DEPARTMENT OF PSYCHOLOGY

CONSTRUCTING AND UPDATING SPATIAL REPRESENTATIONS: A DEVELOPMENTAL APPROACH

DOCTOR OF PHILOSOPHY DISSERTATION

CHRISTOS MICHAELIDES

2018

DEPARTMENT OF PSYCHOLOGY

CONSTRUCTING AND UPDATING SPATIAL REPRESENTATIONS: A DEVELOPMENTAL APPROACH

CHRISTOS MICHAELIDES

A Dissertation Submitted to the University of Cyprus in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

May 2018

VALIDATION PAGE

Doctoral Candidate: Christos Michaelides

Doctoral Thesis Title: Constructing and updating spatial representations: A developmental approach

The present Doctoral Dissertation was submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy at the Department of Psychology and was approved on the 3rd of May 2018 by the members of the ***Examination Committee****.*

Examination Committee:

Research Supervisor: ____

Marios Avraamides, Associate Professor

Committee President: ____

Panayiotis Stavrinidis, Assistant Professor

Committee Member: ____

George Spanoudis, Associate Professor

Committee Member: ____

Tina Iachini, Professor

Committee Member: ____

Jan Wiener, Professor

DECLARATION OF DOCTORAL CANDIDATE

The present doctoral dissertation was submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy of the University of Cyprus. It is a product of original work of my own, unless otherwise mentioned through references, notes, or any other statements.

Christos Michaelides

……………………………………..

ΠΕΡΙΛΗΨΗ

Ο πρωταρχικός στόχος της εργασίας ήταν η πειραματική αξιολόγηση της ικανότητας παιδιών διαφόρων ηλικιών (6-, 7-, 8-, 9-, 10-, 11-χρονων), καθώς και ενηλίκων (19-, 35-, 60-χρονων), να διαμορφώνουν και να ανανεώνουν νοερά χωρικές αναπαραστάσεις για διατάξεις αποτελούμενες από πολλαπλά αντικείμενα. Συγκεκριμένα, η μελέτη εξετάζει: (1) την ακρίβεια της χωρικής μνήμης για διατάξεις που περιέχουν πολλαπλά αντικείμενα σε διάφορες ηλικιακές ομάδες, (2) την αποτελεσματικότητα νοερής ανανέωσης των προϋπαρχουσών χωρικών αναπαραστάσεων λόγω της μετακίνησης των συμμετεχόντων στο χώρο, και (3) την ανθεκτικότητά αυτών των αναπαραστάσεων μετά από μια διαδικασία αποπροσανατολισμού. Οι συμμετέχοντες κλήθηκαν να μελετήσουν μια διάταξη 4 αντικειμένων τοποθετημένων σε προκαθορισμένες θέσεις στην περιφέρεια ενός στρογγυλού χαλιού με διάμετρο 3 μέτρα. Μόλις απομνημόνευαν τη χωρική διάταξη, και ενώ βρίσκονταν στην αρχική θέση μελέτης και θέασης των αντικειμένων (*συνθήκη προσανατολισμού*), ο ερευνητής τοποθετούσε στα μάτια τους μια καλύπτρα και τους ζητούσε να δείξουν τα διάφορα αντικείμενα. Εν συνεχεία, στη *συνθήκη ανανέωσης*, ο ερευνητής περιέστρεφε τους συμμετέχοντες 45^{o} δεξιόστροφα και τους ζητούσε ξανά να δείξουν τα αντικείμενα από τη νέα τους θέση. Τέλος, στη *συνθήκη του αποπροσανατολισμού*, οι συμμετέχοντες κλήθηκαν να δείξουν τα 4 αντικείμενα μετά από 30 δευτερόλεπτα συνεχόμενης υποβοηθούμενης περιστροφής, η οποία είχε ως αποτέλεσμα τον αποπροσανατολισμό τους. Για τη στατιστική ανάλυση των αποτελεσμάτων χρησιμοποιήθηκαν διάφορες μετρήσεις. Η ηλικία των συμμετεχόντων (9 διαφορετικές ηλικιακές ομάδες), το φύλο (άντρας, γυναίκα), η χωρική βραχύχρονή τους μνήμη (χαμηλή, μέτρια, ψηλή) και το προτιμώμενο χέρι για την εκτέλεση διαφόρων δραστηριοτήτων (δεξιόχειρες, αριστερόχειρες, αμφίχειρες) συμπεριλήφθηκαν ως μεταβλητές πρόβλεψης της ακρίβειας και της ταχύτητας δείξης προς τα αντικείμενα. Τα αποτελέσματα έδειξαν ότι παρόλο που όλοι οι συμμετέχοντες παρέμειναν προσανατολισμένοι (ενώ ήταν δεμένα τα μάτια τους) και μπόρεσαν να δείξουν με ακρίβεια τα διάφορα αντικείμενα, τα μικρά παιδιά και οι πιο ηλικιωμένοι συμμετέχοντες ήταν λιγότερο ακριβείς σε σύγκριση με τις υπόλοιπες ηλικιακές ομάδες. Στη συνθήκη ανανέωσης, οι συμμετέχοντες μπορούσαν να δείξουν με ακρίβεια τα διάφορα αντικείμενα, γεγονός που υποδεικνύει ότι οι διάφορες ιδιοθετικές πληροφορίες είναι αρκετές για την ανανέωση και επικαιροποίηση των αποθηκευμένων χωρικών αναπαραστάσεων. Ωστόσο, το γεγονός ότι κάποιοι συμμετέχοντες (σε διάφορες ηλικιακές ομάδες) δεν μπόρεσαν να ανανεώσουν τόσο αποτελεσματικά τις αναπαραστάσεις τους όσο άλλοι, δείχνει ότι αυτή η διαδικασία

πιθανόν να παραμένει μια πιθανή πηγή προβλημάτων καθ' όλη τη διάρκεια της ζωής. Στη συνθήκη του αποπροσανατολισμού, για να μπορέσουν οι συμμετέχοντες να δείξουν τα αντικείμενα, έπρεπε πρώτα να υιοθετήσουν ένα υποκειμενικό προσανατολισμό. Όσοι από αυτούς υιοθέτησαν έναν από τους δύο προσανατολισμούς από τους οποίους προηγουμένως είχαν δείξει τα αντικείμενα (συνθήκη προσανατολισμού ή συνθήκη ανανέωσης), ήταν ταχύτεροι και ακριβέστεροι, συγκρινόμενοι με τους συμμετέχοντες που υιοθέτησαν άλλους τυχαίους προσανατολισμούς. Είναι ενδιαφέρον ότι οι δύο προσανατολισμοί με τους οποίους οι συμμετέχοντες είχαν προηγούμενη εμπειρία, επιλέχθηκαν κυρίως από την πλειοψηφία των ενηλίκων ηλικίας 19 και 35 ετών. Το φύλο και το προτιμώμενο χέρι των συμμετεχόντων δεν διαφοροποίησαν σημαντικά τις επιδόσεις τους στη δείξη των διαφόρων αντικειμένων. Αυτό που φαίνεται ότι επηρέασε την ικανότητά τους να δείχνουν με ακρίβεια τα αντικείμενα είναι η χωρητικότητα της χωρικής βραχύχρονής τους μνήμης. Οι συμμετέχοντες που ανήκαν στην ομάδα χαμηλής χωρικής μνήμης ήταν λιγότερο ακριβείς από εκείνους που βρίσκονταν στην ομάδα υψηλής χωρικής μνήμης, τόσο στη συνθήκη ανανέωσης όσο και στη συνθήκη του αποπροσανατολισμού. Η μελέτη ολοκληρώνεται με την ανάλυση των ευρημάτων σε σχέση με ευρήματα άλλων ερευνών και τις θεωρίες χωρικής νόησης.

ABSTRACT

The primary goal of the current study was to experimentally assess the ability of children at various ages (6-, 7-, 8-, 9-, 10-, 11-year olds), as well as young and older adults (19-, 35-, 60-year old), to construct and update spatial representations of multiple objects. Specifically, the study aimed to examine at different ages: (1) how accurate are spatial memories for layouts containing multiple objects, (2) how well the existing spatial memories are updated with participants' self-movement, and (3) how resilient spatial memories are to disorientation. Participants studied an array of 4 objects placed at predetermined locations on the circumference of a 3m-round carpet. Once they memorized the object array, and while blindfolded, in the *orientation phase*, they were asked to repeatedly point to the different objects from the initial learning orientation. Subsequently, in the *updating phase*, they were again asked to point to the objects after a 45^{o} physical rotation. Finally, in the *disorientation phase*, participants were asked to point to the 4 objects after a 30 seconds disorienting rotation. Analyses were conducted on different directional error measures (i.e., constant, pointing and variable error) and pointing latency, for the 3 experimental phases and the 9 age-groups. The gender, the spatial short-term memory capacity (measured with the Corsi Blocks tapping task), and the hand-preference of participants were also included as predictor variables in separate analyses. Results showed that although all participants remained oriented while blindfolded and were able to point accurately to the different objects, young children and older adults were less accurate than the other age-groups. In the updating phase, participants were able to point to the different objects accurately, indicating that idiothetic cues were sufficient to update their orientation relative to the stable environment. However, not all participants were able to update their spatial representation efficiently, indicating that the updating process remains a possible source of error throughout the lifespan. The disorientation phase entailed that participants adopt a subjective orientation in order to point to the different objects. Participants who adopted one of the two previously experienced orientations (e.g., the learning or the updating orientation) were faster and more accurate than those who adopted other random orientations. Interestingly, these experienced orientations were mostly selected by the majority of 19- and 35-year old adults, and only by a smaller number of children. Finally, although the analyses on gender and handedness did not reveal any significant differences in participant performance, spatial short-term memory capacity influenced performance. Participants in the low spatial memory group were less accurate than those in the high group in both the updating and the disorientation phase. The implications of the findings for theories in spatial cognition are discussed.

ACKNOWLEDGMENTS

I wish to express my profound gratitude to my research supervisor, Professor Marios Avraamides, whom I sincerely thank for his time, guidance, motivation and valuable comments throughout the thesis. It was a beautiful journey… Furthermore, I want to thank the members of my Examination Committee for their enthusiasm and suggestions to improve my work. The current study could not be completed without the help of all those children and adults who have participated in the experiments. My appreciation goes to every one of them. I also want to thank my brother, Andreas, for all the technological help he offered me and for the programming script for the Myo armband. My warmest gratitude goes to my wife Katerina and our children Maria and Kyriaki for their love, support, and patience in waiting for their husband/dad to complete his dissertation.

DEDICATION

This thesis is dedicated to my wife Katerina and our children Maria and Kyriaki.

Σας Αγαπώ!

TABLE OF CONTENTS

LIST OF FIGURES

APPENDIX C

APPENDIX D

LIST OF TABLES

APPENDIX C

APPENDIX D

ORGANIZATION

The present document is divided into five chapters. Chapter 1 provides a general introduction to spatial cognition and the importance of spatial frames of reference on the representation of location. It includes a comparative literature review on the development of egocentric and allocentric frames of reference from infancy to old age and the different theories of spatial representations, along with a description of spatial updating ability. Chapter 2 focuses on the current study. It presents the aims and the hypotheses of the study and discusses its contribution in understanding the development of spatial representations across the lifespan. Chapter 3 presents a detailed description of the methodology adopted in the current study. It describes the selection of the participants, the experimental materials, and apparatus used in the experiments, along with a detailed description of the experimental procedure. Chapter 4 describes the approach adopted for data analyses along with the results of the study. Both conventional and circular statistics were used to analyze the data, with response phase as a within-subjects factor, and age as the between-subjects factor. Separate analyses were also conducted with gender (male-female), spatial short-term memory capacity (based on Corsi's Block tapping task) and handedness (right, left, mixed-handers) as between-subjects factors. Finally, Chapter 5 presents the conclusions of the current study and its contribution is discussed in the context of past research in spatial cognition.

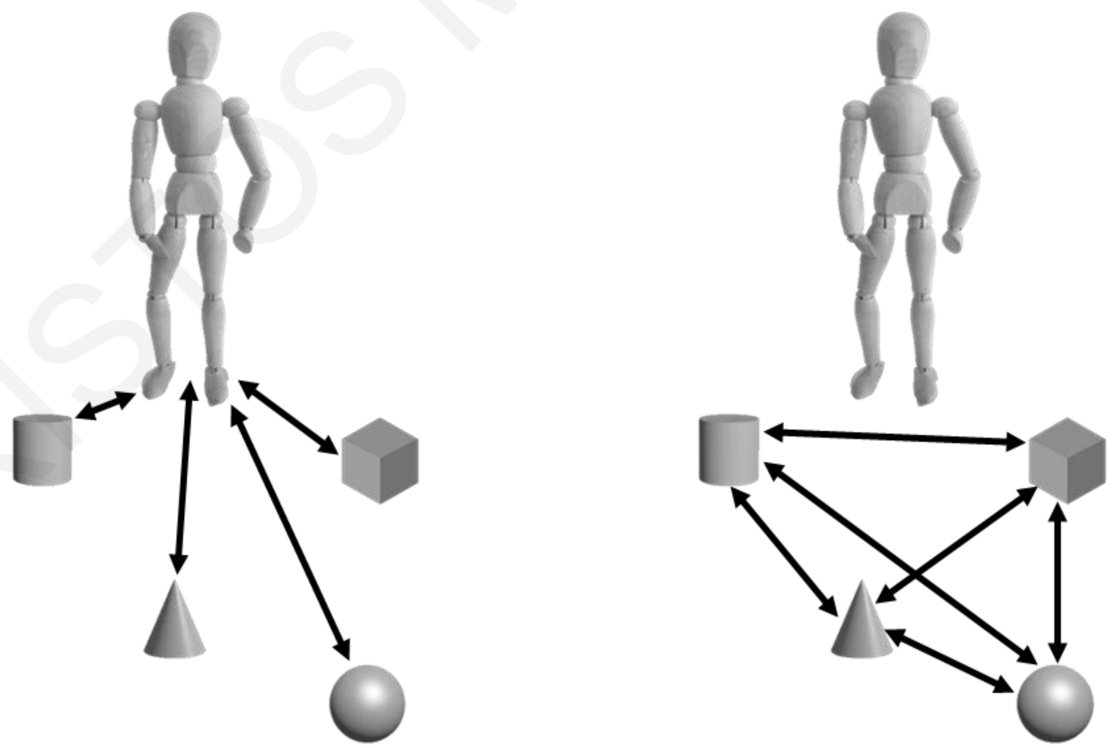
CHAPTER 1 – GENERAL INTRODUCTION

1.1. Spatial cognition and the representation of location

In the technological society of the 21st century, spatial cognition and spatial ability have become popular terms which are often closely associated with success in specific fields of study, such as science, technology, engineering and mathematics (STEM). Although spatial skills are essential in STEM fields (Uttal, Miller, & Newcombe, 2013; Wai, Lubinski, & Benbow, 2009), they are also fundamental to our everyday functioning and are inherent to many tasks that form our daily routines. For example, we find our way to the cafeteria because we remember where it is in relation to where we are standing or to other landmarks on the university campus. Navigating in the environment, trying to read a "You-Are-Here" map, or deciding which box is large enough for the present we have bought, depend on encoding, maintaining, and retrieving spatial information. The subject-matter of spatial cognition is to understand and describe how people represent and manipulate spatial information from their environment and how they use spatial representations for reasoning.

