A large sample of healthy children (n = 814) were examined using a set of EF and lower-level neurocognitive function measures. They performed a series of computerized neurocognitive tasks and passed a cardiovascular fitness examination that was assessed through a Shuttle Run Test performance. The neurocognitive tasks consisted of the Attention Network Test (ANT) that was used to measure information processing, attention processes, and interference control; the Digit Span Task to assess verbal working memory; the computerized Grid Task (GT) to evaluate visuospatial working memory, and the Stop Signal Task (SST) to measure motor inhibition efficiency. Results showed positive relations between cardiovascular fitness with all the executive function measures; information processing and control, visuospatial working memory, and alerting. In addition, no relationships were found between cardiovascular fitness and verbal working memory, cardiovascular fitness and interference control, cardiovascular fitness, and attention accuracy; indicating that not all the neurocognitive components are equally sensitive to cardiovascular fitness. These data suggest that cardiovascular fitness levels correlate better to specific executive functions, particularly to lower-level functions. An explanation for this is that cardiovascular fitness applies its power only on those brain regions that are involved in these specific executive functions.

Given that other studies have indicated strong effects between those cognitive functions (verbal working memory, interference control, attention accuracy) and physical activity (Buck et al., 2008; Davis et al., 2011; Ishihara et al., 2017; Ishihara & Mizuno, 2018; Wang et al., 2013), Meijer et al. (2021) note that the discrepant findings may be due to the measures administered. Specifically, as Meijer et al. note, previous studies used traditional cognitive tasks (e.g., paper and pencil tasks) or administered measures assessing cognitive functions including aspects of executive functioning, while Meijer et al. used computerized neurocognitive that tap specific executive functions.

Performance in racquet sports, like tennis, is also related and influenced by the ability to react as fast as possible to upcoming and changing stimuli. Reaction time is a psychomotor skill and refers to the time that elapses from when a stimulus appears until a response is given (Kaplan et al., 2019; Kovacs, 2019; Reigal et al., 2019,). That is, reaction time is an accurate measure that evaluates the capacity of the cognitive system to process information (Reigal et al., 2019). The speed with which athletes respond to various stimuli (reaction time) is determined by the speed of the sensorimotor cycle, which includes the detection of the initial stimulus, information transfer through the afferent nerves, response generation from the central nervous system, and final response (Reigal et al., 2019).

High-level tennis players are required to respond to a high-intensity repetitive motor activity in a limited time (e.g., adults react to more than 200km/h serving speed in less than one second, but younger players react in a slower ball speed) (Zhang, 2022). Also, elite players need to meet the maximum levels of speed, mobility, pliability, endurance and power (Zhang, 2022). That is, a good reaction speed is needed to predict the direction of the opponent's move and thus the ball's landing point on the court. In the literature it is shown that internal and external factors influence the reaction time for response (Kaplan et al., 2019; Reigal et al., 2019).

Internal factors are those dependent on the athlete including experience, physical condition, alertness, age, gender, fatigue and the dominance of the body member with which one reacts (Kaplan et al., 2019), whereas external factors describe characteristics of the stimulus, such as its intensity or duration (Reigal et al., 2019). As can be seen from sport literature, the influence of the internal factors and specifically cognitive processes are of major importance, since they determine the reaction time performance (Deary & Der, 2005; Reigal et al., 2019). Attention is one of the main investigated factors involved in reaction speed capacity that allows for the activation and selection processes, as well as the distribution and maintenance of psychological activity. (Chun, Golomb & Turk-Browne, 2011; Grigore et al., 2015; Reigal et al., 2019).

Studies show that physical activity leads to the development of distinct aspects of attention and specifically participation in individual sports, as tennis, are related to shorter reaction time, where shorter reaction time is associated with increased years of experience in the sport (Reigal et al., 2019). Reigal et al (2019) assumes that “regular training and the development of physical condition could have an impact on reaction time, directly by the training of the capacity to respond to a given stimulus and indirectly by the impact it would have on cognitive functioning”. Despite the limited number of studies comparing reaction time in racquet athletes and sedentary controls, there are few findings indicating an association between tennis participation and reduced visual reaction time (Grigore et al., 2015; Kaplan et al., 2019; Turner et al., 2022; Xu et al., 2022). On the contrary novices are found to need longer time to detect and react to stimuli.

Kaplan et al (2019) studied 56 adult volunteers (18-30 years), of whom 36 were racquet athletes (badminton, table tennis, tennis) who participated for at least 2 years and 20 were sedentary controls. Visual as well as auditory reaction time was measured through a software program. Results indicated that between the two groups there was a significantly shorter reaction speed for the racquet players. Although women non-players needed longer visual reaction time than non-athlete men, there was no significant difference across men and women racquet athletes. Jain et al (2015) support that the reaction time difference between men and women who exercise consistently is eliminated and comparable to those of men.

In line with these results, Xu et al (2022) aimed to study the association between tennis experience and executive functions in children, 8-12 years of age. The abilities of inhibitory control, cognitive flexibility and working memory were assessed, through the Stop-signal task, Switching task, and N-back task, respectively. Children were allocated into two groups; a group with less than 12 months training and a group with more than 12 months training. Results indicated that there was no significant association between accuracy or reaction time for the two groups in the Stop-Signal Task. Likewise, there was no significant difference between the two groups for the accuracy variable in the Switching task and in the N-back task. However, the experimental group showed faster reaction time in the Switching task as well as in the N-back task, irrespective of the working memory loads, compared to the control group. According to Grigore et al. (2015) this could be because prolonged tennis training improves players' decision-making abilities and reduces response delay times. Thus, it adapts the mind to intense conditions.

Grigore et al (2015) examined the simple reaction time, the discrimination reaction time, the decision time, the vigilance (alertness) and the sport performance of 12 elite Romanian junior male tennis players, aged between 15 and 17 years with a competitive experience between 6 and 9 years. Results revealed a positive association between the decision time and the performance of the athletes, as seen from their ranking position. Junior players with an experience of 6 to 9 years exhibit fast mental processing speed for identifying the correct stimuli. It is assumed that such mental preparation in training, guided by the coaches, can improve athlete's capacity to rapidly detect the target stimuli and generate response on time (Grigore et al., 2015). They also found a significant association between vigilance and tennis performance. That is, when tennis players generate more accurate answers, keep a reduced number of errors, omissions and delayed responses during tasks that require reaction to a certain event, this aspect is associated with a better performance of the tennis players on the court.

Turner et al (2022) aimed to investigate the role of age and maturation as mediators on the association between tennis experience and cognition in junior beginner to intermediate-level tennis players. Forty-eight tennis players (males =33, females =15) aged between 9-18 years, were tested on processing speed, complex attention and cognitive flexibility, problem-solving capacity, working memory and reaction time. Their results indicate that age and maturation, rather than the exposure to tennis training, are related to cognitive performance for players older than 13 years of age (Turner et al., 2022). These findings suggest that cognitive performance is not linked to tennis experience when controlling age and maturation variables. Additionally, the positive association between tennis experience and cognitive performance is found to be stronger in younger athletes, specifically those under 12 years old, who still have not reached peak maturation. For those, greater tennis experience is related to superior cognitive performance (Turner et al., 2022).

According to the threshold hypothesis, this finding may be due to the reduced growth rate of executive functions in late adolescence into young adulthood. The positive effect of tennis experience on cognitive performance can be rendered to the improvements in executive function that occur between late childhood (7–12 years of age) and early adolescence (13–15 years of age), which are thus entailed with developmental changes in the prefrontal cortex (Turner et al., 2022). In addition, once players have reached a high level of experience or expertise, the further (positive) contribution of tennis to executive functions weakens. That is, although executive functions are positively correlated with the engagement in a sport, this relationship is less strong when a sufficient skill level is acquired (Turner et al., 2022).

Many researchers have studied the impact of visual search skills on advanced performance. They were mostly interested in identifying the visual cues and the visual search patterns and strategies applied by elite tennis players that allow them minimize delays in the perceptual (efficiency of visual search) -cognitive (time of making accurate decision)- motor (movement initiation) process, through of which they maximize anticipation levels, efficiency, and initiation of movement ("Visual Search In Tennis. Crucial Feature for Successful Performance," 2020). According to Wolfe (2020) efficient visual search performance is determined by the ability to guide attention toward relevant cues and the speed at which one rejects distracting stimuli. Additionally, in the visual search performance, a wide range of mechanisms are involved, like peripheral visual acuity, the ability to move the focus of attention, the ability to divide visual attention among multiple tasks and objects and meta-cognitive strategies in coordinating complex activities (Trick & Enns, 1998).

Elite players benefit from their ability to ignore less relevant cues and recognize and focus on the relevant visual ones, a behavior that is guided by the past similar content stored in long-term memory (Murray & Hunfalvay, 2017). Specifically, information in long-term memory, which is the set of past experiences of the task specific repetitions through years of intentional practice, guides attention toward critical cues (Wolfe, 2020). In the case of tennis players, certain game patterns are recalled so the athlete can immediately support the working flow when facing an experience like the one experienced before. As soon as the scene is recognized, the information from long-term memory diverts attention (the gaze) to the important cues to perceive for initiating the perceptual -cognitive- motor process. ("Visual Search In Tennis. Crucial Feature for Successful Performance," 2020).

Gaze control indicates how long and where a person visually focuses prior to engaging in a motor action and it is part of the visual search process (Murray & Hunfalvay, 2017). Translating it into the tennis field, gazing on the meaningful cues for example to opponent's posture orientation makes it easier to extract important data for predicting opponent's movement towards the ball. It allows more time to process essential task-relevant signals and speed up the reaction (ball's shot) and pressuring the opponent **(**Murray & Hunfalvay, 2017; Rosker & Majcen Rosker, 2021)

Tennis players' attention can be relocated in the visual field without making any noticeable eye movements while changing the point of fixation, giving priority to sources of information located outside of the fovea, in the periphery ("Visual Search In Tennis. Crucial Feature for Successful Performance," 2020). Ryu and colleagues (2013) support this by indicating that information being processed through peripheral vision plays a significant role in the combination of perceptual-cognitive-motor performance for athletic success. For a tennis player, this enables to employ fixations between the two points of interest (the current and future position of the opponent and the ball trajectory) and thus identify motion patterns that could finally influence the decision making towards action (“Attention In Tennis-Transition From External To Internal Focus Of Attention”, 2020). Murray (2016) supports that athlete of higher skill level use different visual search strategies than the lesser skilled ones. They employ fixations on different locations in the playing area prior to initiation of a movement, thus minimizing the time needed to extract information about the opponent’s movement and therefore demonstrate better reaction time (Murray, 2016; Rosker & Majcen Rosker, 2021).

Several possible mechanisms may explain the relationship between physical activity and cognition. Those are categorized into physiological mechanisms and learning-developmental mechanisms. Several physiological changes in the brain may be induced by physical exercise, including increased cerebral blood flow, alterations in brain neurotransmitters, changes in the structure of the central nervous system and modified arousal levels (Best, 2010; Sibley & Etnier, 2003). The learning-developmental mechanisms, on the other hand, suggest that movement and physical exercise provide learning experiences which help foster and stimulate cognitive development, especially in early childhood. Also, skills and associations that are learned through exercise can be transferred to the learning of other relationships and concepts (Sibley & Etnier, 2003).

Together, past studies provide evidence that tennis activity, as well as the frequency of engagement in the sport, constitute fundamental variables for improved EFs and thus for reaching sporting success. Physical exercise and habitual practice in the sport improve the skills acquired from a tennis player, as the EFs are the first to be trained. Since participation in tennis requires high cognitive effort, due to its unpredictable environment, it may serve as cognitive training to optimize EFs. It is possible that individuals who develop strong executive control skills are far more likely to engage in physical activities and become athletes (Jacobson & Matthaeus, 2014; Wang et al., 2016). Simultaneously the gradual practice of these cognitive skills leads to further improvements in one's cognitive functionality and performance on the court.

Chronic, even regular engagement in exercise, is a simple means for people to enhance a range of EFs as well as to achieve more enduring improvements in cognition. Better cognitive outcomes result from the combination of aerobic exercise along with tennis training, rather than just exercise alone. Also, the proficient performance in the sport and the high gains in EFs are often reflected and seen in cognitive tasks that require extensive amounts of cognitive control (Chaddock et al., 2011; Lineweaver et al., 2020). Thus, since executive functions are trainable throughout the lifespan, there is the potential to intervene and engage people, especially children and adolescents, in programs aiming to develop their abilities in sports (Diamond, 2013). As inferred by the literature, practice holds the key to improved performance.

Despite the research reviewed above, there are still gaps in the relation of EFs and tennis performance, especially across children and adolescents. More research at those ages is required, since most studies are focused on adults. In addition, there is a need to study athletes of all tennis levels or athletes with different years of tennis experience, to examine whether they do really exhibit performance differences in EFs. To our knowledge there is no past study focusing on children in Cyprus that investigated the relation between tennis and cognitive processes such as inhibition, reaction speed and visual search capacity.

First, I hypothesized that tennis players would exhibit better performance compared to non-players, in a Reaction Speed Task. Secondly, I expected that tennis players would score higher on inhibitory control of attention compared to non-players, in the Whack-a-Mole task. I also estimated that, in a Visual Search Task, tennis players would outperform non-players in visual search capacity. Lastly, the executive control network would be the most likely of the three attentional skills (ANT) to predict successful performance in tennis. In other words, tennis players would exhibit faster reaction time in identifying and resolving cognitive conflicts and exerting cognitive inhibition, compared to the control group. In addition, the relationships between the various mental mechanisms and how they relate to successful tennis performance were examined.

Materials and Methods

Participants

Thirty-six Greek Cypriot children aged 14-16 (13 boys, 23 girls) participated in the study. All children were typically developed with normal or corrected-to normal vision. Participants were classified into athletes and non-athletes based on their engagement in tennis. The experimental group consisted of 18 tennis players (10 boys, 8 girls) whereas the control group consisted of 18 non-players (3 boys, 15 girls). Controls had no athletic engagement or dance participation, for at least the last 5 years, nor any tennis experience ever. Participants were recruited from social media as well as from leaflets that were given to tennis academies in Nicosia and Larnaca.

Materials

Coaches' assessment: An assessment was provided by the coach of each participant in the experimental group (on a 3-point and 7-point Likert scale), indicating his/her efficiency and skill level. Specifically, the answers on the 3-point Likert scale were: 1= novice, 2= amateur, 3= elite, whilst on the 7-point Likert scale statements were: 1= very low performance, 2= low performance, 3= somehow low performance, 4= average performance, 5= somehow high performance, 6= high performance, 7= very high performance.

Demographics variables: Participants were asked to fill in a form their age, gender, years of tennis experience, frequency in hours of tennis training, whether he/she is member of the Cyprus national tennis team, any past participation with other sport/dance (and for how long), attentional difficulties or medical issues.

The Attention Network Test (ANT). The adult version of the Attention Network Test (ANT) (Fan et al., 2002) examines the three distinct attentional networks; alerting, orienting and executive control. In each trial a central arrow is presented on the screen and participants are instructed to indicate its direction by pressing the corresponding button (left or right key on the mouse). Four flanker arrows are also presented on the screen, two on each side of the central (target) arrow, pointing either to the same direction (congruent trial) or to a different direction (incongruent trial). There are also neutral trials where the target arrow is presented along with simple lines. In all trials the array of arrows is presented above or below the central fixation point, which is placed in the center of the screen. Each array of arrows is preceded by one of the four conditions that represent warning signals. Those are: a central cue, a double cue, a spatial cue, and a no cue. In the central cue condition, there is an asterisk presented on the center of the screen, at the place of the fixation point. In the double cue condition, two asterisks are presented above and below the fixation point, so that they provide alerting information. In this case, the attention is divided into two possible locations where the target arrow might appear. The spatial cue condition displays an asterisk above or below the fixation cross, orienting the place that the target arrow might be presented.

Whack-a-Mole Task. The Whack-a-Mole Task evaluates inhibitory control, by measuring performance in a computerized Go/No-Go task and taps on response inhibition (Casey et al., 1997). In each trial there are a cartoon mole and a vegetable (eggplant) presented on the computer screen. Children are instructed to press the space button as quickly as possible when the mole appears (Go-trial), but to withhold (inhibit) a response when the eggplant appears (No-Go trial). First, there is a practice trial for the children to become familiar with the task, while still responding as quickly and accurate they can. The task version was obtained from the Sackler Institute for Developmental Psychobiology, and the stimuli were provided by Sarah Getz and the Sackler Institute for Developmental Psychobiology. E-Prime was used to run the task.

Visual Search Task. Visual Search Task (known as “T and L visual search”) is a common attention paradigm (Wolfe et al., 1989). Unlike other visual search tasks, this task forces participants to search serially, resulting in increasing RT with set size while it also requires visual attention. Participants search for targets among distractors that share the same local features with the target, but that differ markedly in global shape. The target stimulus is a flipped “T” that can be presented in any of the four orientations (0°, 90°, 180°, or 270°). The distractors are the letter "L" s presented in any of the same four rotations. The goal of the participants is to indicate the direction of the top of the "T", by pressing the correct arrow key, as quickly and as accurately as possible.

Reaction Speed Task (RST). To evaluate reaction speed, a task from the SpeedPad app created by MentisVR Ltd was used. This task is a VR adaptation of the Batak Pro machine (Quatronics Ltd.) that is used for reaction-speed training in a variety of sports. When the users put on the VR head-mounted-display (HMD), they are presented with an array of round discs that change color to blue in a random order. Participants are instructed to move their arms as quickly as possible to touch with a handheld controller each disc as soon as it changes color. The number of correct responses within a specified time interval (60 seconds) is used as participant's score.

Procedure

Children were tested individually at a quiet place, either at their tennis academy or at their private place. First, the parent of each participant read and signed an informed consent for participation. Then, children filled out a demographics questionnaire and after they carried out the reported tasks by, first, taking a comfortable position seat in front of a computer's desktop screen. The tasks were carried out in the following order: Attention Network Test (ANT), Whack-a-Mole Task, Visual Search Task, Reaction Speed Task.

Regarding ANT, participants were presented single examples of array of arrows, and they were asked to indicate the direction of the central arrow by pressing the appropriate mouse button (left or right). They were told that sometimes the central arrow is flanked by lines without an arrow and that other times, other four flanker arrows are also presented, two on each side of the central arrow. In the second case their attention should be on the central arrow to indicate its direction. Participants were also informed that when a spatial cue is presented, the fish would appear at that location. First, children completed a practice block with 24 trials, where response feedback was automatically provided by the computer. During this time, the experimenter was present to ensure the child's understanding of what is required before the experimental phase begins. The testing phase consists of 192 trials, divided into 4 blocks of 48 trials. Each trial represents one of 12 conditions in equal proportions: three target types (congruent, incongruent and neutral) × four cues (no cue, central cue, double cue and spatial cue). Trials begin with the presentation of the fixation point between 400-1600 ms and sometimes a warning cue follows for 150 ms, depending on the condition (no cue, central cue, double cue, spatial cue). A brief fixation period of 450 ms appears after the disappearance of the cue, followed by either the appearance of the target and flanker, or by the appearance of the target alone. The display is available on the screen until a response is given, for a maximum of 1700 ms. Participants must maintain their gaze on the fixation point and respond as accurately and quickly as possible throughout the task.

The Whack-a-Mole Task followed on the same computer. It consists of a total of 220 trials, divided into 4 blocks. From these, 165 are Go trials that appear 75% of the time and 55 are No-Go trials that appear 25% of the time, and are preceded by 1, 3, or 5 Go trials (about 82% of the times), which were randomized and distributed equally into four blocks. In addition, No-Go trials are preceded by 2 or 4 Go trials (about 18%) to prevent participants from inferring the previous pattern. Participants are encouraged to focus on the fixation point and respond as quickly and accurately as possible to the targets, but not that fast as to make errors. Response feedback was provided for each trial throughout the task. First, there was a practice trial and then the experimental phase began.