Although spatial cognition is a vast domain, according to Vasilyeva and Lourenco (2012) a key aspect which unites much of it, is the representation of location. Remembering a specific location is relational in nature, as it can only be achieved by processing information based on distance and direction which is defined relative to a specific point of origin or a particular frame of reference (Kelly, Avraamides, & McNamara, 2010; Mou & McNamara, 2002; Ruggiero, Iachini, Ruotolo, & Senese, 2009). We can either specify the position of an object with respect to our self, by saying for example that the ball is in front of me, or by referring to other objects or landmarks in the environment: the ball is under the table. Identifying a specific location is achieved by structuring spatial information in coordinate systems, known as frames of reference. Reference frames are stable, but at the same time flexible to code and update the representations of the surrounding space and the relations within it (Zaehle, Jordan, Wüstenberg, Baudewig, Dechent, & Mast, 2007).

Frames of reference are a central organizing concept in the study of spatial memory and cognition, acting like anchor-points in organizing and representing spatial information (Ruggiero et al., 2009; Shusterman & Li, 2016). In that sense, spatial representations are intrinsically linked to the context of a spatial reference system which is the conceptual basis for determining spatial relations among various objects (Friedman, 2005; Kelly et al., 2010; Klatzky, 1998; Ruggiero et al., 2009). Theoretical and empirical work on spatial representations suggests that spatial information can be stored in our memory based on two classes of reference frames: egocentric and allocentric (Avraamides & Kelly, 2008; Burgess, 2006; Iachini, Ruotolo, & Ruggiero, 2009; Kelly et al., 2010; Lester, Moffat, Wiener, Barnes, & Wolbers, 2017; Mou, McNamara, Rump, & Xiao, 2006; Paillard, 1991; Ruggiero, D'Errico, & Iachini, 2016; Vasilyeva & Lourenco, 2012; Zaehle et al., 2007; for a review see Klatzky, 1998). An egocentric frame of reference is used when locations are specified with respect to one's own body (or a specific part of one's body), maintaining thus self-to-object relations (Figure 1a). On the other hand, by using an allocentric frame of reference objects are located and defined based on their relations with other features in the surrounding environment, which are independent of the viewer's position (Figure 1b). Thus, allocentric encoding defines object-to-object relations, and the derived spatial representations are centered on specific features of the surrounding space. According to Shusterman and Li (2016), the term allocentric reference frame is often used to describe a location based on cardinal directions (e.g., north/south), another person's perspective, or a bird's-eye view.



(a) Egocentric (b) Allocentric

Figure 1. Egocentric and allocentric frame of reference.

The egocentric frame of reference is necessary for visual guided action which requires the precise computation of self-to-objects relations, as when avoiding obstacles while moving in a room full of furniture or when grasping an object. To do so, our brain must compute the position of a specific target in egocentric coordinates (Milner & Goodale, 2008). Waller (2006) and Wang (2012) proposed that the egocentric frame of reference is always available and offers an automatic and implicit way for representing spatial locations. However, the derived egocentric representations are not always effective because according to Iachini and Ruggiero (2006) they maintain the specific perspective under which spatial information has been experienced and encoded. In contrast, an allocentric frame of reference is thought to be a more flexible way of solving spatial tasks, because spatial information generated from it remains unchanged and independent of the viewer's momentary location and perspective. Allocentric representations are important in recognizing objects and scenes or planning future movements in extrapersonal-far space (Ruggiero et al., 2009; Vasilyeva & Lourenco, 2012).

Studies on the anatomical and functional base of egocentric and allocentric spatial coding have showed that they are partly unique domains which recruit distinct brain regions (Avraamides & Kelly, 2008; Burgess, 2008; Galati, Pelle, Berthoz, & Committeri, 2010; Ruggiero et al., 2009; Zaehle et al., 2007; but see Wolbers & Wiener, 2014). Results from different functional neuroimaging studies (for a review see Byrne, Becker, & Burgess, 2007; Galati et al., 2010) suggest that egocentric coding involve parts of the superior parietal cortex and frontal regions, while the formation of allocentric representations relies on parietal and retrosplenial subregions and the hippocampal formation. Based on functional imaging data, Zaehle et al. (2007), proposed the existence of a hierarchical processing system, in which allocentric representations require more processing resources than the egocentric ones. Thus, allocentric coding is believed not only to develop later in ontogenesis but also to be based on egocentric coding.

Although the ability to encode in an allocentric frame of reference seems to develop later than the egocentric (Piaget & Inhelder, 1967) and is thought as the most advanced form of spatial ability (Wang, 2012), both frames of reference are important and essential in representing spatial information and performing spatial actions in the surrounding environment. The information derived from both reference frames is usually integrated to allow successful spatial processing (Barca, Pezzulo, & Castelli, 2010; Byrne et al., 2007; Burgess, 2006). After all, an organism is a composition of potentially independent although associated systems, which work in parallel (Weiskrantz, 1990). In this sense, the egocentric and allocentric frames of reference are not mutually exclusive, but rather complement and interact with each other (Nadel & Hardt, 2004). Although many spatial tasks can be solved either way, some may rely more on one reference frame than the other. For example, grasping a chocolate bar that is in front of me is more likely accomplished within an egocentric framework, whereas trying to explain to someone how to find my house is more likely to involve an allocentric representation. The spatial task defines which frame of reference will be used, as according to Barca et al. (2010), the selection of the appropriate frame is highly action-specific.

1.2. The development of spatial frames of reference

An interesting and relatively unexplored research area on the development of spatial cognition is the search for the starting points and the possible focal points of change in the use of spatial frames of reference, as well as the study of mechanisms underlying their development (Iachini, Ruggiero, & Ruotolo, 2009; Moffat, 2009; Montefinese, Sulpizio, Galati, & Committeri, 2015; Vasilyeva & Lourenco, 2012). Given that previous research has well-established the importance of egocentric and allocentric frames of reference in memory organization (e.g., Kelly et al., 2010), two questions that arise are how reliance on one or the other type of reference frames –or on both of them- changes from childhood to adulthood and then from adulthood to old age, and to what extent these reference frames affect spatial performance over development.

From a developmental point of view, the most accessible spatial code –even for infants- is our own body and external references seem to develop later in life (Barca et al., 2010). According to some scientists, we perceive spatial information in an egocentric manner, and therefore the critical component of spatial memory is egocentric experience which allows us to take in information from what is around us and plan actions in space (Filimon, 2015; Iachini & Ruggiero, 2006; McNamara & Valiquette, 2004; Ruggiero et al., 2009; Shusterman & Li, 2016; Wang, 2012; Wang & Spelke, 2000).

The primacy of egocentric encoding in spatial memory organization is not something new. It was initially proposed by Piaget and Inhelder (1967), whose theoretical framework and empirical approach had a profound impact on subsequent research on spatial cognition. Piaget claimed that the initial understanding of spatial extent involved a qualitative distinction of the sensory world into the categories of reachable (near) and unreachable (far) and this initial concept was centered on the self itself. Decentering -the ability to conceptualize different aspects of a situation simultaneously- was seen as a progressive process, termed as the egocentric-allocentric shift. One of Piaget's major contributions is describing the age in which children switched from an egocentric to an allocentric frame of reference, with the well-known "three mountain task". Piaget and Inhelder (1967) proposed that infants and young children begin their life with only primitive and basic spatial abilities which are mostly topological. In the beginning, children can determine the location of an object in their environment based on an egocentric internal model in which the center of reference is their self. Only around the age of 10 children can understand and use projective (i.e., order) and Euclidean (i.e., angles and distance) information and can switch to a different frame of reference with an origin other than the self. From that point of view, the egocentric frame is considered to be inherent while the allocentric is considered to be acquired (Friedman, 2005).

Subsequent research on the development of spatial cognition challenged many of Piaget's claims, including not only the age norms he proposed but also the view that early spatial representations were purely egocentric (Nardini, Burgess, Breckenridge & Atkinson, 2006; Newcombe & Huttenlocher, 2000; Newcombe, Uttal, & Sauter, 2013; Vasilyeva & Lourenco, 2012). Experimental evidence showed that even infants could locate objects based on features of the surrounding environment, suggesting the use of an allocentric frame of reference. In an early experiment, Acredolo (1987) placed 11-months infants in a square room with only two identical windows in the wall, to the infant's left and right side. After teaching them, with the help of an auditory cue, to anticipate the appearance of an adult playing peekaboo in one of the two windows, she moved the infants so that the position of the event was reversed (i.e., rotated by 180^{o}). Acredolo found that infants were able to take into account their self-movement and use salient external landmarks (e.g., flashing lights and stripes) to track the location of the event. Lew, Bremner, and Lefkovitch (2000) used Acredolo's experimental design with younger infants and showed that even 8.5-months infants were able to remain oriented after displacement and locate a target from a novel position with the help of less distinctive landmarks (e.g., differently painted lanterns). These experimental findings suggest that from an early age, children possess some complex spatial skills. They can use direct and indirect landmarks to reorient themselves and take into account their movement to relocate themselves in space.

Although infants and young children seem able to use egocentric and allocentric representations at an early age, according to Vasilyeva and Lourenco (2012) this ability is quite limited and under development. Using a more complex experimental design, Nardini et al. (2006) asked 3 to 6-year olds to recall the location of a hidden toy placed in an array of 12 identical containers, bordered by specific landmarks (e.g., toy houses and animals). In one condition, Nardini et al. rotated the whole array while children maintained their initial learning orientation, and asked them to find the hidden toy. Results showed that performance at age 3 and 4 was significantly below chance, implying that young children systematically used an incorrect search strategy. Although children could use visual cues from the layout in which the toy was hidden, only 5- and 6-year-olds could effectively retrieve and use allocentric representations based on the array itself, in a task that required the inhibition of egocentric responses due to the rotation of the array. According to Nardini et al., the above-chance performance of the 5- and 6-year olds in retrieving the hidden toy was due to an emerging ability to rely on an allocentric representation of the layout that included spatial information about the bordering landmarks. Indeed, such a representation could have allowed the older children to compute the new egocentric location of the hidden toy after layout rotation by taking into account the changes in the locations of visible bordering landmarks. In a re-examination of these results, Negen and Nardini (2015) proposed that although even some 4-year olds could use the correct allocentric representation on some trials, the egocentric representational system was easier to use and more salient, so young children at that age had a tendency to use it first.

Previous research showed that spatial behavior during childhood was influenced by egocentric solutions such as view matching by familiarity or on updating one’s position during self-movement. In order to preclude any egocentric recall and test the emergence of allocentric representations during childhood, Nardini, Thomas, Knowland, Braddick, and Atkinson (2009) designed an experiment which could only be solved if participants used the external structure of the environment to reorient themselves. Nardini et al. hid a toy in one of two identical boxes placed on the left and right side of a large rectangular box with a different color on its front and back. Children at ages between 4 to 8 years saw where the toy was hidden and they were asked to search for it after being disoriented (turned while sitting blindfolded on an office chair) and placed on the same or the opposite side of the testing room. When children were asked to retrieve the toy from the viewpoint they saw it being hidden, their attempts were successful in all age groups. When they searched for it from the opposite viewpoint, 4-year olds were systematically incorrect, implying the use of the same egocentric strategy in both same-view and different-view conditions of the experiment, while 5-year olds performed at chance. Only 6- and 8-year olds were able to use the structural relations between the landmarks and the toy to reorient themselves in a viewpoint-independent, allocentric manner. This finding implies that allocentric representations develop later during childhood and are part of mature spatial cognition.

Similar findings were obtained with a virtual reality task known as StarMaze. In their experiment, Bullens, Iglói, Berthoz, Postma, and Rondi-Reig (2010), asked 5-, 7- and 10-year olds to locate a hidden goal location in an environment consisted of a pentagon with five lanes radiating from the corners of it. At the beginning of the experiment, children were asked to learn a particular route to the goal location. Then, Bullens et al. changed the departure point without children knowing it, and they asked children to perform two consecutive tasks: the multiple strategies task and the allocentric task. In the multiple strategies task, children were left to spontaneously use either an egocentric strategy (based on a sequence of body-turns performed in training trials) or an allocentric strategy (based on environmental cues) to reach the goal location. In the allocentric task, children were rewarded if they only used the allocentric strategy. Results showed an increase in the spontaneous use of the allocentric strategy with age and a gradual progressive change from a simpler egocentric to a more complicated allocentric strategy between 5- and 10-years of age. Both younger and older children showed a preference for the egocentric strategy, which was also the case in a similar study with adults (Iglói, Zaoui, Berthoz, & Rondi-Reig, 2009), indicating that the egocentric strategy was not abandoned with age. According to Bullens et al., only the 10-year-olds showed comparable performance to adults in the allocentric task, suggesting that the efficient use of this strategy emerges somewhere between 7- and 10-years of age.

According to Millar (1994), to represent allocentric spatial relationships, one must be first able to detach from the initial egocentric learning perspective. This effort might be especially demanding for young children, whose brain is still under development (Newcombe & Huttenlocher, 2000, 2006; Ruggiero et al., 2016), resulting in lower spatial performance compared to adults, regarding accuracy and response time. According to Moraleda, Broglio, Rodríguez, and Gómez (2013), several studies suggested that during childhood there is a developmental transition in the way children represent spatial locations, from an initial egocentric to an allocentric frame of reference. A critical developmental point in which a transition towards the ability of using allocentric representations occurs, seems to emerge somewhere around the age of 7-8 years (e.g. Lehnung, Leplow, Ekroll, Benz, Ritz, Mehdorn, & Ferstl, 2003; Leplow, Lehnung, Pohl, Herzog, Ferstl & Mehdorn, 2003), with the ability undergoing significant development until adolescence when specific brain regions reach full maturation (Pine, Grun, Maguire, Burgess, Zarahn, Koda, Szeszko, & Bilder, 2002).

Whereas there is consensus on that children's spatial ability is not at the same level as that of adolescents and adults (Newcombe & Huttenlocher, 2000), it is generally accepted that children engage in allocentric responding much earlier than previously thought. Scientists agree that school-aged children are capable of using both egocentric and allocentric frames of reference to represent their environment, although it is not yet clear when they are able to efficiently integrate spatial information derived from both reference frames (Nardini, Jones, Bedford, & Braddick, 2008; Nardini et al., 2009; Vasilyeva & Lourenco, 2012).

It seems that allocentric representations develop later, or at least they are selected for action at a later developmental stage (Nardini et al., 2009), with egocentric representations initially having the central role in human spatial cognition (Wang, 2012; Wang & Spelke, 2000, 2002). This may be related to the way we experience the environment and the way this experience changes with aging. From infancy to adulthood there is a progressive increase of the explored places, whereas during aging there is limited interaction with new environments and a withdrawal into private life, as a result of the normal age-related decline of physical and psychological resources (Montefinese et al., 2015). These progressive behavioural, neurological and functional changes might also result in declines in the quality of spatial representations, although this is an area that received little attention in studies of aging and relatively little data are available on the use of different reference frames in aging (Moffat, 2009; Montefinese et al., 2015).

So far, studies have investigated age-related changes in mental imagery and basic visuospatial and navigational abilities (e.g., Harris, Wiener, & Wolbers, 2012; Iachini, Poderico, Ruggiero, & Iavarone 2005; Iachini, Ruggiero & Ruotolo, 2009; Wiener, Kmecova, & de Condappa, 2012), and results revealed a normal age-related decline in selective spatial abilities, as older individuals show decreased accuracy in performing spatial tasks and take more time to complete them. In an early study, Kirasic (1991), compared the navigational abilities of young (21-33 years old) and older women (62-86 years old) in familiar and unfamiliar supermarket environments and found that the elderly had more difficulties acquiring spatial information in unfamiliar surroundings and had poorer allocentric performance.