Regarding the Visual Search Task, participants are instructed to search on a computer screen, for the flipped "T" s (one at a time) among letters "L". Once they find the "T" they have to press the arrow key associated with the direction of the top of the "T". Each trial begins with a fixation point presented on the center of the screen (remains for 400ms), on which participants are asked to focus their gaze. The fixation cross is followed by a short blank interval (400 ms), which is then followed by the first display that remains until a response is given. Trials vary in the items ("L" s, distractions) per display from 2, 6, 10, 14, 18. Also, in between blocks, smalls breaks can be taken.

After that, participants will be engaged in the visual reality task, the Reaction Speed Task. Participants donned an Oculus Quest 2 HMD and they were immersed in a virtual environment depicting a gym environment with a stage in the center. They were instructed to respond as quickly as possible by moving their arms to touch every disc that becomes blue. Participants began with a practice session, where they were presented with an array of 9 discs arranged in a 3x3 grid in front of them. The practice trial lasted for 15 seconds. Then, they are given a short break before the RST begins. The RST is completed in 4 levels; 9 discs, 15 discs, 19 discs and 24 discs and participants were given 60 seconds to complete each round. Upon the completion of the task, the HMD was removed.

Ethics

The Cyprus National Bioethics Committee approved this study. The purpose and the procedure were explained both to the parents and to their children, underlining that no harm will be caused. Also, they were informed about voluntary participation and their right to withdraw from the study at any time point. Then, parental informed consent was provided to proceed to the experiment. Each participant was assigned a number to associate the data from all tasks, which were kept confidential, and analyzed collectively. In addition, parents were given the program director's contact information in case they had any questions or needed clarification.

Statistical Analysis

Regarding ANT, I computed three scores for each participant using their response time data for correct responses only. For the Alerting score, I subtracted the response time for double cue trials from that of no cue trials. To compute the Orienting score, I subtracted the response time for spatial cue trials from that for central cue trials. The Conflict score was estimated by subtracting the response time for congruent trials from the response time for incongruent trials. For the Whack-a-Mole task, based on the Signal Detection Theory, I calculated d’ scores (i.e., the standardized difference between the means of the Signal Present and Signal Absent distributions) for each participant using the hit rate (i.e., % of targets responded to from target-present trials) and the false alarm rate (i.e., % of distractors responded to from target-absent trials). I also computed the mean reaction time score (for the go-trials) for each participant. For the Visual Search Task, each participant yielded five reaction time scores that corresponded to each of 5 different set size of stimuli (2,6,10,14, or 18). Regarding RST, each participant has four scores that indicated the number of discs touched correctly within a specified time interval of 1 minute under 4 different task levels with 9, 15, 19, or 24 discs. Scripts in the R programming language (https://www.r-project.org/) were used for pre-processing the data. The main statistical analyses were carried out using Jamovi 2.3.21 (www.jamovi.org).

Results

To compare athletes vs. non-athletes in terms of their performance on the Reaction Speed Task and the Visual Search Task, I carried out Repeated Measures Analyses of Variance (ANOVA). Furthermore, to compare the performance of the two groups on the d-prime score and reaction time on the Whack-a-Mole Task, and on the three ANT networks (alerting, orienting and conflict scores), I carried out Independent Samples T-Tests. Respective analyses were also conducted with IVs being sex and age. To investigate potential relations across all the dependent variables, as well as relations between participants' self-reported statements and RST performance, correlation analyses were performed.

Demographic characteristics of the participants

The sample consisted of 36 participants, of which 18 were tennis players. Five of them were members of the National tennis team. According to coaches' reports, 4 athletes were novices, 7 were amateur and 7 were elite. Regarding athlete's self-reported measures for the years of tennis experience, descriptive results were as follows: M= 3.21, SD= 3.76, Min= 5 months, Max=10 years. Years of tennis experience were differentiated across sex (Boys: M=4.95, SD=3.91, Girls: M=2.22, SD=3.37). With regards to the frequency of training (hours per week), athletes reported: M=4.36, SD=6.85, Min=1, Max=22, where boys report more hours of weekly training than girls (Boys: M=8.69, SD=7.90, Girls: M=1.91, SD=4.83).

Comparisons between groups on the RST performance

The analysis revealed a significant main effect for the disc level F (3, 102) = 192.47, $p <$ .001, $\eta^2 = .850$, showing that as the number of discs in the display increased, participant's performance decreased. There was also a main effect for group F (1,34) = 30.5, $p < .001$, $\eta^2 = .473$, where athletes (*M* = 49.4, *SE* = 1.39) demonstrated higher scores than non-athletes (*M* = 38.5, *SE* = 1.39). These main effects were qualified by a significant group x disc level interaction, F (3,102) = 9.78, $p < .001$, $\eta^2 = .223$. As it can be seen in *Figure* 1, athletes had significantly higher scores than non-athletes at all disc levels, but a larger difference was evident in the 9-disc level.

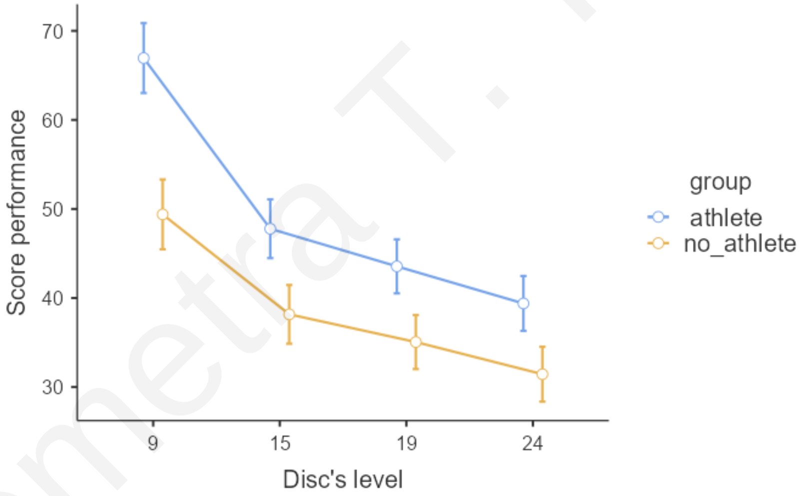


Figure 1. Interaction between group and disc level for the RST

Comparisons between groups on the d-prime score and reaction time (Whack-a-Mole Task)

Independent Samples T-Tests were performed to examine group differences for the Whack-a-Mole Task (Table 1). Results showed that although athletes had higher d-prime scores (*M* = 3.87, *SD* = 0.519) than non-athletes (*M* = 3.55, *SD* = 0.506), the difference fell short of significance, *t* (34) = 1.87, *p* = .070. (Figure 2). The analysis for reaction time for hits showed that athletes were significantly faster (*M* = 362, *SD* = 41.9) than non-athletes (*M* = 419, *SD* = 66.8), *t* (34) = -3.07, *p* = .004 (Figure 3).

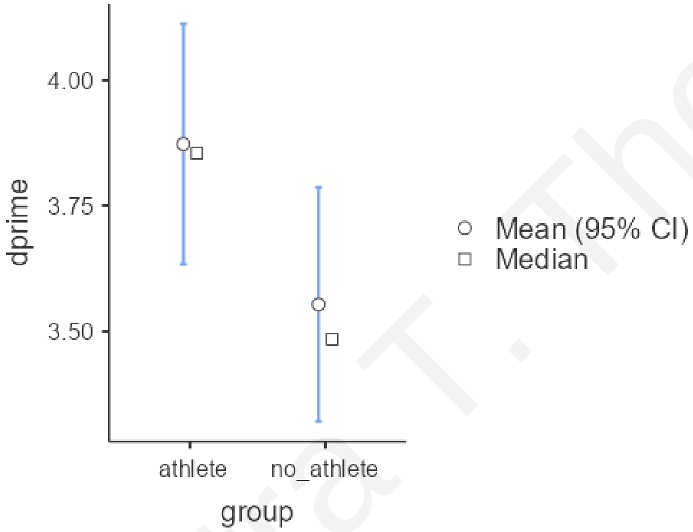


Figure 2. Difference in d-prime score between athletes and non-athletes, in the Whack-a-Mole Task. Error bars represent 95% Confidence Intervals

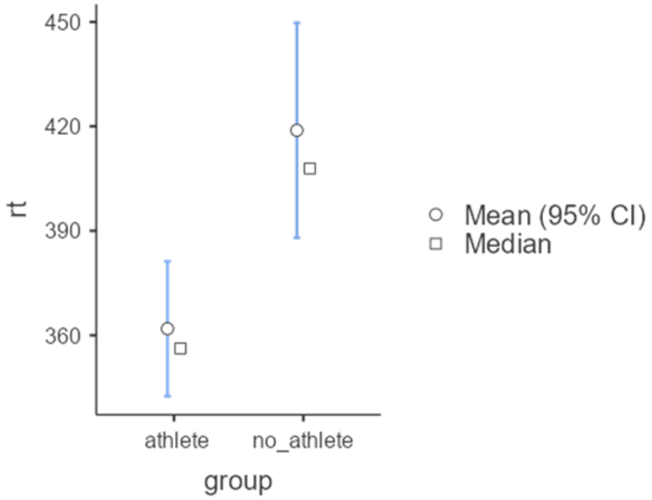


Figure 3. Difference in reaction time scores between athletes and non-athletes, in the Whack-a-Mole Task. Error bars represent 95% Confidence Intervals

Table 1: Independent Samples T-Test for the Whack-a-Mole variables between experimental and control group

Variable	**Group**	**Mean**	**SD**	**t**	**df**	**p**
d-prime	Athlete	3.87	0.519	1.87	34	0.070
	non_athlete	3.55	0.506			
reaction time	athlete	362	41.9	-3.07	34	0.004
	non_athlete	419	66.8			

<ins>Comparisons between groups on the performance (reaction time) in the Visual Search Task</ins>

I ran a Repeated Measures Analysis of Variance (ANOVA) to examine the effect of group (athlete or non-athlete) on the performance in the Visual Search Task. Results indicated a significant main effect for the set size in the Visual Search Task, F (4, 136) = 179.75, p <

.001, $\eta^2 = .841$. (Figure 4) That is, as the number of distractors in the display increased, performance on the task decreased. Importantly, this was the case for both groups. Neither the main effect of the group nor the interaction was significant.

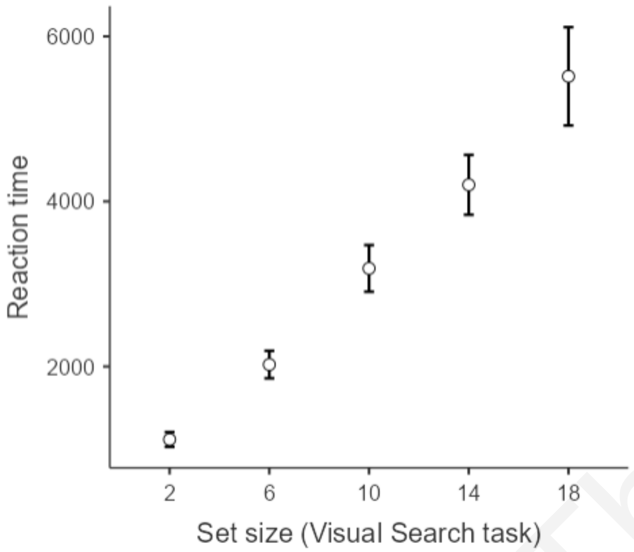


Figure 4. Main effect for the set size in the performance (reaction time) on the Visual Search Task. Error bars represent 95% Confidence Intervals

Comparisons between groups on the 3 attentional networks of ANT

Independent Samples T-Tests were conducted to compare athletes and non-athletes on the three networks of the ANT: alerting, orienting, conflict. Results indicated no statistically significant differences in any attentional network. Specifically, the results for the alerting variable show that athletes (*M* = 60.9, *SD* = 33.6) and non-athletes (*M* = 83.8, *SD* = 48.9), *t* (34) = -1.64, *p* =.110 do not differ in terms of their ability to maintenance arousal and sustain vigilance to cues. With regards to the orienting network, results indicate that athletes (*M* = 52.0, *SD* = 22.7) do not significantly differ from non-athletes (*M* = 47.2, *SD*

= 36.1), *t* (34) = 0.48, *p* =.636) in their ability to select information from multiple sensory inputs. It was also found that the mean conflict score (executive control network) was statistically equal across athletes (*M* = 98.6, *SD* = 37.6) and non-athletes (*M* = 117.7, *SD* = 66.6), *t* (34) = -1.06, *p* =.297). Findings are presented in Table 2.

Table 2: Independent Samples T-Test for the ANT variables between experimental and control groups

Variable	**Group**	**Mean**	**SD**	**t**	**df**	**p**
alerting	Athlete	60.9	33.6	-1.64	34	0.110
	non_athlete	83.8	48.9			
orienting	athlete	52.0	22.7	0.48	34	0.636
	non_athlete	47.2	36.1			
conflict	athlete	98.6	37.6	-1.06	34	0.297
	non_athlete	117.7	66.6			

Correlations between Reaction Speed Task's performance and study's variables

To examine associations between the RST and other variables, correlation coefficient analyses were performed using Pearson's r. Results revealed some significant correlations between the RST and the Whack-a-Mole Task (Table 3). Precisely, the performance of the participants at the 9-disc level of the VR task correlated negatively with the reaction time, as measured in the Whack-a-Mole Task, *r* (36) = -0.46, *p* < .05. In addition, the performance in the 15-disc level of the VR task correlated with the reaction time, as measured in the Whack-a-Mole Task, *r* (36) = -0.42, *p* = .012. Similarly, there was a moderate negative relationship between the RST performance on the 24-disc level and the reaction speed in the Whack-a-Mole Task, *r* (36) = -0.46, *p* = .004. It can be observed that the lower reaction time participants exhibited in the Whack-a-Mole Task, the better their performance was in the RST.

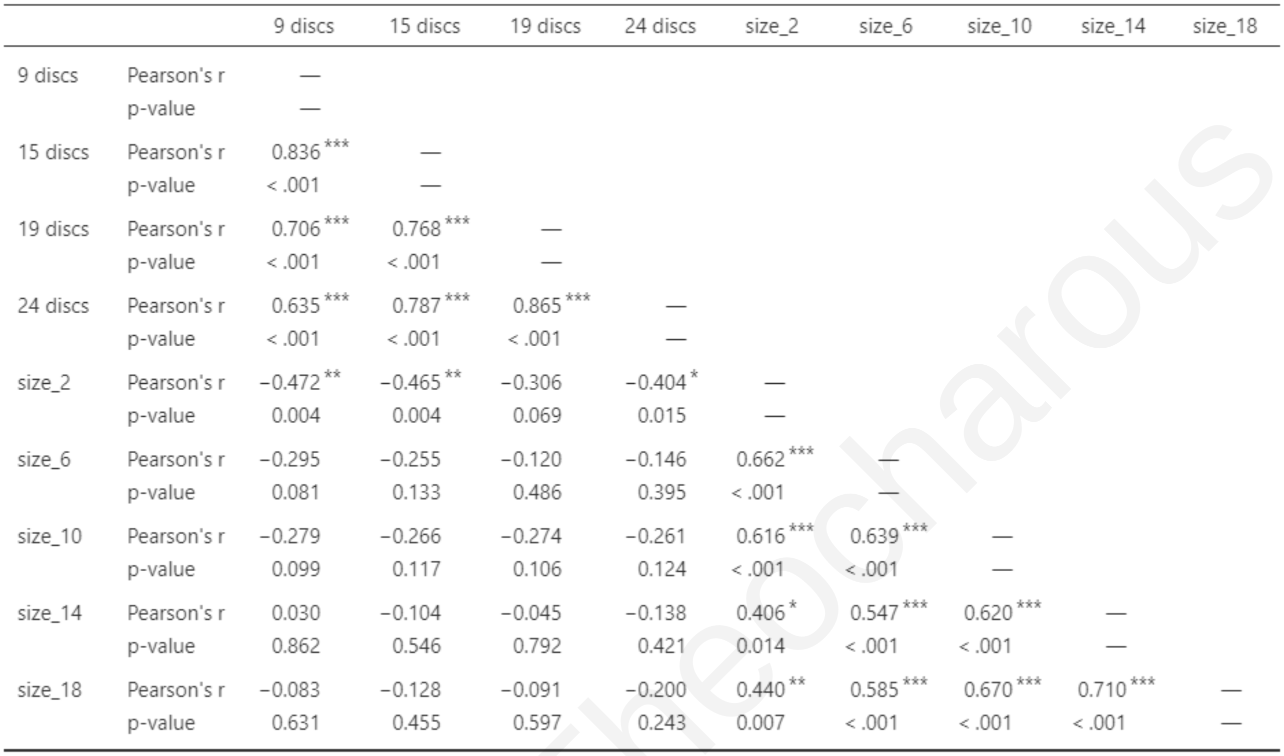
Table 3: Correlations between RST and Whack-a-Mole task

		9 discs	**15 discs**	**19 discs**	**24 discs**	**rt**	**d-prime**
9 discs	Pearson's r	—					
	p-value	—					
15 discs	Pearson's r	0.836 ***	—				
	p-value	< .001	—				
19 discs	Pearson's r	0.706 ***	0.768 ***	—			
	p-value	< .001	< .001	—			
24 discs	Pearson's r	0.635 ***	0.787 ***	0.865 ***	—		
	p-value	< .001	< .001	< .001	—		
rt	Pearson's r	-0.460 **	-0.416 *	-0.327	-0.464 **	—	
	p-value	0.005	0.012	0.052	0.004	—	
d-prime	Pearson's r	0.281	0.231	0.118	0.079	0.044	—
	p-value	0.097	0.176	0.492	0.647	0.798	—

Note. * p < .05, ** p < .01, *** p < .001

I also explored possible significant associations between RST performance and the performance in the Visual Search Task. Results indicate that the performance in the 9-disc level, the 15-disc level and the 24-disc level of the VR task correlated negatively with performance in the Visual Search Task (Set size 2); *r* (36) = -0.47, *p* = .004, *r* (36) = -0.47, *p* = .004, *r* (36) = -0.40, *p* = .015 respectively (Table 4).