Jansen, Schmelter, and Heil (2010) used a desktop virtual environment task to investigate the process of spatial knowledge acquisition in younger, middle-aged and older adults (20 to 70 years). Participants were asked to learn a route through a virtual maze and recall specific landmarks in it. Results revealed a general decline in the spatial memory of older participants, who took more time to both learn a new route and retrieve landmarks from memory, indicating an age-related difficulty in tasks that require the use of allocentric strategies. In another study, Harris et al. (2012) also tested the navigational strategies of young (mean 22 years) and older adults (mean 69 years) on a virtual maze task. Participants viewed a plus-shape maze and after approaching the central junction they had to turn either right or left to find a reward. In some trials, participants were rewarded for making the correct response (egocentric strategy) or for going to the correct place (allocentric strategy). Results showed that older participants performed worse during trials which required the use of an allocentric navigational strategy, and Harris et al., suggested that older adults have difficulties to switch from an egocentric response-based to an allocentric place-based strategy.

The difficulties of older adults in tasks that required the use of allocentric navigational strategies were also documented in other studies. Wiener et al. (2012) asked young (mean 21 years) and older adults (mean 69 years) to learn different routes in a virtual environment, consisting of multiple four-way intersections. Following this, participants were transported to a segment of a particular route, either in the previously experienced direction (route repetition) or in the opposite direction (route retracing). Participants were asked to identify the travel direction (e.g., repetition or retrace), and indicate the direction in which the route continued given the current direction. The results revealed that overall performance was worse for older than younger adults, and older adults had greater difficulties in retracing than in repeating the route. According to Wiener et al., route repetition can be solved based on previously formed egocentric representations, whereas route retracing requires allocentric processing which is more affected by aging. In another experiment, Wiener, de Condappa, Harris, and Wolbers (2013) asked younger (mean 21 years) and older adults (mean 75 years) to learn, through a virtual environment, a specific route that consisted of 4 four-way intersections. Participants were then guided toward an intersection, either from the previously experienced direction (same-direction trials) or from a new one (different-direction trials), and were asked to recall the route, based on different navigational strategies: beacon ("Turn toward X"), associative cue ("Turn right at X"), and allocentric-place strategy (spatial configuration of cues). Results showed that all participants performed better in the same-direction than in the different-direction trials, and younger adults performed better than older adults in both the same-direction and the different-direction trials. Interestingly, older and younger adults used different strategies to solve the task. According to Wiener et al., in the same-direction trials, the use of any of the 3 navigational strategies would result in correct responses. However, successful performance in the different-direction trials required the use of the allocentric-place strategy. Older participants (unlike the younger ones) repeatedly failed to use the allocentric strategy when approaching an intersection from a new direction and persisted in using the beacon strategy. Wiener et al. concluded that older adults remain biased in their response strategies and have difficulties in ignoring their egocentric strategy preferences. According to Lester et al. (2017), when a task requires switching between different frames of reference, aged participants have difficulties to switch from an egocentric to an allocentric strategy. These results are in line with other studies which showed that older adults had more difficulties in allocentric than in egocentric navigation tasks, and that older adults preferred to use egocentric than allocentric strategies to navigate in their environment, even when such strategies are maladaptive to task performance (for a review see Lester et al., 2017).

The difficulties of aging humans are not restricted to tasks that requires the use of an allocentric navigational strategy. Montefinese et al. (2015) asked young and older adults to memorize the location of a target object in a virtual living room according to fixed markers in the room (allocentric frame based on the environment), unstable cues (allocentric frame based on objects), and to the viewer's perspective (egocentric frame). Results showed that older people performed worse than young participants in both allocentric conditions, suggesting an aging-related impairment in the allocentric spatial coding. No differences were found between young and older participants in the egocentric condition. The above findings support the retrogenesis hypothesis claiming that cognitive changes in healthy aging reverse the order of acquisition in mental development (Reisberg, Kenowsky, Franssen, Auer, & Souren, 1999).

Notably, research has also documented difficulties among the elderly for spatial tasks requiring egocentric encoding. In one study, Iachini, Ruggiero, and Ruotolo (2009) compared the capacity of healthy adults to use egocentric and allocentric reference frames, by asking them to provide distance judgments about triads of easily nameable and well-known 3-dimensional objects. Results showed that the allocentric performance seemed to be relatively preserved with age, while the egocentric one showed a significant deterioration starting from the age of 70 and onward, implying that aging had only partly affected spatial processing.

To the best of my knowledge, only the study by Ruggiero et al. (2016) has provided some preliminary data on the ability to process spatial information in healthy participants from 6 to 89 years of age. In their experiment, participants were asked to make verbal, spatial judgments about the locations of three-dimensional objects (sphere, cylinder, pyramid, cone, cube, parallelepiped). Each time a triad of these objects was chosen and placed on a desk in front of the participant, who had to memorize their positions. Then the objects were removed, and the participant was asked to provide either an egocentric verbal judgment for the objects ("which object was closer to you?") or an allocentric one ("which object was closer to the cone?"). Results showed that both 6-7 years old children and 80-89 years old adults were slower and less accurate in their spatial judgments in comparison to all other age groups. Although egocentric judgments were faster and more accurate than allocentric judgments, the two spatial components were affected differently by age, as the egocentric performance was lower in 6-7 year-olds and adults from 60 years and onward, while the allocentric one was pretty similar among the different age-groups. The experimental studies so far have generated conflicting conclusions on how aging affects the egocentric and the allocentric frame of reference, and it remains unclear which spatial components are associated with a normal age-related decline and which ones remain intact. More developmental research on spatial representations is needed, to establish a baseline of the normal functioning of important spatial processes at different ages.

1.3. Theories of spatial representations

Different theories and models of spatial memory have presented accounts for how frames of reference are used to represent spatial information (e.g. Holmes & Sholl, 2005; Mou et al., 2006; Mou, McNamara, Valiquette, & Rump, 2004; Wang, 2012; Wang & Spelke, 2000; for a review see Avraamides & Kelly, 2008; Byrne et al., 2007). Most of them include an egocentric system which represents transient self-to-object relations which decay rapidly in the absence of sensory-perceptual support. Their key difference concerns the existence or not of an allocentric system in which inter-object relations are represented in an enduring allocentric form. For example, in Wang and Spelke's model (2000), spatial representations rely primarily on an online transient egocentric system that is constantly updated as one moves. Both self-to-object and object-to-object relations are perceived as egocentric representations, and only the geometric shape of the environment is represented allocentrically (Wang, 2012). Sholl's model includes both an egocentric and an allocentric coding subsystem (Holmes & Sholl, 2005; Sholl & Nolin, 1997). The egocentric system represents self-to-object relations which can be effortlessly updated as a result of self-movement, and directs motor activity in the environment (e.g., reaching and grasping objects). The allocentric system codes object-to-object spatial relations in an orientation-independent manner. Similarly, the model proposed by Mou et al. (2004), also consists of two subsystems: an egocentric and an environmental subsystem. The egocentric subsystem codes transient self-to-object representations which are used for locomotion. The environmental subsystem represents the enduring features of familiar environments in an orientation-dependent manner.

In a series of experiments, Wang and Spelke (2000) examined the use of the egocentric and allocentric frame of reference, in a study that requires participants to point to targets after movement. The authors asked adults participants to study an irregular configuration of 6 objects placed in an experimental room, before entering a small chamber in the middle of it. Participants were asked to point to different objects under several conditions while blindfolded: after a small rotation, after continuous turning for 1 minute with and without a directional cue, or after being disoriented, and then while oriented in the environment. Wang and Spelke's conjecture was that if participants were using an offline enduring allocentric representational system while pointing to unseen objects, disorientation would not affect their estimations of relative directions to different objects. Results showed that the error in estimating the relative directions increased after the disorientation procedure, leading Wang and Spelke to suggest that participants relied on an online transient egocentric system that was constantly updated as they moved. They concluded that navigation depends on egocentric spatial representations which are updated as one moves, but without visual recalibration, disorientation weakens the updating procedure and disrupts configuration knowledge.

A substantial body of research has questioned Wang and Spelke's views, indicating that at least adult participants form an allocentric representation for inter-object relations and use it to locate objects in their surrounding environment (e.g., Burgess, Spiers, &

Paleologou, 2004; Holmes & Sholl, 2005; Mou et al., 2004, 2006). Waller and Hodgson (2006) challenged the primacy of transient egocentric representations that Wang and Spelke (2000) proposed, and suggested instead that both egocentric and allocentric representations are formed during learning objects locations. Waller and Hodgson based their hypothesis on the observation that even after disorientation in Wang and Spelke's experiments, participants' ability to retain some knowledge of relative directions to targets was much below chance performance. According to Waller and Hodgson, the disorientation procedure resulted in switching reliance from a precise but transient representation to a more enduring but coarser representation. In conclusion, theories of spatial representations suggest that we can use multiple systems to represent the spatial relations around us and navigate in the surrounding environment, and the selection depends each time on the task. Both egocentric and allocentric representations are integrated and interact to allow a comprehensive perception of the world.

1.4. Spatial Updating

People act in three-dimensional space in which egocentric spatial relations are constantly changing as a result of self-movement. Keeping track of how these relations change is achieved through a mechanism known as *spatial updating* (Bennett, Loomis, Klatzky, & Giudice, 2017; Wang, 2004, 2007; Wang & Spelke, 2000).

Previous studies (e.g., Farrell & Robertson, 1998; Farrell & Thomson, 1998; Rieser, 1989; Wang, 2004) suggested that spatial updating is an automatic process that takes place continuously during movement, and could even be obligatory, in the sense that at least in some circumstances,it might be beyond conscious control and hard to suppress. Evidence for the automaticity of spatial updating comes from studies documenting the ease with which participants are able to accurately and quickly point to object locations following physical movement (e.g., Farrell & Robertson, 1998; Farrell & Thomson, 1998; Rieser, 1989). The obligatory nature of spatial updating was proposed based on results showing that individuals cannot easily ignore their self-movement in order to point to objects as if they hadn't moved (Farrell & Thomson, 1998; May & Klatzky, 2000). However, other scientists did not find evidence of automaticity in spatial updating due to participant's self-movement (e.g., Finlay, Motes, & Kozhevnikov, 2007; Motes, Finlay, & Kozhevnikov, 2006; Waller, Montello, Richardson, & Hegarty, 2002). For example, in one experiment, Motes et al. (2006) asked participants to study and memorize a scene of 11 objects and then make same-different judgments, either after they had moved around the scene or after the scene was rotated. The analysis did not reveal any significant differences in scene recognition accuracy between the 2 experimental conditions, leading Motes et al. to question the view that self-movement leads to automatically-updated spatial representations (but see Simons & Wang, 1998 for different results with a similar task).

According to Finlay et al. (2007), the failure of some studies to find evidence of automaticity in spatial updating despite individuals' self-movement, might be related to the use of different frames of reference for representing scenes or object locations. If individuals encode objects in a transient egocentric frame of reference which is centered on the body, self-movement will automatically result to an update of the self-to-object spatial representations (Bullens, 2009; Mou et al., 2004). In contrast, if enduring allocentric representations are formed using a reference frame that is external to the self, these representations are not automatically updated by self-movement. Notably, according to He and McNamara (2017), Mou et al. (2004), and Wang (2017) allocentric, object-to-object representations can also be updated, but they require more attentional control and additional computations, which increase updating workload.

Many studies provided evidence that when people physically move to a new standpoint, they continuously and effortlessly update spatial relations between themselves and objects in their environment, presumably by relying on the idiothetic information that accompanies physical movement (e.g., vestibular signals, proprioceptive and optic flow information). Rieser (1989) showed that adult participants could more quickly update their egocentric spatial representations of an array of objects and point to the objects without vision following real- than imagined movement. This finding was also reported by Presson and Montello (1994). In that study, blindfolded participants were asked to point to previously- memorized locations of 3 objects, after performing actual or imagined movements (translations and rotations). Results showed that participant's pointing was more accurate after physical than imagined rotations. In another experiment by Simons and Wang (1998), participants were asked to study a layout of 5 objects placed on a table, and later identify which object was moved to a new position. In the test-phase, half of the participants physically moved to a new standpoint, and the other half viewed a rotated array while they remained at the learning position. Although the two conditions provided exactly the same visual information at the test-phase, participants were more accurate in detecting layout changes in the condition that followed self-movement. This suggests that information acquired through physical movement enhance spatial updating.

The contribution of physical movement in updating previously formed spatial representations was also shown in experiments that required individuals to view a target and walk to it without vision, over long distances. In one such experiment, Rieser, Ashmead, Talor, and Youngquist (1990) found that participants could accurately walk without vision and stop very close to a previously seen target, placed up to 22m away in an open field. Based on this and other results, Rieser (1989) argued that movement provides individuals with proprioceptive information that allows them to update their representations automatically. Interestingly, Newcombe, Huttenlocher, Drummey, and Wiley (1998) showed that not only adults but even 22-months old infants were able to rely on both visual and self-movement information to update their spatial representations, in a task that required walking to the opposite side of a rectangular sandbox to search for a hidden object. Studies with infants and young children showed that egocentric updating performance appears quite early in spatial development. In one of the early experiments in cognitive development, Huttenlocher and Presson (1973) asked third and fifth-grade children to study an array of 3 objects placed on a table and describe its appearance from a new perspective after imagining moving around the array or after actually walking around it while it was covered. Results showed that children made fewer errors when they were asked to walk to a new position around the table, than when they were asked to imagine their movement.

Using the same paradigm, Nardini et al. (2006) asked 3 to 6-year olds to recall the location of a hidden toy placed in an array of 12 identical containers, bordered by distinct landmarks (e.g., animals, toy houses). In one condition, children were asked to maintain their initial position while Nardini et al. rotated the array. In another condition, the children were asked to walk to a new position while the array remained still. Results showed that performance at ages 3 and 4 did not differ from chance when the array was rotated, and only from the age of 5 and onward performance was above chance. In contrast, children's' performance was better after physically walking to a new standpoint than when the array was rotated. Although these results indicate that the ability to spatially update locations based on self-movement is present at a young age, it seems to improve dramatically between 3 and 6 years and possibly continues to change even after the age of 6 to reach the adult level.

In a more recent study that employed virtual environments, Negen, Heywood-Everett, Roome, and Nardini (2017) showed that 3.5- and 4-year-old children could locate a hidden object better than chance when they pointed to it either from the learning standpoint or a novel standpoint they adopted through physical movement. Interestingly, when children were teleported to the new standpoint, only older children could point to the hidden object at better than chance levels. The youngest children performed at chance levels in the absence of self-motion information, suggesting that they were not able to update the spatial relations and did not encode the location of the hidden object relative to other landmarks in the environment.

Although these studies showed that even young children's updating performance benefits from physical movement, only sparse past research has examined spatial updating performance across the lifespan. In one of the few studies carried out, Bennett et al. (2017) asked young (mean age = 23.5 years) and older adults (mean age = 68.5 years) to study and memorize a layout containing 1, 3 or 6 coloured lights placed on a room floor, and to walk while blindfolded to a specific target either directly or after walking to a specific direction and turning to walk to the target when instructed. The task required participants not only to encode, retain, and update spatial locations from memory but to also execute locomotor responses to one or more targets. Results showed that both younger and older adults were able to update self-to-location representations, and walk to the unseen target(s) with accuracy. However, older adults walked farther from the target location and required more decision time than younger adults. Bennett et al. proposed that the observed decrements in older adult's performance reflect the general decline in spatial processing due to aging, rather than a specific deficiency in spatial updating per se.

Despite the fact that spatial updating is fundamental to everyday life, little research has been done to describe how it develops across the lifespan. The main body of experimental research has been restricted in the spatial updating processes in young adults (e.g., Avraamides, 2003; He & McNamara, 2017; Farrell & Thomson, 1998; Finlay et al., 2007; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Motes et al., 2006; Mou et al., 2006; Waller & Hodgson, 2006; Waller et al., 2002; Wang, 2004; Wang & Brockmole, 2003; Wang & Spelke, 2000; Wang, Crowell, Simons, Irwin, Kramer, Ambinder, …& Hsieh, 2006; Wolbers, Hegarty, Buchel, & Loomis, 2008). Fewer studies have examined spatial updating in children (e.g., Huttenlocher & Presson, 1973; Kruger & Jahn, 2015; Nardini et al., 2006; Negen et al., 2017) and infants (Newcombe et al., 1998), and only recently has the focus turned to older adults by comparing their performance with that of younger individuals (e.g., Bennett et al., 2017; Giudice, Bennett, Klatzky, & Loomis, 2017; Zhong & Kozhevnikov, 2016). Overall, this brief review of the previous literature indicates that the developmental trajectory of spatial updating, from childhood to old age, is fragmented and remains largely unknown. Although studies with infants and young children provided evidence that this ability is present quite early, it is yet not clear whether it develops gradually through childhood to reach the adult end state and whether it declines as a result of aging. One of the goals of the current study is to assess the ability of children and adults at various ages to update their egocentric spatial representations for layouts containing multiple objects, using the same experimental task. Besides being part of our daily life, spatial updating -and spatial ability in general- is a fundamental component of human intellect. Therefore, understanding how it develops throughout the lifespan is interesting from both a theoretical and a practical point of view.

CHAPTER 2 – THE CURRENT STUDY

The representation of location is one of the subject-matters of spatial cognition. However, our understanding on how people form and update their spatial representations is limited, as much of previous research is restricted on one (mostly undergraduate students) or two age-groups (e.g., children or adults). Trying to describe the developmental course of this spatial ability is not only interesting from a theoretical point of view but also necessary as it will provide a baseline of what is expected at different ages. Such a baseline may be useful not only for identifying the pathological cognitive decline in older adults but also for re-evaluating the teaching methods in the school environment, based on how children of different ages learn. Thus, any attempt to understand and describe spatial representations will benefit from the employment of a developmental lifespan approach.

The primary goal of the study is to experimentally assess the ability of healthy participants aged from 6 to 80 years, to construct and update spatial representations of multiple objects. Specifically, the study aims to examine at different ages: (1) how accurate are spatial memories for layouts containing multiple objects, (2) how well the previously formed spatial memories are updated during short self-movement, and (3) how resilient spatial memories are to disorientation.

The study adopts the paradigm of Wang and Spelke (2000), which was used to study the nature of the spatial representations that support egocentric responses to memorized locations. In the experiment I conducted, participants were asked to study the layout of four target objects placed on the circumference of a round carpet at different locations, and then point to the objects under 4 conditions: (1) with their eyes open (*training phase*), (2) blindfolded while standing at the initial learning orientation (*orientation phase*), (3) blindfolded after a small rotation of 45 degrees (*updating phase*) and (4) blindfolded after a 30 seconds disorienting rotation (*disorientation phase*).

The training phase served as practice, allowing participants to become familiar with the equipment that was used and provided a measurement of how accurate pointing responses can be towards visible locations. The orientation phase served as a baseline of pointing without vision but under conditions of orientation, while the updating phase provided data on participants' ability to update egocentric locations following a rotation of 45°. Finally, the disorientation phase examined whether the internal consistency of the spatial representation could be disturbed, as a result of disorientation induced by 30 seconds of assisted rotation. In all the experimental phases, participants' performance was assessed by pointing to different targets using an air-mouse.

Before they were introduced to the experiment, participants were tested for their handedness -the preference to use one hand more than the other when completing a task. Reio, Czarnolewski, and Eliot (2004) suggested that spatial ability has a multidimensional nature, which according to Pontillo (2010) might be affected not only by age, experience, and gender but also by handedness. Annett (1970) proposed that hand-preference affects performance abilities (e.g., accuracy and pointing latency) especially under eyes-closed conditions (Ittyerah, Gaunet, & Rossetti, 2007). Therefore, I decided to include handedness as a variable in my study to examine the potential relationship between handedness and participants' pointing responses to previously memorized locations, because it might add something useful in existing literature.

Albeit handedness has been studied for years, the findings of different studies on its relation to spatial and other cognitive abilities have been contradictory. For decades, handedness was used by neurologists and psychologists as a marker for cerebral lateralization (Annett, 2002; Reio et al., 2004). According to Voyer (1996), the human left hemisphere processes mostly verbal stimuli, whether right hemisphere is more specialized for visuospatial functions (for a review see Vogel, Bowers, & Vogel, 2003). This hemispheric asymmetry led a number of scientists to propose that left-handedness –which is mostly guided by the right hemisphere, was associated with better performance in specific spatial tasks (Annett, 2002; Reio et al., 2004). In an experiment, Reio et al. (2004) asked adult participants to complete different paper-and-pencil spatial tests and found that left-handers performed better than right-handers on mental rotation, spatial visualization, and visual exploration tasks, whether right-handers were better than left-handers on a spatial location memory task. However, McKeever, Rich, Deyo, and Conner (1987) found that left-handers performed worse than right-handers on a spatial visualization test (i.e. the Stafford Identical Blocks Test). In a large longitudinal study with young children, Johnston, Nicholls, Shah, and Shields (2009) found that right-handers performed better than left-handers in tasks designed to assess general cognitive abilities. Other studies did not reveal any significant differences between right- and left-handers. For example, Snyder and Harris (1993) did not find any differences due to handedness on a spatial visualization test (the Stafford Identical Blocks Test), or in a task that required 3D drawing ability. In a more recent experiment, Pontillo (2010) investigated the extent to which handedness influenced performance in simulated telerobotic tasks. She asked adult participants to manipulate a robotic arm in a virtual environment in order to perform different tasks (e.g., moving the robotic arm from position A to position B while avoiding obstacles, or moving a specific component 2 meters from the target), and found no significant difference between right and left-handed participants.

Even though most people are right-handed (Annett, 2002; Perelle & Ehrman, 1994; Willems, Van der Haegen, Fisher, & Francks, 2014), a substantial proportion of the human population is left-handed. Perelle and Ehrman (1994) analyzed data from a large international survey on handedness (12,000 participants from 32 countries) and found that the proportion of left-handed people was estimated from 2.5% to 12.8% depending on the country. Despite the variations in the proportion of left-handers in the different studies, scientists agree that roughly 10% of humans prefer to use their left hand for writing, throwing or brushing their teeth (Perelle & Ehrman, 1994; Willems et al., 2014). Even though traditionally, left-handers were excluded from studies in order to reduce variance in the data, Willems et al. proposed that left-handers should be included in experimental designs at about 10% -which is the average historical proportion corresponding to their population frequency- in the same way, that participant's gender is taking into account.

Nine different age-groups (6-, 7-, 8-, 9-, 10-, 11-year olds, 19-, 35-, 60-year old adults) were formed based on previous research showing that important developmental changes in different spatial abilities occur between 6 and 11 years of age, and also between late childhood and early adulthood (e.g., Hund & Foster, 2008; Hund & Plumert, 2003; Michaelides & Avraamides, 2017; Newcombe & Frick, 2010; Plumert, Franzen, Mathews & Violante, 2017; Recker & Plumert, 2009). During the primary school years, children seem capable of using both egocentric and allocentric frame of reference to represent their environment, although it is not clear when these representations begin to interact or when their use begins to alternate efficiently (Nardini et al., 2008, 2009; Vasilyeva & Lourenco, 2012). A number of scientists proposed that this seem to emerge at around 6-7 years of age, ultimately resulting in the ability to build complex spatial representations from 10 years of age onward (e.g. Bullens et al., 2010; Nardini et al., 2006, 2008). Furthermore, the six child groups map to the six grades of primary school in Cyprus (6, 7, 8, 9, 10 and 11 years are the mean ages of Grades 1, 2, 3, 4, 5 and 6 respectively), providing a convenient way to test children during school hours. Additionally, research with healthy older participants typically reports an age-related decline in selective spatial abilities which starts between 60 and 70 years of age (Iachini, Ruggiero, & Ruotolo, 2009; Ruggiero et al., 2016). Thus, the extent of the particular sample allows shedding some light on issues about spatial reference frames that are currently pending in the literature.

2.1. Hypotheses

Hypothesis 1: Recent studies (e.g., Michaelides & Avraamides, 2017; Plumert et al., 2017) showed that younger children are less accurate than older children and adults in reconstructing from memory an array of multiple objects. Therefore, I expect that spatial memories in the orientation phase will be less accurate for younger children, than older children and adults.

Hypothesis 2: Although previous studies showed that self-movement provides useful vestibular and motor efference cues which can be used to update spatial memories accurately, the updating process is not perfect. Updating accumulates error which is problematic for long distances. Although in the present experiment, the updating phase involves only a short rotation, I expect that there will be decrements in participants' pointing performance compared to the orientation phase.

Hypothesis 3: In the disorientation phase, blindfolded participants must adopt a subjective orientation, to point to the different objects. Previous research with adults (e.g., Holmes & Sholl, 2005; Mou et al., 2006) showed that when people are disoriented, some of them adopt the orientation experienced during learning. I expect that participants, who will adopt one of the two previously experienced orientations (e.g., the learning or the updating orientation) as their subjective orientation, will be more accurate and faster in their pointing judgments, than those who will adopt other random orientations.

Hypothesis 4: I expect that participants will perform worse in the disorientation phase than in the orientation and the updating phase, either because of switching to a more enduring but coarser allocentric representation or because egocentric vectors will be disturbed due to disorientation. If disorientation switches reliance from an egocentric to an allocentric representation, the decrement might be more prominent for younger children, who may have no allocentric representation to switch to, compared to other age-groups. If however, people continue to rely on egocentric vectors for their spatial representations, there is no reason to expect that the decrement would differ across age-groups, as the disorientation process will disturb the egocentric vectors.

Hypothesis 5: After studying the locations of the different objects, participants were blindfolded for the whole experiment without having the opportunity to refresh their memory for the object array. In order to point to the different objects in the 3 response phases, blindfolded participants had to rely on previously formed mental spatial representations. I expect that participants with high spatial short-term memory capacity will be more accurate in their pointing performance, than those with low spatial short-term memory capacity.

Hypothesis 6: Despite the fact that there is still a controversy about the conditions under which gender differences are observed in spatial abilitiy, scientists agree that they depend largely on the type of spatial task used (Iachini, Ruggiero, Ruotolo, & Pizza, 2008; Voyer, Voyer, & Bryden, 1995). Therefore, based on previous findings from studies that used Wang and Spelke's (2000) paradigm with adult participants, I do not expect any gender differences on pointing accuracy and latency.

Hypothesis 7: Although hand-preference might influence participants' accuracy while pointing to a target with vision available, I expect that pointing to different objects while being blindfolded would not affect participants' pointing accuracy and latency.

2.2. Significance of the study

Taking into account that prior research has recognized the significance of spatial frames of reference in memory organization (e.g., Kelly et al., 2010; Mou & McNamara, 2002; Ruggiero et al., 2009; Shusterman & Li, 2016), it is quite surprising how little is known about their developmental course from childhood to old age. The results gathered so far are controversial and scientists have not reached conclusions about the starting points and the focal points of change in the use of spatial frames of reference or about the aspects of spatial performance that decline with age or remain intact (Montefinese et al., 2015; Ruggiero et al., 2009).

Although there is a substantial body of experimental research on spatial frames of reference, this has been restricted in the use of egocentric and allocentric frame of reference in adults –mostly undergraduate university students (e.g. Avraamides & Kelly, 2005; Burgess et al., 2004; Hegarty & Waller, 2004; Holmes & Sholl, 2005; Iachini, Ruotolo, & Ruggiero, 2009; Igloi et al., 2009; McNamara Rump, & Werner, 2003; Mou et al., 2004, 2006; Ruggiero et al., 2009; Wang et al., 2006; Wang & Spelke, 2000), or children (e.g. Bullens et al., 2010; Nardini et al., 2006, 2009; Negen & Nardini, 2015; Negen et al., 2017; Vasilyeva & Lourenco, 2012). Fewer studies have approached spatial reference frames by comparing the performance of children to that of adults (e.g. Nardini et al., 2008), or by comparing older to younger adults (e.g. Harris et al., 2012; Iachini, Ruggiero, & Ruotolo, 2009; Jansen et al., 2010; Montefinese et al., 2015; Wiener et al., 2012, 2013).

According to Cowan, Naveh-Benjamin, Kilb, and Saults (2006), a prerequisite to assess the life-span development of different psychological processes is to test both school-age children and older adults with the same experimental methods. No study so far has appraised egocentric and allocentric spatial processes throughout the entire lifespan using the same experimental task, even when such an attempt can clarify their characteristics and the extent to which they form distinct functions. I deem that this research gap might have narrowed our understanding of how these spatial representational systems emerge, develop and interact across the lifespan.

A developmental study on egocentric and allocentric representations could provide useful insights into their distinct features and in the way different ways of processing spatial information interact across the lifespan. It would also contribute to the debate on the retrogenesis hypothesis, according to which the functional loss observed in healthy aging reverses the order of functional acquisition in the normal developmental process (Reisberg, Kenowsky, Franssen, Auer, & Souren, 1999). In development, allocentric coding is thought to be acquired later than egocentric (Piaget & Inhelder, 1967). If there is a difference in the use of egocentric and allocentric reference frames between children and adults, or between younger adults and the elderly, and a preference of younger children and the elderly to use egocentric reference frame, this would support the retrogenesis hypothesis for spatial abilities. Such findings would be of important theoretical but also clinical relevance. From a theoretical point of view, they would further our knowledge about spatial cognition, while from an applied perspective they would contribute to developing more targeted efforts to address the functional problems resulting from healthy aging. Such developmental work might provide some preliminary data in forming a baseline of normal spatial functioning through the lifespan.

CHAPTER 3 – METHODOLOGY

3.1. Participants

A total of 216 healthy participants (116 females), ranging from 6 to 80 years old took part in the study. Participants were divided into 9 age-groups -- 6-, 7-, 8-, 9-, 10-, 11-year old children, 19-, 35-, 60-year old adults -- with 24 participants in each group. The distribution of gender in the different age groups was about equal (Table 1).

Children were recruited from two public primary schools, one in the Nicosia and the other in the Larnaca districts in Cyprus. The 19-year-old adults were recruited from an undergraduate psychology course at the University of Cyprus, while the 35- and the 60-year-old participants were volunteers from the community (e.g., faculty and staff at the two primary schools, their friends and family, and others recruited by word of mouth). All participants had a normal or corrected-to-normal vision and reported good general health and no physical or sensory impairment.

The study protocol was approved by the Centre of Educational Research and Evaluation of the Cyprus Pedagogical Institute as well as from the Ministry of Education and Culture (Ref. No: 7.15.01.25.5/5). All parents provided informed consent for the participation of their children to the study, after reading an information letter that was sent to them. All participants verbally agreed to participate in the experiment and were informed that they could withdraw at any time without any consequences. None of them was aware of the purpose of the study or had partaken in a similar experiment before. University students received course credit and children received a small prize and a participation certificate.