Table 4: Correlations between RST and Visual Search Task

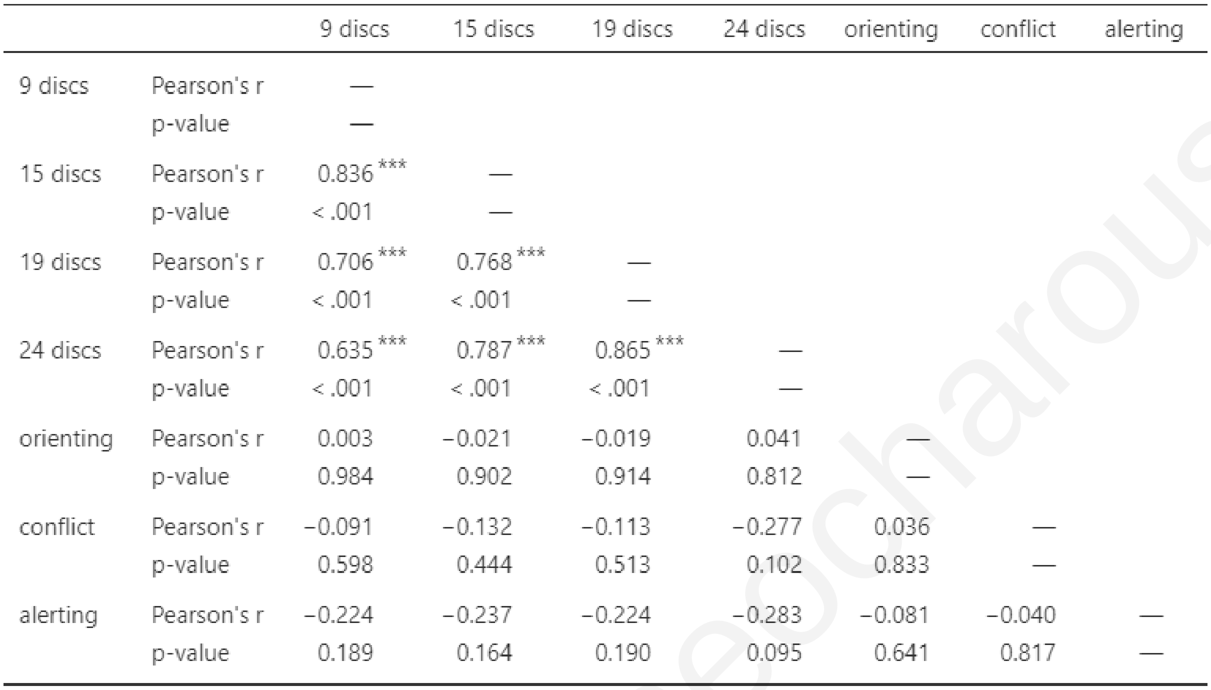


		9 discs	15 discs	19 discs	24 discs	size_2	size_6	size_10	size_14	size_18
9 discs	Pearson's r	—								
	p-value	—								
15 discs	Pearson's r	0.836 ***	—							
	p-value	< .001	—							
19 discs	Pearson's r	0.706 ***	0.768 ***	—						
	p-value	< .001	< .001	—						
24 discs	Pearson's r	0.635 ***	0.787 ***	0.865 ***	—					
	p-value	< .001	< .001	< .001	—					
size_2	Pearson's r	−0.472 **	−0.465 **	−0.306	−0.404 *	—				
	p-value	0.004	0.004	0.069	0.015	—				
size_6	Pearson's r	−0.295	−0.255	−0.120	−0.146	0.662 ***	—			
	p-value	0.081	0.133	0.486	0.395	< .001	—			
size_10	Pearson's r	−0.279	−0.266	−0.274	−0.261	0.616 ***	0.639 ***	—		
	p-value	0.099	0.117	0.106	0.124	< .001	< .001	—		
size_14	Pearson's r	0.030	−0.104	−0.045	−0.138	0.406 *	0.547 ***	0.620 ***	—	
	p-value	0.862	0.546	0.792	0.421	0.014	< .001	< .001	—	
size_18	Pearson's r	−0.083	−0.128	−0.091	−0.200	0.440 **	0.585 ***	0.670 ***	0.710 ***	—
	p-value	0.631	0.455	0.597	0.243	0.007	< .001	< .001	< .001	—

Note. * p < .05, ** p < .01, *** p < .001

Potential relationships between the RST and the attentional networks of ANT (alerting, orienting, conflict) were also explored, but no statistically significant correlations have been found. (Table 5)

Table 5: Correlations between RST and ANT



		9 discs	15 discs	19 discs	24 discs	orienting	conflict	alerting
9 discs	Pearson's r	—						
	p-value	—						
15 discs	Pearson's r	0.836 ***	—					
	p-value	< .001	—					
19 discs	Pearson's r	0.706 ***	0.768 ***	—				
	p-value	< .001	< .001	—				
24 discs	Pearson's r	0.635 ***	0.787 ***	0.865 ***	—			
	p-value	< .001	< .001	< .001	—			
orienting	Pearson's r	0.003	−0.021	−0.019	0.041	—		
	p-value	0.984	0.902	0.914	0.812	—		
conflict	Pearson's r	−0.091	−0.132	−0.113	−0.277	0.036	—	
	p-value	0.598	0.444	0.513	0.102	0.833	—	
alerting	Pearson's r	−0.224	−0.237	−0.224	−0.283	−0.081	−0.040	—
	p-value	0.189	0.164	0.190	0.095	0.641	0.817	—

Note. * p < .05, ** p < .01, *** p < .001

<u>Correlations between Self-Reported measures and study's dependent variables</u>

To examine associations between the years of tennis experience of the participants and the dependent variables, correlation analyses were performed. Findings showed a statistically significant negative correlation between years of experience and reaction time, as measured in the Whack a Mole Task (r = -0.48, p = .003). There was also a negative correlation between the years of experience and the set size 2, as measured in the Visual Search Task (r = -0.40, p = .015). Finally, years of experience were positively correlated with the performance on all disc levels of the RST. The associations for the 9,15,19,24 discs were: r = 0.699, p < .001, r = 0.626, p < .001, r = 0.618, p < .001, r = 0.589, p < .001 respectively. (Table 6)

Table 6: Correlations between years of tennis experience and study's dependent variables (RST, Whack-a-Mole task, Visual Search task)

		Years of experience	**9 discs**	**15 discs**	**19 discs**	**24 discs**	**rt**	**Visual Search task (set size 2)**
Years of experience	Pearson's r	1						
	p-value							
9 discs	Pearson's r	**0.699*****	1					
	p-value	< .001						
15 discs	Pearson's r	**0.626*****		1				
	p-value	<.001						
19 discs	Pearson's r	**0.618*****			1			
	p-value	<.001						
24 discs	Pearson's r	**0.589*****				1		
	p-value	<.001						
rt	Pearson's r	**-0.476****					1	
	p-value	0.003						
Visual Search task (set size 2)	Pearson's r	**-0.401***						1
	p-value	0.015						

Note. * p < .05, ** p < .01, *** p < .001

I further explored whether the frequency of tennis training, as measured by hours per week, correlated with the dependent variables of the study. Results demonstrated a negative correlation between the hours of training per week and the reaction time, as measured in the Whack a Mole Task ($r = -0.34$, $p = .040$). In addition, there were positive correlations between the hours of training and all the disc levels of the RST, thus indicating better task performance as the tennis experience is greater. The positive associations for the 9,15,19,24 discs, are: $r = 0.534$, $p < .001$, $r = 0.584$, $p < .001$, $r = 0.626$, $p < .001$, $r = 0.608$, $p < .001$ respectively. (Table 7)

Table 7: Correlations between frequency of tennis training (hours per week) and study's dependent variables (RST, Whack-a-Mole task, Visual Search task)

		Frequency of training	**rt**	**9 discs**	**15 discs**	**19 discs**	**24 discs**
Frequency of training	Pearson's r	1					
	p-value						
rt	Pearson's r	**-0.344***	1				
	p-value	0.040					
9 discs	Pearson's r	**0.534*****		1			
	p-value	< .001					
15 discs	Pearson's r	**0.584*****			1		
	p-value	< .001					
19 discs	Pearson's r	**0.626*****				1	
	p-value	< .001					
24 discs	Pearson's r	**0.608*****					1
	p-value	< .001					

Note. * p < .05, ** p < .01, *** p < .001

Also, coaches' assessment regarding their athletes' skill level was also ran in correlational analyses to the RST performance. Results indicate that athletes who exhibit "somehow low performance", according to their coaches, perform lower scores in the 19-disc level on the RST task (r = - 0.491 p = 0.039). Accordingly, the rest disc levels, 9,15,24, were also negatively correlated with the "somehow low" skill level of the tennis players but fell short of significance. Results for each disc level are as follows: r = - 0.448 p = 0.062, r = - 0.376, p = 0.124, r = - 0.417, p = 0.085, respectively.

Comparisons across sex and age on the RST performance – VR task

I ran a Repeated Measures Analysis of Variance (ANOVA) to compare the effect of the independent variable of sex (boys, girls) on the performance on the RST. Results revealed a statistically significant main effect for both disc level and sex, *F* (3,102) = 152.98, $p < .001$, $\eta^2 = .818$ and *F* (1,34) = 9.95, $p = .003$, $\eta^2 = .226$ respectively. As shown in Figure 5, boys had better scores (*M*= 49, *SE*= -1.99) than girls (*M*= 41, *SE*= -1.50) in the RST. No statistically significant interaction was obtained.

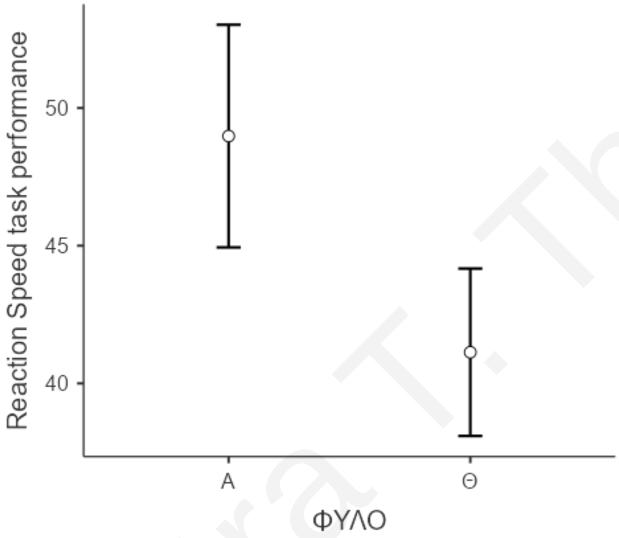


Figure 5. Main effect for sex in the RST performance

I also examined the effect of age (14,15,16) on the performance in the RST, through a Repeated Measures ANOVA. Results documented a main effect for the disc level, *F* (3,99) = 161.48 $p < .001$, $\eta^2 = .830$ which was followed by a significant interaction effect between age and disc level *F* (6,99) = 3.76, $p = .002$, $\eta^2 = .185$. (Figure 6). One-way ANOVAs were conducted to compare the age groups on each disc level (9,15,19,24) of the RST, with no main effects being statistically reliable; *F* (2) = 5.57, *p* = .103, *F* (2) = 1.45, *p* = .260, *F* (2) = 0.03, *p* = .970, *F* (2) = 0.01, *p* = .91 respectively. The results show that although there was a trend for the 16-year-old participants to have better performance at the 9-disc level, this was not statistically significant.