Table 1

Summary Demographics for Participants in the 9 Age-Groups (N=216)

	6-year old children	7-year old children	8-year old children	9-year old children	10-year old children	11-year old children	19-year old adults	35-year old adults	60-year old adults
Mean Age	78.96	90.17	102.83	114.75	126.83	139.92	232.71	427.42	682.96
SD of Age	3.48	3.60	3.60	3.59	3.80	3.64	12.22	74.23	130.73
Gender: M/F	12/12	12/12	13/11	10/14	11/13	12/12	9/15	12/12	9/15
R-handed	23	22	21	21	20	22	21	21	23
L-handed	--	1F	1M/1F	2M/1F	2M/1F	1M/1F	1M/1F	1F	1M
Mix (R-hand)	1M	1M	--	--	1M	--	1M	1M/1F	--
Mix (L-hand)	--	--	1M	--	--	--	--	--	--
N	24	24	24	24	24	24	24	24	24

Note. Mean age is in months. M = male; F = female. R-handed = right-handers; L-handed = left-handers; Mix (R-hand) = mix-handers with right-hand preference; Mix (L-hand) = mix-handers with left-hand preference.

3.2. Materials and Apparatus

3.2.1. Experimental materials

A round carpet with a 3m diameter was used for the experiment. A smaller round red carpet with a 48cm diameter was placed on it to mark the participants' standpoint (Figure 2). Four stuffed animals -- a duck, a dog, a cat and a rabbit -- were placed on the edge of the larger carpet at a predetermined angular arrangement. All four were 13 cm in height, and 8 cm in width and they were selected on the basis of pilot testing showing that they could be recognized and named by participants of all ages, and they did not share any obvious semantic associations. The names of the targets –which all comprised of two-syllable words in Greek (cat-γά/τα, dog-σκύ/λος, duck-πα/πί, rabbit-λα/γός)- were announced to participants through a 5-meter wired Sennheiser HD 201 headphone set connected to a Lenovo IdeaPad Z580 laptop computer. The experimenter gave any additional information needed during the experiment, through a Speedlink SL-8708-BK Lucent desktop microphone. The experimental protocol and data logging were controlled by a script written in the C# programming language.

Figure 2. A view of the carpet and the surrounding target objects placed on its circumference.

The angles of pointing responses were measured by a Myo armband (Thalmic Labs, North America) that participants wore in their predominant forearm. The Myo armband is a wearable device that uses electromyography to read electrical signals emitted by the muscles and the motion of a person's forearm and convert them into gestures. For the purpose of the present study, a program was created in C# that was able to extract the angle of the arm of the user during pointing. The program used the native C++ library of Myo to obtain the yaw (rotation) without taking into account the height or the relative position of the participant. The Myo could return the rotation of the subject's arm when participants clicked the air mouse with an accuracy of +- 1 degree. The main advantage of using the Myo is that it allows natural pointing by extending one's arm than deflecting a joystick. In a past experiment, in which adult participants had to explore an immersive virtual environment, McCullough, Xu, Michelson, Jackoski, Pease, Cobb, ... and Williams (2015) found that this armband allowed more finely calibrated pointing responses compared to a joystick. Additionally, Myo armband does not require a camera to record the user's movements, and thus allowing the experimenter to leave the limited confines of an experimental lab and study behaviors in environments so far inaccessible to this type of research - in this case, a primary school setting. Especially for younger children participating in the study, having the opportunity to perform the experiment not in a laboratory but in a classroom placed in their familiar school environment, adds ecological validity to the research.

An air-mouse (Y-10W wireless mouse) they held in their hand allowed participants to point towards the targets-objects and click during pointing responses to log their response. The duration of each pre-recorded auditory instruction message (e.g., "Point to the rabbit") was 2.5 seconds, and pointing latency was measured from the completion of the instruction until the click of the air-mouse.

During the 3 experimental phases, participants were asked to wear a Mindfold mask (Mindfold Inc., Tucson, AZ). This facemask is made of an opaque black plastic covered with soft foam padding on the inner side and an adjustable Velcro head strap. The mask is comfortable to use and induces total darkness even with eyes open. All equipment used in the experiment is shown in Figure 3.

Figure 3. The equipment used in the experiment (laptop computer, Myo armband, air-mouse, blindfold, microphone, and headphone set).

3.2.2. Handedness test

To examine any possible effect of handedness on participant's performance, the Edinburgh Handedness Inventory –short form was administered (Appendix A). It is based on the widely used Edinburgh Handedness Inventory (Oldfield, 1971) but it has simpler instructions and only four items. Participants were asked to indicate their hand preferences in two activities (writing and throwing) and two objects (toothbrush and spoon), by selecting one of five response options: always right, usually right, both equally, usually left, and always left. Based on their responses, a laterality quotient score (LQS) was calculated for each participant, ranging from -100 (left-handers) to 100 (right-handers). Based on their score, participants were divided into four groups (Table 1): right-handers (LQS +61 to +100), mixed-handers-right hand preference (LQS 0 to +60), mixed-handers-left hand preference (LQS -60 to 0) and left-handers (LQS -100 to -61).

Previous research showed that this simple 4-item inventory could effectively measure a single handedness factor and showed high reliability, factor score determinacy, and correlation with scores on the original inventory (Veale, 2014). Children were asked to write their name on a piece of paper, throw a foam ball with one hand, use a toothbrush to show how they brush their teeth, and hold a spoon and pretend eating soup, while adults were asked to indicate their hand preference in the previously mentioned activities.

3.2.3. Corsi's Block test

After completing the experiment, participants' spatial short-term memory was tested with the Corsi's Block Test. This simple test has been used extensively for the last 45 years, not only in clinical but also in experimental studies investigating spatial information processing (e.g., Berch, Krikorian, & Huha, 1998; Nichelli, Bulgheroni, & Riva, 2001; Orsini, Grossi, Capitani, Laiacona, Papagno, & Vallar, 1987; Piccardi, Iaria, Ricci, Bianchini, Zompanti, & Guariglia, 2008). According to Wang and Carr (2014), this test is typically considered to measure spatial short-term memory. As can be seen in Figure 4, the task used in the current study consisted of 9 identical 3 X 3 cm wooden blocks affixed to a 23 X 28 cm wooden baseboard, in the original Corsi's (1972) positions.

Figure 4. A perspective of the Corsi task (from the vantage point of the examiner) based on the original display developed by Corsi (1972).

After participants watched the experimenter tapping a particular sequence of blocks one at a time, at a rate of 1 block per second, they were asked to repeat the pattern in the same order as the experimenter did. For accurate administration of the task and record of participant's performance, blocks were numbered although only visible from the experimenter's side. The task began with two blocks and difficulty increased with longer block patterns up to 9 different blocks which followed specific tapping sequences (Appendix B). Participants continued to a longer sequence until they responded incorrectly on three out of five trials for a given pattern length. The longest pattern length that was correctly reproduced was the spatial span score for each participant, with a minimum score of 2 and a maximum of 9.

3.3. Experimental design

The experiment followed a 9 (age: 6-7-8-9-10-11-year-olds, 19-35-60-year-old adults) X 3 (response phase: orientation, updating and disorientation phase) mix factorial design, with response phase as within-subjects factor and age as a between-subjects factor. The gender of the participants, their hand preference (right, left, mixed-right, mixed-left handers) and their Corsi's Block score were also recorded and used in the analyses. All participants received the same order of phases: orientation, updating, and disorientation, but within each phase, the 4 objects were announced in randomized order. Participants had to point to each object 4 times in each experimental phase, yielding a total of 48 times.

3.4. Procedure

Each participant was tested individually in a quiet classroom at the university or the children's school and received the same instructions and experimental phases. Before they were introduced to the experiment, participants were tested for their hand preference with the Edinburgh Handedness Inventory –short form (Appendix A). After that, the four stuffed animals-targets were presented, and participants were asked to name them to ensure that they could identify each object by name correctly. Participants could freely move around the carpet and study the objects from various angles taking as long as they needed, before assuming the standpoint on the smaller red carpet (Figure 2). While standing on the smaller red carpet, they were once again asked to study and memorize the positions of the objects. In general, regardless of age, participants spent about a minute studying the configuration of the objects.

The Myo armband and the air-mouse were also demonstrated, and the experimenter briefly explained their use. Then, the experimenter adjusted the Myo armband on the participant's preferred arm, just below the elbow, and informed them that they could freely rotate their head and torso but they could not move their feet from the red carpet. Participants were also instructed to point to each object with their arm fully extended and without rotating their wrist. When participants indicated that they had memorized all locations, they were asked to stand still on the smaller red round carpet facing forward while the experimenter placed the headphones over their ears (Figure 5). Then, participants were asked to point to the 4 target-objects under 4 phases: (1) with their eyes open (training phase), (2) blindfolded from the initial learning orientation (orientation phase), (3) blindfolded after rotating 45 degrees clockwise (updating phase) and (4) blindfolded after a 30 seconds disorienting rotation (disorientation phase) that guided them to a new orientation 315 degrees clockwise from the initial perspective (Figure 6).

Each trial of the experiment started with the experimenter pressing the spacebar on the laptop to deliver the audio message (e.g., "Point to the dog"). The sequence of the 16 pre-recorded auditory instructions (4 to each object) within each experimental phase was randomized for each participant. Participants were instructed to point towards each announced object by turning their hand fully extended, and to push the trigger on the air-mouse. Before beginning the 3 experimental phases, participants completed the training phase. In the training phase, participants while at their learning orientation position and with their eyes opened, listened through their wired headphones the experimenter asking them to point towards in front of them and push the air-mouse trigger. This pointing response was used to calibrate Myo armband and identify the point in front of them as 0 degrees. Following this, the experimenter pressed the spacebar on the laptop, and a pre-recorded instruction was delivered asking participants to point towards a specific object. As soon as they pressed the air-mouse trigger, timing ended, and both the response latency and participant's orientation were recorded to a data file by the experimental script. For the participants to hear the following instruction, the experimenter had to press the spacebar on the laptop. Between intervals, a white noise (30-dB sound pressure level, A-weighted) was produced to mask potential external sounds.

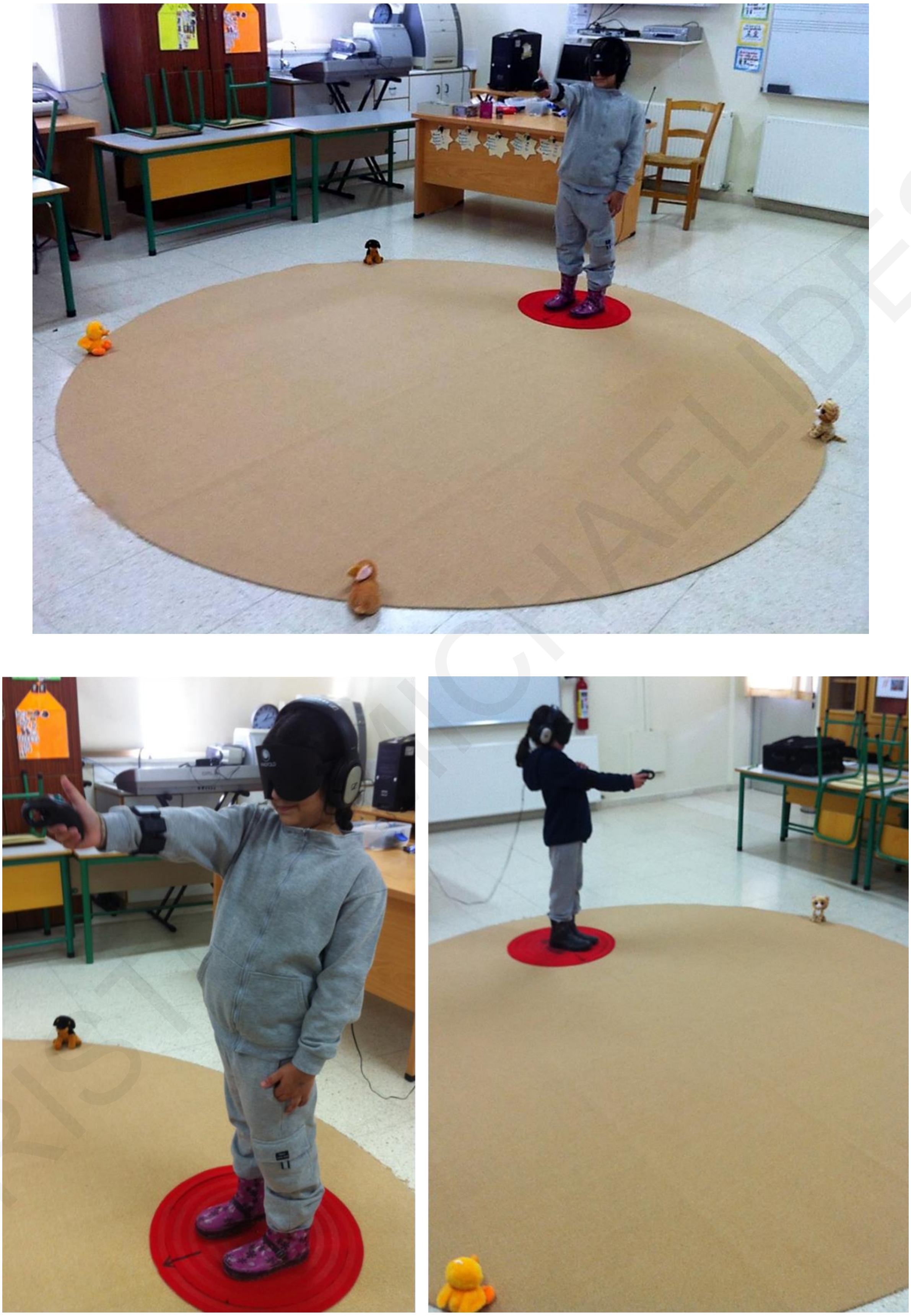


Figure 5. The top panel shows the experimental set-up. The bottom panels present a 9- and a 7-year old child experimenting in their school.

After completing the training phase, participants carried out the orientation phase. First, they donned the blindfold and while at the initial learning orientation position they were asked to point in front of them and push the trigger on the air-mouse, for Myo to recalibrate. The same recalibration procedure was repeated before the beginning of each experimental phase. After Myo recalibration, participants were asked again to point to each object while at the learning orientation, following the same procedure as before. Following the orientation phase, participants carried out the updating phase. While having their eyes closed, the experimenter slowly turned them clockwise at a predetermined angle of 45° (Figure 6) and asked them again to point to the objects following the same procedure as before.

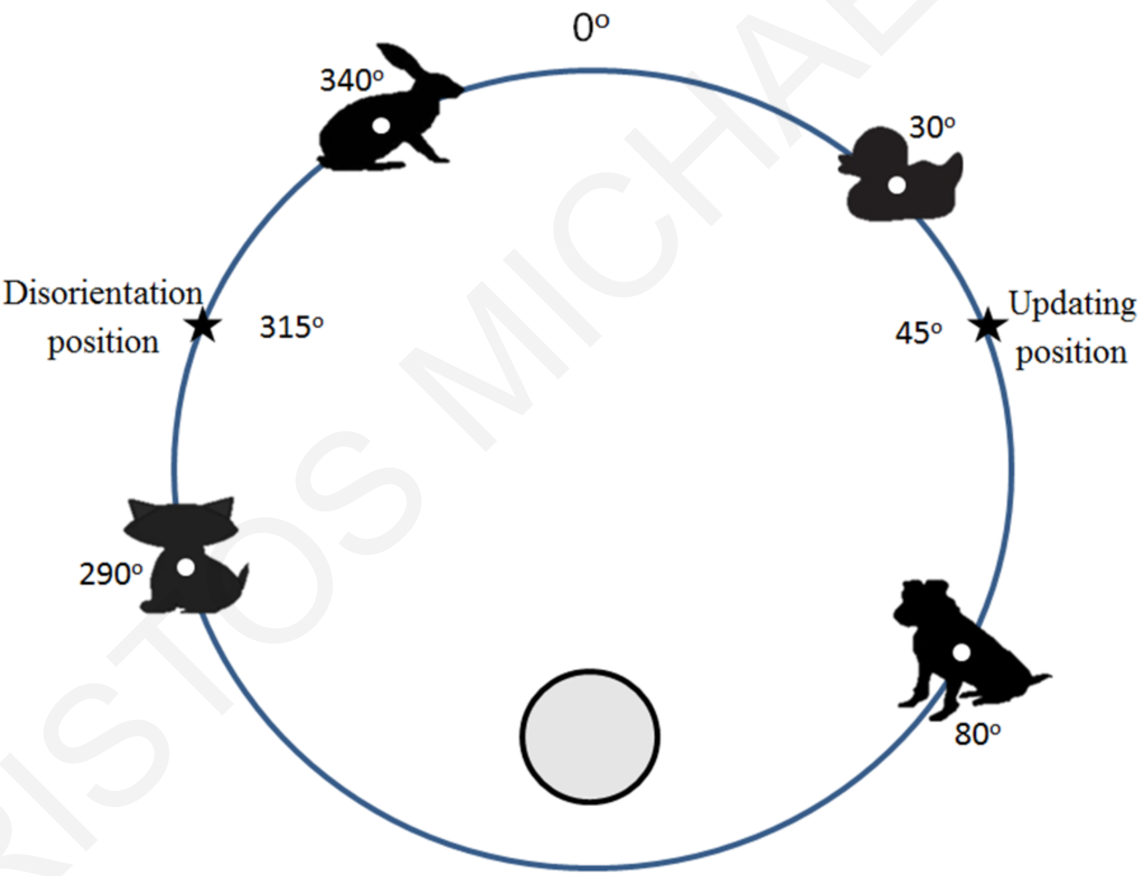


Figure 6. The predetermined angular configuration of the 4 objects with the updating and disorientation positions.

In the disorientation phase, the experimenter spun the blindfolded participants counter-clockwise for 30 seconds, before turning them to face a predetermined orientation that was 315° away from the initial orientation (Figure 6). To eliminate any possible vestibular and somatosensory disturbance on participant’s ability to accurately point to the represented targets due to the rotation procedure, and to prevent potential instability problems especially with older participants, all participants were left to recover for 20 seconds after the disorientation procedure and before the final pointing task. After that, they were asked once again to point to the objects as fast and accurately as they could, following the same procedure as in the previous phases. During the 3 blindfolded phases, the experimenter constantly moved around the carpet so as not to serve as a potential directional cue for the participants.

After the completion of the disorientation phase of the experiment and while participants were still blindfolded, they were asked to indicate which direction they thought they were facing by naming an object from the room that was in front of them. The participants' reported sybjective orientation allowed the experimenter to determine whether participants were able to update their orientation during the rotation, and was used in the analyses. Once the disorientation phase was completed, participants were asked to remove the blindfold-mask and the Myo armband, and sit across a table facing the experimenter, where they were tested with the Corsi's Block Test (Figure 4). The total time required for the completion of the experiment was 20-25 minutes for each participant.

CHAPTER 4 – DATA ANALYSIS

Both conventional and circular statistics were used to analyze the data. More specifically, a repeated-measures Analysis of Variance (ANOVA) was used to analyze the data for the two directional error measures (i.e., pointing and variable error) and pointing latency, with response phase (orientation, updating, disorientation phase) as a within-subjects factor, and age (6-, 7-, 8-, 9-, 10-, 11-year olds, 19-, 35-, 60-year old adults) as the between-subjects factor. Separate ANOVAs were also conducted with gender (male-female), spatial short-term memory (low, medium, high score on Corsi's Block test) and handedness (right, left, mixed-handers) as between-subjects factors. As responses and the resulted signed errors were circular variables (ranging from 0^o to 360°), the constant error was analyzed using circular statistics (Batschelet, 1981). All circular statistics (e.g., the Rayleigh test, the Watson-Williams F-test and the Hotelling's Paired Test) and graphs were produced using the Oriana 4 Circular Statistical Analysis software (Kovach Computing Services, Wales, UK).

The constant error corresponds to the heading error of Wang and Spelke (2000) and is used to assess the participant's perceived facing direction. For each participant and each experimental phase, the individual error for each of the 4 objects was computed by subtracting the object's veridical egocentric location from the pointing response. The mean of the 4 signed individual errors (one for each object) represented the constant error of the participant for that phase.

Variable error in each phase was computed as the standard deviation of the signed errors of the pointing responses to the 4 objects. It indicates how accurately an object is localized relative to the other objects of the spatial array. Thus, the variable error is considered as an index of the internal consistency of the spatial representation (Wang & Spelke, 2000) and is small if an accurate allocentric representation has been formed. Notably, the variable error could be small even with a large constant error. This will occur if responses to all objects deviate from the correct response to the same extent, e.g., when a participant misjudges her facing orientation relative to the layout.

Finally, *pointing error* was defined as the standard deviation of the successive pointing responses to the same object in each response phase, averaged across the 4 targets. Pointing error represents the uncertainty (or noise) in pointing to the same object from the same perspective and as such, it can influence the level of variable error. In the current experiment, the 30-seconds disorienting rotation that preceded the disorientation phase could have caused participants to be uncertain about their facing direction. However, to be able to point to the different objects, participants had to adopt some viewpoint. If they were not sure about their actual viewpoint, they might have systematically altered their pointing responses to the same object from one trial to the other. Doing so, however, could lead to large variable error even if participants had retained an accurate allocentric representation. To account for this possibility, Wang and Spelke (2000) proposed the following mathematical equation to compute the amount of variable error that is expected due to the variability in pointing error:

$$Predicted\ increase\ in\ variable\ error = \frac{increase\ in\ pointing\ error}{\sqrt{N}}$$

According to this equation, the predicted increase in variable error due to pointing error equals the obtained increase in pointing error divided by the square root of the number of times to which an object was pointed at within a response phase (4 in current experiment). I have used this formula to examine whether increases in variable error from one experimental phase to the other could be fully accounted or not by increases in pointing error.

4.1. Results

4.1.1. The effect of age

Constant error. Constant error was assessed with the Rayleigh test, which evaluates the null hypothesis of a uniform random distribution indicative of disorientation, by testing the significance of the mean vector length (r). This measure ranges from 0 to 1; when observations are randomly distributed, r is close to 0 and the circular variance is close to 1. Constant error was expected to be unimodally distributed around 0 in both the orientation and the updating phase if participants remained oriented while blindfolded and if they could keep track of their movement during the 45° rotation. Indeed, results showed that the length of the mean vector (r) was close to 1 in both phases (Orientation = .95 and Updating = .86) and the circular variance was close to zero (Orientation = .05 and Updating = .14). As seen in Table 2, the constant error was tightly concentrated around the mean direction in each phase. Also, as shown in Figure 7, constant error in the orientation phase for all participants remained within a quadrant ranging between -44^{o} and 48^{o}, while in the updating phase it spanned across two quadrants ranging between -80^{o} and 84^{o}, suggesting that not all participants were highly accurate in updating their facing orientation.

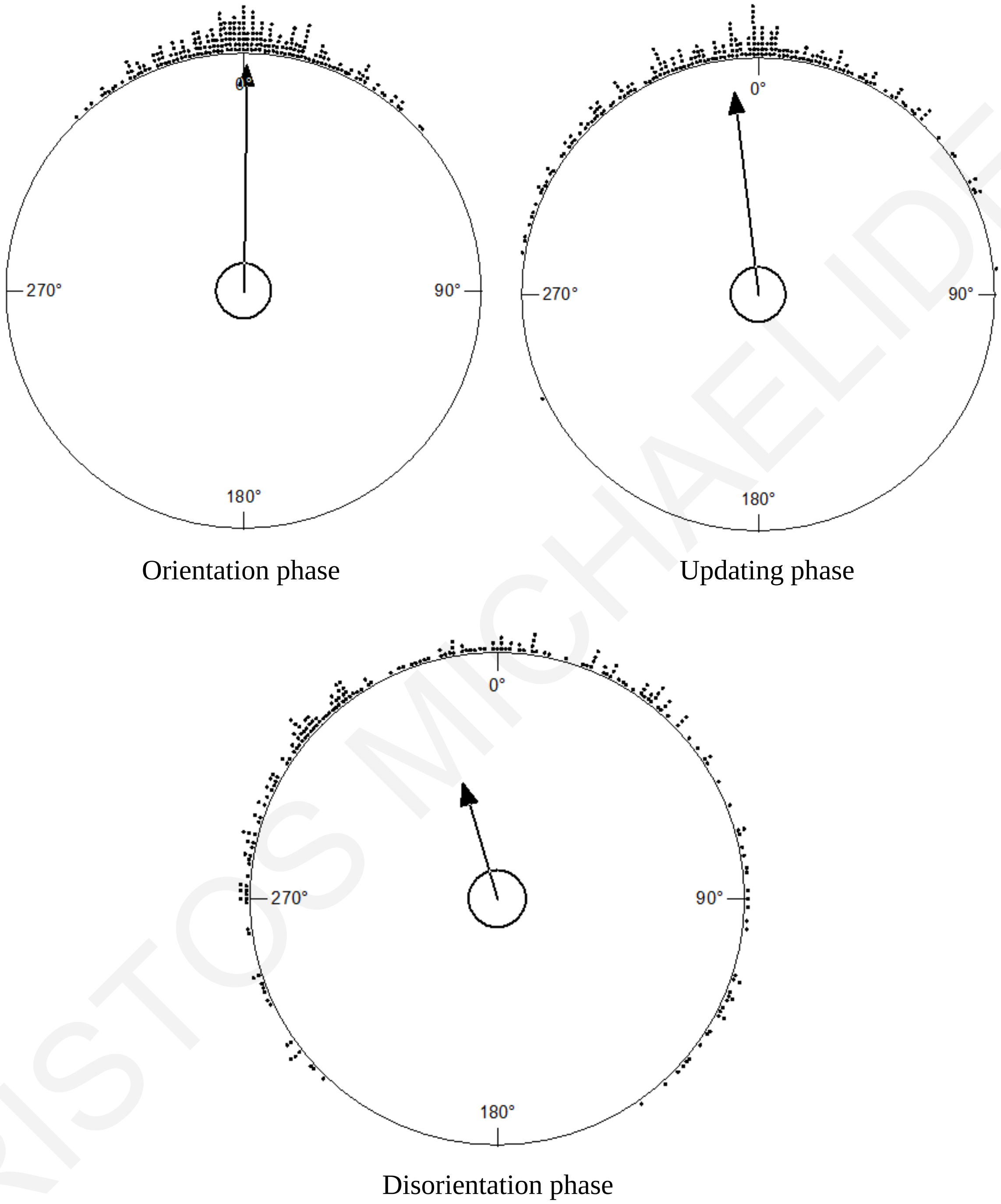


Figure 7. Constant error with the mean vector length (r) in the 3 response phases. Each dot represents a single participant (N=216). The arrow indicates the direction and the magnitude of the mean vector.

In the disorientation phase, the circular deviation of constant error was widely dispersed (between -136^{o} and 146^{o}). The the length of the mean vector was smaller (*r* = .49) and the circular variance larger than the corresponding values the orientation and the updating phase (Table 2). Still, the Rayleigh test showed that the distribution of constant error was not random, $p < .001$. However, a closer look at the individual errors within the disorientation phase suggests that participants were disoriented. As seen in Figure 8, participants' individual errors for the 3 of the 4 objects (duck, dog, rabbit) were scattered away from the correct egocentric location of that object. The only exception was the response for the cat. For 73 of the 216 participants (33.8%), the signed individual error extended within the 60^o circular sector that included the veridical location of the cat. In fact, the X^2 multisample test (Batschelet, 1981) with only the three objects (dog, duck, rabbit) and dividing the circle into six equal 60^o sectors, resulted in a random distribution of constant error around the circle, implying that participants were disoriented, $X^2(10)=15.64$, $p = .11$. Additionally, almost all participants (208 of the 216, 96.3%), after the completion of the disorientation phase and while being blindfolded, indicated an incorrect facing direction when they were asked by the experimenter to verbally report which way they thought they were facing by naming an object that was in front of them (Table 1, Appendix C). Based on that, and due to the fact that previous experiments (e.g., Holmes & Sholl, 2005; Mou et al., 2006; Waller & Hodgson, 2006; Wang & Spelke, 2000) showed that the disorientation procedure followed in current experiment was successful at inducing a state of disorientation, I conclude that participants were disoriented during the disorientation phase.

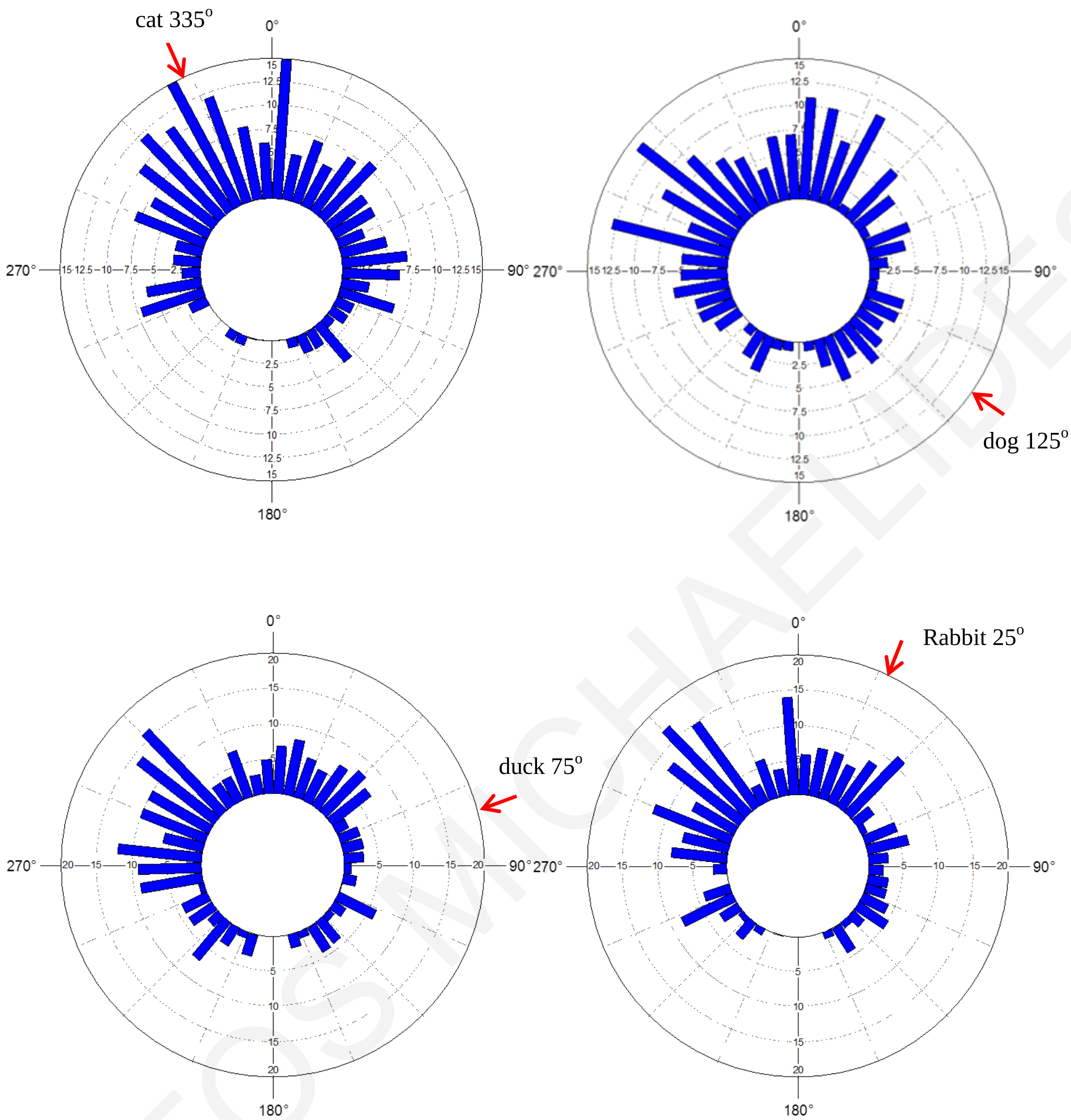


Figure 8. Participants' signed individual errors for each object in the disorientation phase. The red arrow indicates the veridical egocentric location of each object.