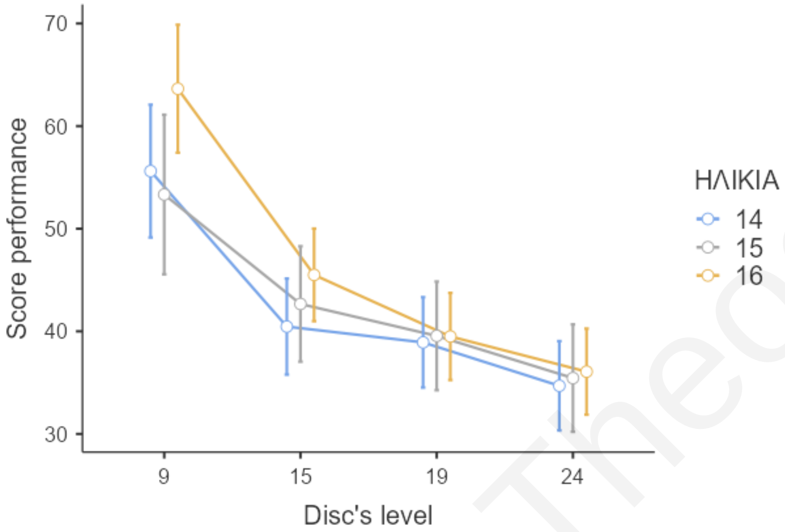


Figure 6. Interaction effect for disc level X sex in the RST performance

Discussion

The primary purpose of the study was to examine which cognitive skills and how they relate to advanced tennis performance. The study compared tennis players and non-players in their performance in 3 attentional networks, in inhibitory control of attention, in reaction time, and in visual search processes through traditional computerized tasks as well as in a virtual reality environment. My aim was to examine whether the two groups are differentiated in their cognitive skill levels, indicating a cognitive advantage for people who participate in tennis. Results support the hypotheses to a large extent.

First, I explored differences between the experimental and control groups with regards to the performance on the RST. Each participant's score is the number of correct responses given within a specified time interval (60 seconds). The analysis showed that as the number of discs presented on the display increased, participant's performance decreased. This is expected, since as the stimuli were increasing on the display, participants needed more time to find the target and thus their performance score was reduced. As hypothesized, there was a main effect for group indicating that tennis players exhibit higher scores at all disc levels than non-athletes. This finding suggests that athletes have more advanced skills in detecting and responding to a target. This finding is in line with previous research (Deary & Der, 2005; Kaplan et al., 2019; Reigal et al., 2019; Zhang, 2022), which documents that a tennis player needs to be alert throughout the match/task to scan, detect the visual field and react as early as possible to perceptual targets. My finding suggests that tennis players spatially orient attention quickly towards the disc that is changing color from a particular location on the display, therefore making the decision-making process (motor response) faster, than of those of non-athletes. Moreover, there was an interaction effect for group x disc level, indicating that athletes perform even better in the 9-disc level, which assesses simple reaction time. Perhaps VR performance at the 9-disc level entails only the ability to detect and execute fast movements toward targets, where athletes outperform non-athletes, while larger arrays entail additional processes that may operate equally across the two groups.

Regarding my hypotheses, tennis players would exhibit better reaction time and inhibitory control than non-athletes in the Whack-a-Mole task, results in general are in line with my expectation. What is found is that the two groups significantly differed in their reaction time performance for hits, where tennis athletes reacted faster to upcoming stimuli that non tennis athletes. Also, tennis players demonstrated better attentional inhibition score as measured by the d-prime, although the difference was not significant. Thus, overall, findings are in line with my hypothesis that tennis players can inhibit a prepotent response faster than non-players (Buck et al., 2008). According to Wang and colleagues (2013) efficient inhibitory attentional control is related to performance in tennis, since the ability to inhibit prepotent actions is vital for attaining success. That is, tennis players need to suppress response when the ball is going out of bounds and in general be able to avoid executing unnecessary or incorrect actions. Thus, a well-developed attentional inhibition skill level enhances performance since fewer errors are committed. However, literature indicates that the relation between exercise and cognition may change across the lifespan (Buck et al., 2008). Particularly in children, improvement in tasks requiring executive control has been associated with the development of the frontal lobe (Buck et al., 2008; Chaddock et al., 2011). That is why during adolescent children demonstrate difficulties in ignoring irrelevant stimuli due to their poor inhibitory control which is not fully developed until this time (Buck et al., 2008). According to Meijer and colleagues (2021), physical exercise promotes neurocognitive processes and neural mechanisms that support performance and learning processes. Based on this, an explanation for the non-significant difference between the groups on inhibitory control might be the prior experience of some non-athletes in sports and dance. This might have influenced the results, since many children in the control group have already practiced some cognitive skills.

My hypothesis that athletes would demonstrate better visual search skills was not confirmed. Indeed, the reaction time of athletes in all the set sizes did not statistically differ from that of non-players. By that, I cannot assume that tennis players in this study demonstrate more efficient visual search strategies than their nonathletic counterparts, as it is proposed in most of the literature (Murray & Hunfalvay, 2017; Rosker & Majcen Rosker, 202; Wolfe, 2020). It seems that both athletes and non-athletes in my study are equally efficient in serial search for targets among distractors that share the same local features with the target (but differ markedly in global shape) as well as in visual attention.

Similarly, athletes did not differ from non-athletes in the ANT. In the present study, tennis players were not significantly better than non-players in identifying and resolving cognitive conflicts and exerting cognitive inhibition. On the contrary, past research supports systematically the superiority of athletes from non-athletes and their less skilled counterparts in the inhibitory control of attention (Jacobson & Matthaeus, 2014; Vaughan & Laborde, 2021). An explanation for the nonsignificant difference may be the previous experience in sports and dance of some of the controls, which might have contributed to improvements in EFs. In addition, Hillman et al. (2014) as well as Best (2010) suggest that this executive function is more sensitive to the effects of physical exercise (than other cognitive functions). Thus, the engagement of some participants from the control group, in some extracurricular activities in the past, might have helped them improve those EF's as well.

Likewise in the attentional networks of alerting and orienting, no difference between the groups was observed, which is in line with previous research showing no advantage for athletes (Perez et al., 2014; Wang et al., 2016). It is worth noting that alerting scores seemed to favor athletes, although the difference was not statistically significant. This result points out that the presence of cues is less helpful for athletes, than they are for non-athletes. It is possible that athletes can maintain their arousal, direct their attention, and detect a target easily, either guided by a cue or not.

Several other results from the current study are also noteworthy. Correlations were carried out among the performance in the RST and other variables, to examine how the cognitive skills of the tasks administered (Whack-a-Mole task, Visual Search task, ANT) relate to the performance in the RST. First, there was a negative correlation between reaction time, as measured in the Whack-a-Mole task, and the 9,15 and 24th disc level of the RST. This suggests that the execution of the two tasks recruits some common cognitive and motor processes. Precisely, the faster reaction time one exhibits in the Whack-a-Mole task, the better performance acquires in the RST. Participants who were faster in responding to the former task, touched more discs within a specified time interval in the latter task.

Another notable result is the finding of a negative correlation between the Visual Search Task (Set size 2) and the performance in the 9,15 and 24th disc level of the RST. That is, the faster the visual search attention was, the superior the performance on the RST was as well. In other words, the performance on the RST was negatively correlated with the more basic level of the Visual Search Task. Intuitively, one would think that a participant who can carry out higher performance in the 24 discs-level of the RST, would be also efficient in detecting fast the target (“letter”) in the most demanding level of the Visual Search Task (Set size 18). Thus, both tasks recruit visual search processes. However, my results suggest that this is not the case. My conjecture for this result is that set size 2, does not involve search processes, but rather evaluates simple reaction time. Respectively, in the 15-, 19- and 24-disc level of the RST, no visual search processes are involved. Although participants at those levels needed to turn their head to search for the colored disc, it was not difficult to detect it. Target discs were popping out, making it easier for the participant to distinguish it from the rest of the stimuli. Thus, RST seems to rely less on attentional processes relating to visual search. On the contrary, in the Visual Search task a conjunction search is needed, making it difficult to find the target, leading thus to increased reaction time. According to Kozik & Enns (2021), visual search is the effortful search that occurs when the target and distractor items are very similar to one another, and attention must be deliberately pushed to candidate items until the target is found. Therefore, the RST is useful for the evaluation of fast reaction to stimuli and it is not related either to visual search processes nor to attentional inhibition. It is also noted that none of the attentional networks of the ANT were found to be associated with the performance in the RST.

Correlational analyses were also performed to examine the relationship between the self-reported statements of athletes (years of tennis experience, frequency of training) and their performance in the RST. Results point out some useful findings that are in tune with previous literature. That is, years of tennis experience were negatively correlated with the reaction time measure, in the Whack-a-Mole task. What is shown is that the more experienced tennis players demonstrated faster reaction time to target stimuli than lesser experienced ones. As it is argued in the literature, greater tennis experience can determine the reaction speed performance (Deary & Der, 2005; Kaplan et al., 2019; Reigal et al., 2019). Xu and colleagues (2022) showed that although tennis experience is not always associated with accuracy (as it is also found in our study) it does associate with shorter reaction times. According to Reigal and colleagues (2019), regular training and thus the development of physical condition can have an impact on reaction time, directly by the training of the capacity to respond to a given stimulus and indirectly by the impact on cognitive functioning. Further, a negative association was found between years of tennis experience and the performance on the Visual Search task at set size 2. As was mentioned before, set size 2 does not seem to recruit visual search processes, but simple reaction speed. Thus, it is reasonable to consider that since set size 2 evaluates reaction time to a given target, it supports the idea that years of tennis experience can predict reaction time. Finally, years of tennis experience were found to be positively related to the performance in the RST at all disc's levels. This finding indicates that the specific task is effective at distinguishing experts from novices.

Moreover, the frequency of tennis training was found to be negatively correlated with the reaction time, as recorded in the Whack-a-Mole task. That is, tennis players with increased and more frequent training sessions could react faster to visual stimuli. Additionally, more frequent tennis training was positively related to the performance in the RST at all disc's levels, indicating a superiority for athletes that train increased hours in detecting and reacting faster to stimuli. According to Grigore and colleagues (2015), prolonged tennis training improves players' decision-making abilities and reduces response delay times. Thus, it adapts the mind to intense conditions. In addition, tennis players who exhibit "somehow low performance", according to their coaches, perform low scores on the 19 disc level of the RST.

Gender as well as age differences in the RST performance were investigated. Notably, significant main effects for both disc level and sex were found. As the disc level was increasing, 9,15,19,24 discs, both boys and girls achieved lower scores. That is reasonable and expected since the increase of stimuli on the display leads to more delay time to detect the target. Further analyses regarding the main effect found for sex, indicate that there is a performance advantage for boys. This finding was not expected, since it somehow rejects the previous findings of the advanced performance in the VR task, due to group condition. Some could reasonably claim that since sex differences influence the performance in the RST, then previous findings for group condition might not be valid. Also, in the experimental group most athletes were boys (B: 10, G: 8) whereas the control group consisted mostly of girls (G: 15, B: 3). So, the differences noted before might be attributed to the skills of boys rather that to the skills of tennis players and thus not to the cognitive benefits of the engagement with the sport. According to Jain and colleagues (2015), although, in the majority, women non-players need longer visual reaction time than non-athlete men, there is no significant difference across men and women racquet athletes. Thus, it is supported that the reaction time difference between men and women who exercise consistently is eliminated and comparable to those of men. However, my last result cannot yet confirm this.

In addition, the analysis of differences between age and performance in the RST revealed a main effect for the disc level. That means, as the disc level was increasing all age groups performed lower scores. A statistically significant interaction effect was also observed for the disc level and age, since there was a trend for the 16-year-old participants to be better at the 9-disc level, which however was not significant. No main effect was detected for the age, confirming (as found before) the influence of years of experience in the advanced performance in the task. That is, even young players (i.e., 14-year-old) with long tennis experience reach high task performance. This finding comes in contrast to that of Turner and colleagues (2022) who found that age and maturation, rather than the exposure to tennis training, are related to cognitive performance for junior beginner to intermediate-level tennis players older than 13 years of age. Their findings suggest that cognitive performance is not linked to tennis experience when controlling for age and maturation variables. They claim that the positive association between tennis experience and cognitive performance is found to be stronger in younger athletes, especially those under 12 years old, who still have not reached peak cognitive maturation. For those, greater tennis experience is related to superior cognitive performance (Turner et al., 2022). The inconsistent findings between Turner's and colleagues (2022) study and mine, may be attributed to the skill level of athletes examined. They have studied junior beginner to intermediate-level tennis players, whereas I studied novice, amateur as well as elite players. That is, it seems that the effect of frequent and long-term tennis training on cognition is greater on advanced level athletes, rather than on beginner and intermediate level ones. Also, since adolescent athletes begin to reach peak maturation of cognitive skills by that age, it is plausible that their efficiency level in the sport begins to be determined to a greater extent, by the frequency and years of training.

Bearing in mind the previous reported research and my results, discrepancies across studies may be due to the characteristics of our sample size. Mainly, the heterogeneity in the sample and gender differences might be contributed to the reported results, thus they should be interpreted with caution. Overall, my results indicate that athletes and non-athletes exhibit performance differences in cognitive tasks, especially in reaction time measures. They do not statistically differ in inhibitory control of attention, in attentional networks and visual search processes. In addition, practice effects, through years of tennis experience and training frequency, can be obtained on the RST performance, on the Whack-a-Mole task as well as on the Visual Search task (set size 2), suggesting that those tasks could be efficient tools for training tennis players. Gender seems to intervene in the relationship between group condition and RST performance, although additions of participants in the groups should be made, to confirm the validity of the results. Finally, age does not seem to be a critical variable in my study, to contribute to the development of cognitive functions. The important conclusion from this result is that even young players with long tennis experience reach high cognitive gains.

Limitations and Suggestions for Future Studies

The specific study displays some limitations. First, my sample was relatively small and there was an imbalance in the number of boys and girls between the two groups. In the control group girls exceeded boys by 12 and in the experimental group boys exceeded girls by 2. From our results it seems that there is a gender effect, which is noted as a significant constraint of the study. Therefore, my results might be attributed to gender rather than to group condition, which was the factor of my interest in this project. In addition, some of my participants in the control group had previous experience in a sport or dance, which might have contributed to the small number of statistically significant differences between the groups on study’s variables. Despite much of my results are in line with previous research, I cannot generalize the findings into other ages.

In line to these limitations, I could progress this research study by matching the two groups in terms of gender. That said, I will be able to show that the differences found in cognition, between athletes and non-athletes, are linked to the gains of tennis training rather than to gender. Moreover, a future replication could compare different age groups to examine the mediating role of age. That would be, whether greater improvements of tennis training on cognition are seen in late childhood and early adolescence rather than in adult players, who begin to face a reduced growth rate of executive functions. Also, it could be interesting to examine whether our findings are consistent with the long-term gains of tennis engagement reported in the sport literature. Finally, replicating current findings in real-life settings would establish the ecological value of the tasks administered and thus encourage further implementation in the field.

Conclusion

Overall, the results of the present study, document partly the benefits of tennis engagement in cognitive performance, in Greek-Cypriot children. My findings indicate that athletes outperform non-athletes in reaction time measures. They do not statistically differ in terms of the attentional networks and visual search processes, as was first hypothesized. In addition, years of tennis experience and training frequency positively affected the decision-making process and thus the motor reaction speed. Finally, age does not seem to be a critical variable in our study, to contribute to the development of cognitive functions. The important conclusion is that even young players with long tennis experience reach high cognitive gains. Finally, the variable of gender and specifically boys, were found to exhibit better performance in the RST, which measures reaction time. From this, a set of further questions open up. If there is indeed a gender effect, it means my results are attributed to the gender rather than to the group condition (athletes, non-athletes), which was the factor of our interest in this project. The continuation of the study should match the two groups in terms of gender, to specify whether differences in cognition, between athletes and non-athletes, are really linked to the gains of tennis training. It is proposed that by developing a greater understanding of the cognitive skills that contribute and enhance tennis performance, I will provide valuable information to coaches in strengthening the training strategies they apply for their athletes' performance improvement. Even if my findings do not support all my hypotheses, they are equally important since they provide further observations to the already existing literature.

References

Alexandru, M. A., & Lorand, B. (2015). Motor Behavior and Anticipation – A Pilot Study of Junior Tennis Players. *Procedia - Social and Behavioral Sciences*, *187*, 448–453. https://doi.org/10.1016/j.sbspro.2015.03.084

Attention In Tennis.Transition From External To Internal Focus Of Attention (2020). Play Smart Tennis. Retrieved May 19, 2023, from https://playsmarttennis.com/2020/06/03/attention-in-tennis- transition-from-external-to-internal-focus-of-attention/

Baddeley, A. (2008). Working Memory Working Memory. *ReCALL*, *20*(4), 1–16. https://doi.org/10.1098/rstb.1983.0057

Best, J. R. (2010). Effects of physical activity on children's executive function: Contributions of experimental research on aerobic exercise. *Developmental review*, *30*(4), 331-351. doi:10.1016/j.dr.2010.08.001

Buck, S. M., Hillman, C. H., & Castelli, D. M. (2008). The relation of aerobic fitness to stroop task performance in preadolescent children. *Medicine and Science in Sports and Exercise*, *40*(1), 166–172. https://doi.org/10.1249/mss.0b013e318159b035

Budde, H., Voelcker-Rehage, C., Pietraßyk-Kendziorra, S., Ribeiro, P., & Tidow, G. (2008). Acute coordinative exercise improves attentional performance in adolescents. *Neuroscience letters*, *441*(2), 219-223. doi:10.1016/j.neulet.2008.06.024

Casey, B. J., Trainor, R. J., Orendi, J. L., Schubert, A. B., Nystrom, L. E., Giedd, J. N., ... & Rapoport, J. L. (1997). A developmental functional MRI study of prefrontal activation during performance of a go-no-go task. *Journal of cognitive neuroscience*, *9*(6), 835-847. https://doi.org/10.1162/jocn.1997.9.6.835

Chaddock, L., Pontifex, M. B., Hillman, C. H., & Kramer, A. F. (2011). A review of the relation of aerobic fitness and physical activity to brain structure and function in children. *Journal of the International Neuropsychological Society*, *17*(6), 975–985. https://doi.org/10.1017/S1355617711000567

Chun, M. M., Golomb, J. D., & Turk-Browne, N. B. (2011). A taxonomy of external and internal attention. *Annual review of psychology*, *62*, 73-101.

Culpin, S. (2018). Effects of long-term participation in tennis on cognitive function in elderly individuals. https://ro.ecu.edu.au/theses/2097

Davis, C. L., Tomporowski, P. D., McDowell, J. E., Austin, B. P., Miller, P. H., Yanasak, N. E., Allison, J. D., & Naglieri, J. A. (2011). Exercise Improves Executive Function and Achievement and Alters Brain Activation in Overweight Children: A Randomized, Controlled Trial. *Health Psychology*, *30*(1), 91–98. https://doi.org/10.1037/a0021766

Deary, I. J., & Der, G. (2005). Reaction time, age, and cognitive ability: longitudinal findings from age 16 to 63 years in representative population samples. *Aging, Neuropsychology, and cognition*, *12*(2), 187-215.