To determine whether the direction and the length of mean vectors differed across the orientation, the updating, and the disorientation phases, I used the Watson-Williams F-test. According to Batschelet (1981), this test should be combined with the careful inspection of the data. As seen in Figure 7, the direction and the length of mean vectors seem to differ among the 3 experimental phases. The analysis revealed a significant difference between the orientation and the updating phase, $F(1, 430) = 10.33$, $p = .001$, and between the orientation and the disorientation phase, $F(1, 430) = 13.5$, $p < .001$. Also, the mean vector was numerically different between the updating and the disorientation phase, $F(1, 430) = 3.49$, $p = .06$.

Further analyses for each age-group within each response phase were conducted, to examine the effect of age. The Watson-Williams F-test was used to detect if the mean directions of different sets of circular data differed significantly from each other (for the circular statistics, see Table 2).

Table 2. Circular statistics for constant error for each age-group in all the response phases

Age-groups	Mean vector (°)	Length mean vector -r	Circular Variance	Circular SD (°)	Standard Error of Mean (°)	Rayleigh Test (Z)	Rayleigh Test (p)
			Orientation phase				
6-year olds	355.36	.94	.06	20.58	4.2	21.1	< .001
7-year olds	353.16	.95	.05	19.17	3.91	21.46	< .001
8-year olds	1.45	.94	.07	21.05	4.29	20.97	< . 001
9-year olds	6.24	.95	.05	17.74	3.62	21.81	< . 001
10-year olds	3.21	.97	.03	14.26	2.91	22.56	< . 001
11-year olds	7.93	.97	.03	14.52	2.96	22.51	< . 001
19-year olds	3.97	.98	.02	11.8	2.41	23	< . 001
35-year olds	1.71	.96	.05	17.32	3.53	21.91	< . 001
60-year olds	354.1	.97	.03	14.95	3.05	22.42	< . 001
Total (N=216)	0.82°	.95	.05	17.80°	1.21°	196.14	< . 001
			Updating phase				
6-year olds	352.53	.84	.16	33.38	6.79	17.09	< . 001
7-year olds	342.14	.82	.18	35.98	7.28	16.18	< . 001
8-year olds	346.19	.84	.16	33.56	6.81	17.03	< . 001
9-year olds	353.05	.83	.17	34.48	6.99	16.71	< . 001
10-year olds	3.83	.85	.15	32.31	6.57	17.46	< . 001
11-year olds	359.38	.85	.15	32.79	6.67	17.3	< . 001
19-year olds	345.75	.94	.06	20	4.08	21.25	< . 001
35-year olds	357.43	.94	.06	20.77	4.24	21.05	< . 001
60-year olds	356.65	.89	.11	28.1	5.72	18.87	< . 001
Total (N=216)	353.03°	.86	.14	31.27°	2.12°	160.35	< . 001
			Disorientation phase				
6-year olds	339.53	.58	.42	59.97	12.89	8.02	< . 001
7-year olds	2.03	.60	.40	57.83	12.27	8.66	< . 001
8-year olds	318.45	.30	.70	89.02	27	2.15	=.12
9-year olds	339.56	.37	.63	80.33	21.28	3.36	= .03
10-year olds	1.98	.59	.41	58.63	12.5	8.42	< . 001
11-year olds	341.03	.49	.51	68.58	15.83	5.73	= .003
19-year olds	328.54	.66	.34	52.23	10.78	10.45	< . 001
35-year olds	4.69	.52	.48	65.13	14.6	6.59	< . 001
60-year olds	320.77	.49	.51	68.51	15.81	5.75	= .002
Total (N=216)	343.44°	.49	.51	68.34°	5.25°	52.06	< . 001

In the orientation phase, results revealed that 6-year olds had significantly larger constant error compared to 11-year olds [$F(1, 46) = 5.8$, $p = .02$] and marginally larger error compared to 9-year olds, $F(1, 46) = 3.73$, $p = .06$. Seven-year olds had larger constant error compared to 9-year olds [$F(1, 46) = 5.82$, $p = .02$], 10-year olds, [$F(1, 46) = 4.11$, $p = .048$], 11-year olds [$F(1, 46) = 8.76$, $p = .005$] and 19-year old adults, $F(1, 46) = 5.37$, $p = .025$. Sixty-year old adults had smaller constant error than 9-year olds [$F(1, 46) = 6.4$, $p = .015$] but larger one compared to 10-year olds [$F(1, 46) = 4.55$, $p = .038$], 11-year olds[$F(1, 46) = 10.26$, $p = .002$] and 19-year old adults, $F(1, 46) = 6.28$, $p = .016$.

In the updating phase, the analysis showed that 10-year olds were significantly more oriented than 7-year olds, $F(1, 46) = 4.68$, $p = .036$. Nineteen-year old adults had significantly smaller constant error than 10-year olds, $F(1, 46) = 5.32$, $p = .026$, and 35-year old adults, $F(1, 46) = 3.81$, $p = .05$ (Figure 9).

In the disorientation phase, 19-year old adults had significantly smaller constant error than 7-year olds [$F(1, 46) = 4.08$, $p = .049$], 10-year olds [$F(1, 46) = 4$, $p = .05$] and 35-year old adults, $F(1, 46) = 4.08$, $p = .049$. Sixty-year old adults had significantly larger constant error compared to 7-year olds [$F(1, 46) = 4.5$, $p = .039$], 10-year olds [$F(1, 46) = 4.43$, $p = .04$] and 35-year old adults, $F(1, 46) = 4.52$, $p = .039$ (Figure 10).

To examine whether the mean vectors from the same age-group differed among the orientation, the updating and the disorientation phase of the experiment, I used the Hotelling's Paired Test. Results showed that in all age-groups, the constant error was the lowest in the orientation phase, intermediate in the updating phase, and the highest in the disorientation phase. For 6-, 8-, 9-, 11-year olds and 19-year old adults, the error differed significantly among all three response phases (all *p's* $< .05$). For 7-, and 10-year olds, constant error in the orientation phase was significantly lower compared to the updating and the disorientation phase (all *p's* $< .05$), but it did not differ significantly between the updating and the disorientation phase. For 35- and the 60-year old adults, constant error in the disorientation phase was significantly higher compared to the orientation and the updating phase (all *p's* $< .01$), but it did not differ significantly between the orientation and the updating phase (See Table 2 Appendix C for a comprehensive list of inferential statistics).

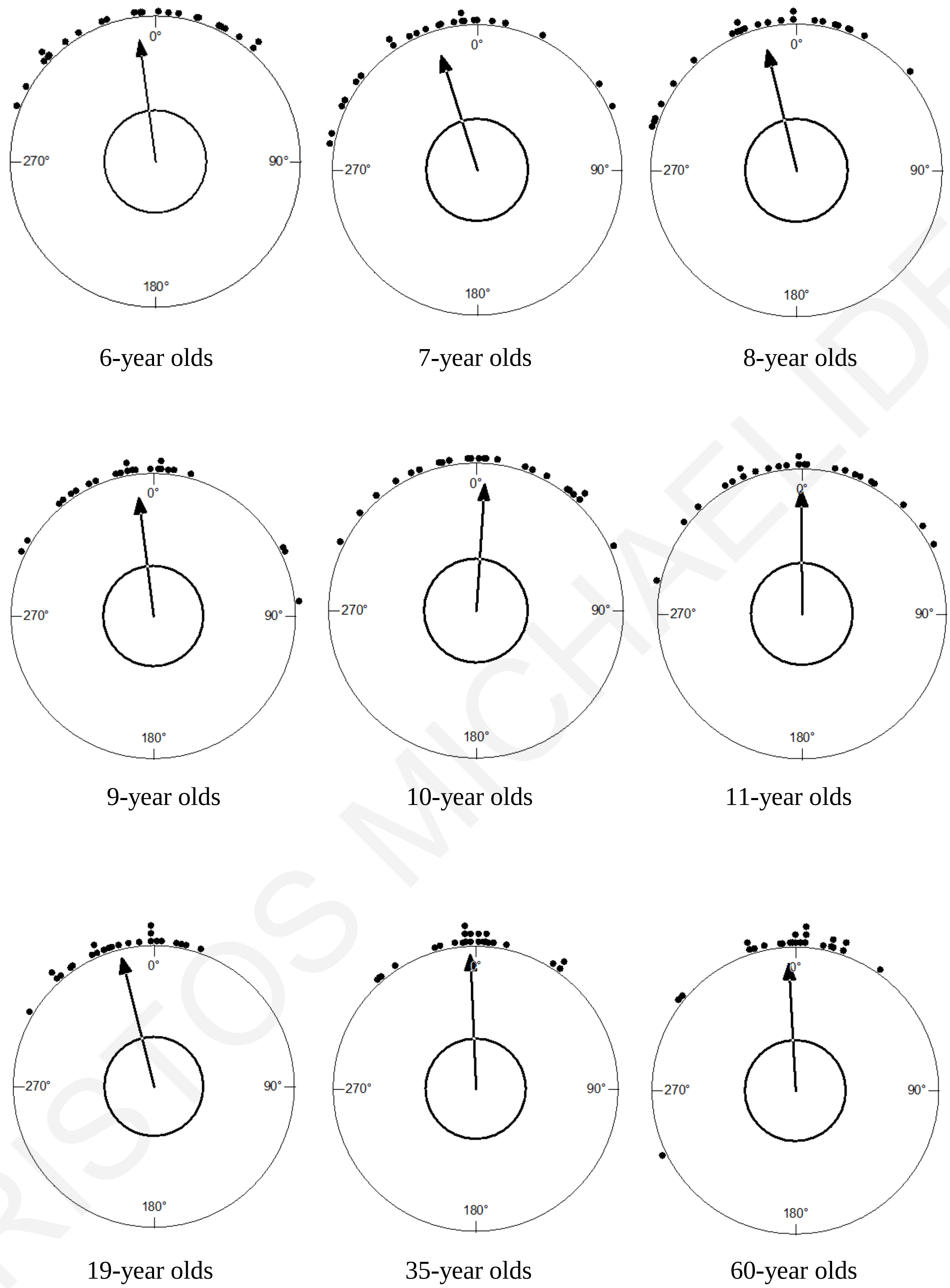


Figure 9. Constant error for each age-group in the updating phase, with the mean vector length, r. Each dot represents the constant error of a single participant (N=24).

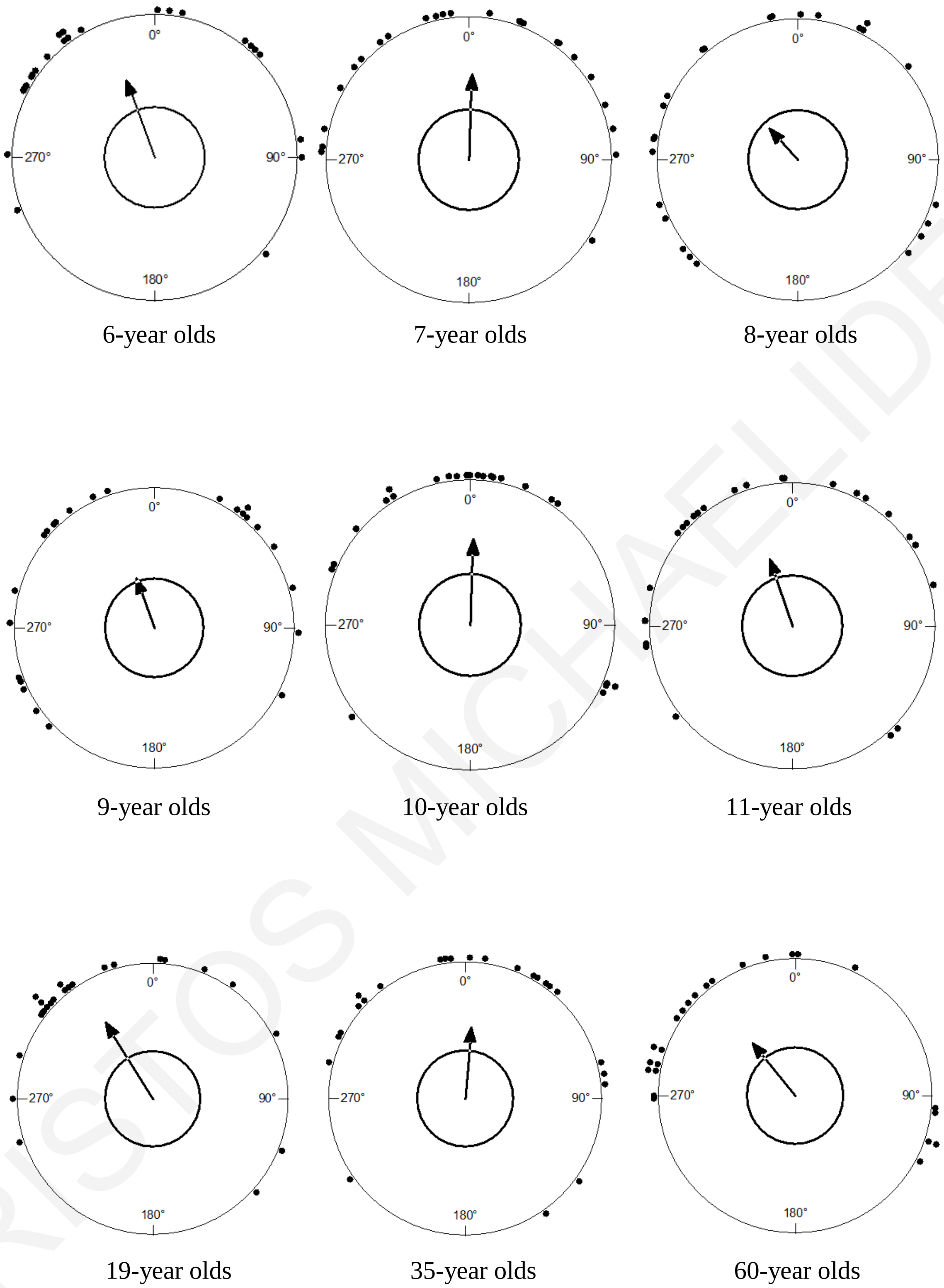


Figure 10. Constant error for each age-group in the disorientation phase, with the mean vector length, r. Each dot represents the constant error of a single participant (N=24).

Overall, the analysis of constant error indicates that participants remained oriented while blindfolded in both the orientation and the updating phase. The results of the updating phase suggest that idiothetic cues were sufficient for all participants, regardless of their age, to update their orientation relative to the stable environment. Nevertheless, the fact that constant error in the updating phase spanned across two quadrants of the circle (between -80^{o} and 84^{o}), suggests that not all participants were highly accurate in updating their facing orientation. In the disorientation phase, participants had to adopt a subjective orientation to be able to point egocentrically. As seen in Table 1 (Appendix C), 44 of the 216 participants (20.4%) responded as if they were in the learning orientation (0^{o}) while another 27 participants (12.5%) as if they were in the updated orientation (45^{o}). Interestingly, these two orientations were selected by the majority of 19- and 35-year old adults (66.7% and 45.8% respectively), but only by a small percentage of participants in the other age-groups (6-, 7-, 8-, 9-year olds: 20.8% and 10-, 11-year olds and 60-year old adults: 33.3%). Thirty-four participants (15.7%) selected the orientation that was directly opposite from the learning orientation (180^{o}), while only 8 participants (3.7%) responded as if they were facing the veridical orientation (315^{o}). The remaining participants (47.7%) adopted a subjective orientation that faced one of the 4 objects in the memorized array (Figure 1 Appendix C).