Diamond, A. (2013). Executive functions. In *Annual Review of Psychology* (Vol. 64, pp. 135–168). Annual Reviews Inc. https://doi.org/10.1146/annurev-psych-113011-143750

Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old (Science (959)). *Science*, *334*(6054), 311. https://doi.org/10.1126/science.334.6054.311-d

Elferink-Gemser, M. T., Faber, I. R., Visscher, C., Hung, T. M., de Vries, S. J., & Nijhuis-Vandersanden, M. W. G. (2018). Higher-level cognitive functions in Dutch elite and sub-elite table tennis players. *PLoS ONE*, *13*(11). https://doi.org/10.1371/journal.pone.0206151

Etnier, J. L., & Chang, Y. K. (2009). The effect of physical activity on executive function: A brief commentary on definitions, measurement issues, and the current state of the literature. *Journal of Sport and Exercise Psychology*, *31*(4), 469–483. https://doi.org/10.1123/jsep.31.4.469

Fan, J., Mccandliss, B.D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience* 14(3):340–347. https://doi.org/10.1162/089892902317361886

Furley, P. A., & Memmert, D. (2010). The role of working memory in sport. *International Review of Sport and Exercise Psychology*, *3*(2), 171–194. https://doi.org/10.1080/1750984X.2010.526238

Grigore, V., Mitrache, G., Paunescu, M., & Predoiu, R. (2015). The decision time, the simple and the discrimination reaction time in elite Romanian junior tennis players. *Procedia-Social and Behavioral Sciences, 190*, 539-544.

Hernández-Mendo, A., Reigal, R. E., López-Walle, J. M., Serpa, S., Samdal, O., Morales-Sánchez, V., ... & Falco, C. (2019). Physical activity, sports practice, and cognitive functioning: The current research status. *Frontiers in psychology*, 2658. https://doi.org/10.3389/fpsyg.2019.02658

Hillman, C. H., Erickson, K. I., & Kramer, A. F. (2008). Be smart, exercise your heart: Exercise effects on brain and cognition. *Nature Reviews Neuroscience*, *9*(1), 58–65. https://doi.org/10.1038/nrn2298

Hillman, C. H., Pontifex, M. B., Castelli, D. M., Khan, N. A., Raine, L. B., Scudder, M. R., ... & Kamijo, K. (2014). Effects of the FITKids randomized controlled trial on executive control and brain function. *Pediatrics*, *134*(4), e1063-e1071. doi:10.1542/peds.2013-3219

Ishihara, T., & Mizuno, M. (2018). Effects of tennis play on executive function in 6–11-year-old children: a 12-month longitudinal study. *European Journal of Sport Science*, *18*(5), 741–752. https://doi.org/10.1080/17461391.2018.1444792

Ishihara, T., Sugasawa, S., Matsuda, Y., & Mizuno, M. (2017). Improved executive functions in 6–12-year-old children following cognitively engaging tennis lessons. *Journal of Sports Sciences*, *35*(20), 2014–2020. https://doi.org/10.1080/02640414.2016.1250939

Ishihara, T., Sugasawa, S., Matsuda, Y., & Mizuno, M. (2017b). Relationship of tennis play to executive function in children and adolescents. *European Journal of Sport Science*, *17*(8), 1074–1083. https://doi.org/10.1080/17461391.2017.1334831

Jacobson, J., & Matthaeus, L. (2014). Athletics and executive functioning: How athletic participation and sport type correlate with cognitive performance. *Psychology of Sport and Exercise*, *15*(5), 521–527. https://doi.org/10.1016/j.psychsport.2014.05.005

Jain, A., Bansal, R., Kumar, A., & Singh, K. D. (2015). A comparative study of visual and auditory reaction times on the basis of gender and physical activity levels of medical first year students. *International Journal of Applied and Basic Medical Research*, *5*(2), 124.

Kaplan, D. S., Yıldırım, C., Akcan, F., Özdal, M., Abakay, Z., & Bağçeci, A. M. (2019). The investigation of visual and auditory reaction time in racket sports by skills and sedentary. *European Journal of Physical Education and Sport Science*.

Kovacs, M. S. (2009). Movement for tennis: The importance of lateral training. *Strength & Conditioning Journal*, *31*(4), 77-85.

Kozik, P., & Enns, J. T. (2021). Athletics and attention: Bi-directional influences in the lab and on the field. *Current Issues in Sport Science*, *6*.

Lineweaver, T. T., Kercood, S., Morgan, E. B., Rampone, S. L., Frank, C. C., McLuckie, S. A., & Reed, M. F. (2020). Working Memory in Collegiate Athletes and Non-Athletes: A Comparison of Team-Sports Athletes, Solo-Sports Athletes, Frequent Exercisers and Infrequent Exercisers. *OBM Integrative and Complementary Medicine, 5*(1), 1–1. https://doi.org/10.21926/obm.icm.2001002

Logie, R. H., & Baddeley, A. D. (1999). Working memory: The multiple-component model. In *Models of working memory: Mechanisms of active maintenance and executive control*. http://cogweb.ucla.edu/Abstracts/Miyake_Shah_99.html#2

Meijer, A., Königs, M., de Bruijn, A. G., Visscher, C., Bosker, R. J., Hartman, E., & Oosterlaan, J. (2021). Cardiovascular fitness and executive functioning in primary school-aged children. *Developmental Science*, *24*(2), e13019. https://doi.org/10.1111/desc.13019

Meijer, A., Königs, M., van der Fels, I. M., Visscher, C., Bosker, R. J., Hartman, E., & Oosterlaan, J. (2020). The effects of aerobic versus cognitively demanding exercise interventions on executive functioning in school-aged children: A cluster-randomized controlled trial. *Journal of Sport and Exercise Psychology*, *43*(1), 1-13.

Murray, N. P., & Hunfalvay, M. (2017). A comparison of visual search strategies of elite and non-elite tennis players through cluster analysis.

Navon, D. (1977). Forest Before Trees: The Precedence of Global Features in Visual Perception. In *COGNITIVE PSYCHOLOGY* (Vol. 9). https://doi.org/10.1016/0010-0285(77)90012-3

Pérez, L., Padilla, C., Parmentier, F. B. R., & Andrés, P. (2014). The effects of chronic exercise on attentional networks. *PLoS ONE*, *9*(7). https://doi.org/10.1371/journal.pone.0101478

Reigal, R. E., Barrero, S., Martín, I., Morales-Sánchez, V., Juárez-Ruiz de Mier, R., & Hernández-Mendo, A. (2019). Relationships between reaction time, selective attention, physical activity, and physical fitness in children. *Frontiers in Psychology*, *10*, 2278.

Rosker, J., & Majcen Rosker, Z. (2021). Skill level in tennis serve return is related to adaptability in visual search behavior. *Frontiers in Psychology*, *12*, 689378.

Rueda, M. R., Fan, J., McCandliss, B. D., Halparin, J. D., Gruber, D. B., Lercari, L. P., & Posner, M. I. (2004). Development of attentional networks in childhood. *Neuropsychologia*, *42*(8), 1029-1040. https://doi.org/10.1016/j.neuropsychologia.2003.12.012

Schmidt, M., Jäger, K., Egger, F., Roebers, C. M., & Conzelmann, A. (2015). Cognitively engaging chronic physical activity, but not aerobic exercise, affects executive functions in primary school children: a group-randomized controlled trial. *Journal of Sport and Exercise Psychology*, *37*(6), 575-591. http://dx.doi.org/10.1123/jsep.2015-0069

Sibley, B. A., & Etnier, J. L. (2003). The relationship between physical activity and cognition in children: a meta-analysis. *Pediatric exercise science*, *15*(3), 243-256. https://doi.org/10.1123/pes.15.3.243

Singer, R. N. (2000). Performance and human factors: Considerations about cognition and attention for self-paced and externally-paced events. *Ergonomics*, *43*(10), 1661–1680. https://doi.org/10.1080/001401300750004078

Trick, L. M., & Enns, J. T. (1998). Lifespan changes in attention: The visual search task. *Cognitive Development*, *13*(3), 369-386.

Turner, M., Ishihara, T., Beranek, P., Turner, K., Fransen, J., Born, P., & Cruickshank, T. (2022). Investigating the role of age and maturation on the association between tennis experience and cognitive function in junior beginner to intermediate-level tennis players. *International Journal of Sports Science & Coaching*, *17*(5), 1071-1078.

Vaughan, R. S., & Laborde, S. (2021). Attention, working-memory control, working-memory capacity, and sport performance: The moderating role of athletic expertise. *European Journal of Sport Science*, *21*(2), 240–249. https://doi.org/10.1080/17461391.2020.1739143

Visual Search In Tennis. Crucial Feature For Successful Performance. (2020). Play Smart Tennis. Retrieved May 19, 2023, from https://playsmarttennis.com/2020/04/20/visual-search-in-tennis-crucial-feature-for-successful-performance/

Voss, M. W., Kramer, A. F., Basak, C., Prakash, R. S., & Roberts, B. (2010). Are expert athletes 'expert' in the cognitive laboratory? A meta-analytic review of cognition and sport expertise. *Applied cognitive psychology*, *24*(6), 812-826. https://doi.org/10.1002/acp.1588

Wang, C. H., Chang, C. C., Liang, Y. M., Shih, C. M., Chiu, W. S., Tseng, P., Hung, D. L., Tzeng, O. J. L., Muggleton, N. G., & Juan, C. H. (2013). Open vs. Closed Skill Sports and the Modulation of Inhibitory Control. *PLoS ONE*, *8*(2). https://doi.org/10.1371/journal.pone.0055773

Wang, B., Guo, W., & Zhou, C. (2016). Selective enhancement of attentional networks in college table tennis athletes: A preliminary investigation. *PeerJ*, *2016*(12). https://doi.org/10.7717/peerj.2762

Wolfe, J. M. (2020). Visual search: How do we find what we are looking for?. *Annual review of vision science*, *6*, 539-562.

Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: an alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human perception and performance*, *15*(3), 419. https://psycnet.apa.org/doi/10.1037/0096-1523.15.3.419

Xu, Y., Zhang, W., Zhang, H., Wang, L., Luo, Y., & Ni, G. (2022). Association between tennis training experience and executive function in children aged 8–12. *Frontiers in Human Neuroscience*, *16*, 924809.

Yu, M., & Liu, Y. (2020). Differences in executive function of the attention network between athletes from interceptive and strategic sports. *Journal of Motor Behavior*, 1–12. https://doi.org/10.1080/00222895.2020.1790486

Zhang, J. (2022). TRAINING METHODS FOR ATHLETES'NEUROLOGICAL REACTION TIMES. *Revista Brasileira de Medicina do Esporte*, *28*, 155-158.