In summary, some age differences in constant error were found within each experimental phase. More specifically, in the orientation phase, both the youngest and the oldest participants in the study had higher constant error compared to older children and younger adults. In the updating phase, the younger children had a higher constant error than older children, who in turn had larger error than adults. Finally, in the disorientation phase, participants in the youngest adult group had lower constant error compared to children and older adults, while older adults had a larger constant error than younger adults.

Pointing error. An ANOVA was carried out for pointing error with response phase (orientation, updating, disorientation) and age-group (6-, 7-, 8-, 9-, 10-, 11-year olds and 19-, 35-, 60-year old adults) as factors. The ANOVA showed a significant main effect for the response phase and for age, $F(2, 414) = 29.21$, $p < .001$, $\eta^2 = .12$ and $F(8, 207) = 6.61$, $p < .001$, $\eta^2 = .20$ respectively. The interaction between the different response phases and age was not significant, $F(16, 414) = 0.69$, $p = .8$, $\eta^2 = .03$.

As seen in Figure 11, overall pointing error increased from the orientation phase (M = 11.95, SD = 7.29) to the updating phase (M = 14.54, SD = 8.81) and further to the disorientation phase (M = 18.27, SD = 13.07), all *p's* < .001.

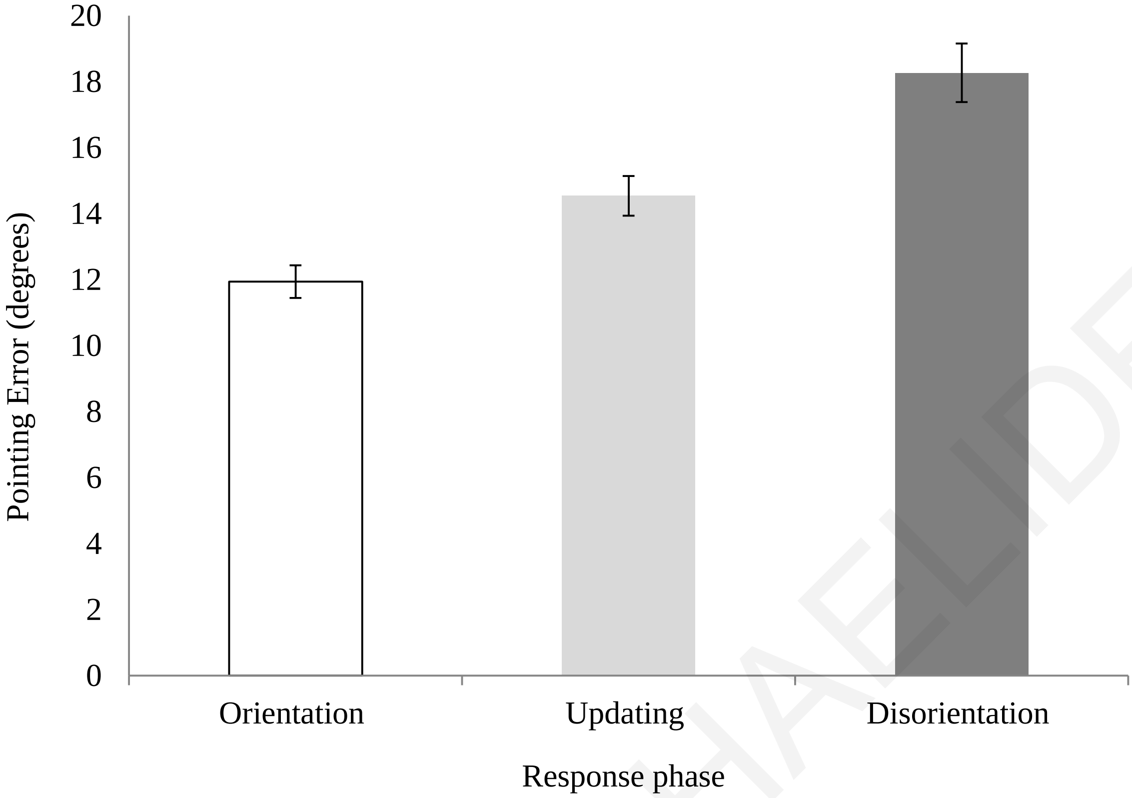


Figure 11. Pointing error in the 3 response phases. Error bars represent standard errors of the mean (N=216).

Despite the lack of a significant interaction, I carried out pair wise comparisons with a Bonferroni correction to examine differences among the experimental phases within each age group. Analyses revealed a significant smaller pointing error in the orientation than in the updating phase in 8-year olds [$t(23) = 2.08$, $p = .049$], 10-year olds [$t(23) = 2.59$, $p = .016$] and 11-year olds [$t(23) = 2.42$, $p = .024$]. Sixty-year old adults had a marginally smaller pointing error in the orientation than in the updating phase, $t(23) = 1.98$, $p = .06$. Thirty five-year old adults had significantly lower pointing error in the updating than in the disorientation phase [$t(23) = 2.54$, $p = .018$], while 6-year olds [$t(23) = 1.93$, $p = .066$] and 60-year old adults [$t(23) = 1.97$, $p = .061$] had marginally lower pointing error in the updating than in the disorientation phase. A significant difference was also observed between the orientation and the disorientation phase, with pointing error being larger in the disorientation phase for 6-year olds [$t(23) = 2.22$, $p = .037$], 7-year olds [$t(23) = 2.36$, $p = .027$], 8-year olds [$t(23) = 2.31$, $p = .03$], 10-year olds [$t(23) = 2.39$, $p = .026$], 11-year olds [$t(23) = 3.72$, $p = .001$], 35-year old [$t(23) = 3.24$, $p = .004$] and 60-year old adults [$t(23) = 2.37$, $p = .026$], and a marginally significant difference for the 9-year olds, $t(23) = 1.94$, $p = .064$. Although pointing error increased from the orientation (M = 9.24, SD = 3.91) to the disorientation phase (M = 10.39, SD = 6.14) in the 19-year old group as well, this increase was not significant, $t(23) = .82$, $p = .42$.

Analyses also revealed significant differences among different age-groups within each response phase (Table 3). A significant effect of age was obtained in the orientation phase, $F(8, 207) = 4.27$, $p < .001$, $\eta^2 = .14$. Six-year olds were less accurate in their pointing judgements than 11-year olds ($p = .049$), 19-year old adults ($p = .008$), 35-year old adults ($p = .009$), and 60-year old adults ($p = .006$), whereas 7-year olds had marginally significant larger pointing error compared to19-year old adults ($p = .068$), 35-year old adults ($p = .075$), and 60-year old adults ($p = .053$). A significant effect of age was also found in the updating phase, $F(8, 207) = 4.16$, $p < .001$, $\eta^2 = .14$. Six-year olds were less accurate in their pointing judgements than 19-year old adults ($p = .05$), whereas 7-year olds were less accurate than 19-year old adults ($p = .009$), 35-year old adults ($p = .014$), and 60-year old adults ($p = .041$). Eight-year olds were also less accurate than 19-year old adults ($p = .028$), and 35-year old adults ($p = .043$). Children from the age of 9 and onwards exhibited comparable performance to each other and to adults, all *p's* > .86. Finally, a significant effect for age was also found in the disorientation phase, $F(8, 207) = 2.84$, $p = .005$, $\eta^2 = .099$. Nineteen-year old adults had significant lower pointing error that both the 6-year olds ($p = .003$) and the 7-year olds ($p = .024$). Older children from the age of 8 and onward showed comparable performance to each other and to adults, all *p's* > .21 (Figure 12).

Table 3. Mean (SD) for pointing error in the different age groups and the four response phases of the experiment (N=216)

	Mean (SD) for each response phase			
Age-group	Orientation	Updating	Disorientation	N
6-years olds	16.71 (9.44)	17.79 (8.52)	25.02 (15.90)	24
7-years olds	15.49 (9.16)	19.03 (10.14)	22.99 (12.23)	24
8-years olds	14.22 (8.07)	18.24 (10.34)	20.52 (11.51)	24
9-years olds	12.42 (7.80)	13.68 (7.76)	17.73 (12.52)	24
10-years olds	10.76 (5.48)	15.15 (9.33)	19.21 (17.93)	24
11-years olds	10.26 (4.97)	15.52 (10.61)	16.50 (7.63)	24
19-years olds	9.24 (3.91)	10.04 (4.88)	10.39 (6.14)	24
35-years olds	9.30 (5.93)	10.34 (5.73)	15.08 (8.71)	24
60-years olds	9.09 (4.70)	11.09 (5.14)	17.01 (15.96)	24
Total	11.95 (7.29)	14.54 (8.81)	18.27 (13.07)	216

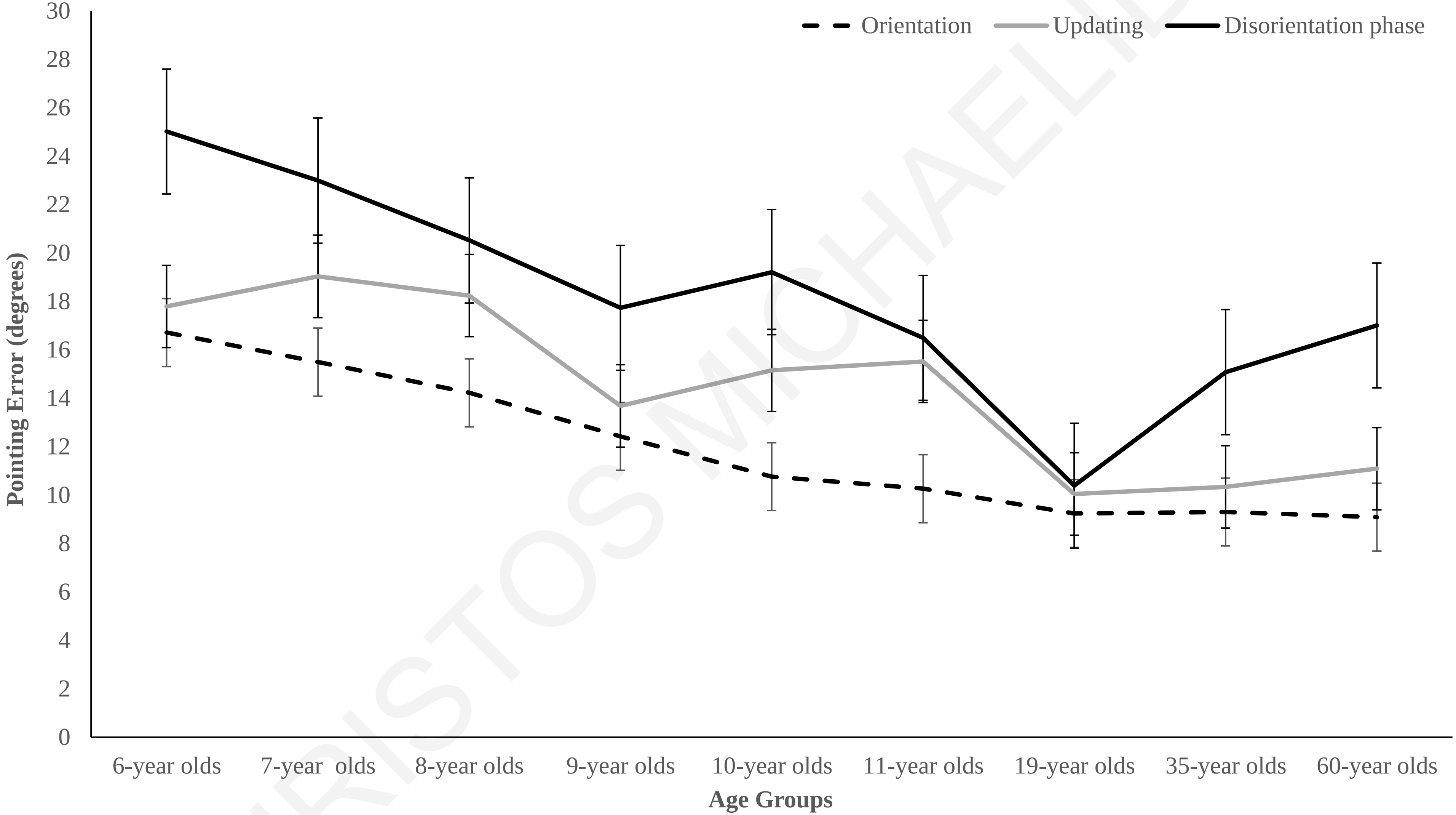


Figure 12. Pointing error for the different age-groups in the 3 response phases. Error bars represent standard errors of the mean.

In summary, the analysis showed a progressive increase in pointing error from the orientation to the updating phase, and from the updating to the disorientation phase. More specifically, 8-, 10-, 11-year olds and 60-year old adults exhibited a significant increase of pointing error from the orientation to the updating phase. This increase shows that the updating procedure is a possible source of error which might inflate variable error. Between the updating and the disorientation phase, 35-year old adults showed a significant increase in their pointing error, while 6-year olds and 60-year old adults had a marginally significant increase. Finally, all age groups showed a significant or numerical increase of pointing error from the orientation to the disorientation phase. Furthermore, within each experimental phase, a significant effect of age was found. In the orientation phase, 6-year olds were less accurate than 11-year olds and all adult groups. Within the updating phase, 6-, 7-, 8-year olds had larger pointing error compared to adults and only from the age of 9 and onward children exhibited comparable performance to each other and to adults. In the disorientation phase, 6-, and 7-year olds had larger pointing error compared to 19-year old adults, while older children showed comparable performance to each other and to adults.

Variable error. The ANOVA on variable error revealed a significant main effect of response phase with variable error being larger in the disorientation phase (M = 28.44, SD = 29.71) compared to the updating (M = 13.99, SD = 8.56) and the orientation phase (M = 8.48, SD = 5.3), $F(2, 414) = 73.39$, $p < .001$, $\eta^2 = .26$ (Figure 13). A significant main effect was also found for age [$F(8, 207) = 3.45$, $p = .001$, $\eta^2 = .12$] but the interaction between the different response phases and age was not significant, $F(16, 414) = 0.91$, $p = .56$, $\eta^2 = .034$.

As with pointing error, I proceeded to explore differences across experimental phases in each age group, despite the lack of a significant interaction. Paired-samples t-test revealed a significant difference between orientation and updating phase in all age-groups (all *p's* < .05) with the exception of 35-year old adults in which the difference was marginally significant, $p = .063$ (see Table 3 Appendix C for statistics on all age-groups). As seen in Table 4, in all age-groups, the variable error was the largest in the disorientation phase, intermediate in the updating phase, and the lowest in the orientation phase. A significant difference was also found between the updating and the disorientation phase in 6-, 7-, 9-, 10-, 11-year olds and 35-year old adults (all *p's* < .05), while a marginally significant difference between the updating and the disorientation phase was observed in 8-year olds ($p = .059$) and 60-year old adults ($p = .06$). In all age-groups, with the exception of 19-year old adults (p = .098), there was also a significant increase in variable error between the orientation and the disorientation phase, all *p's* < .05 (Figure 15).

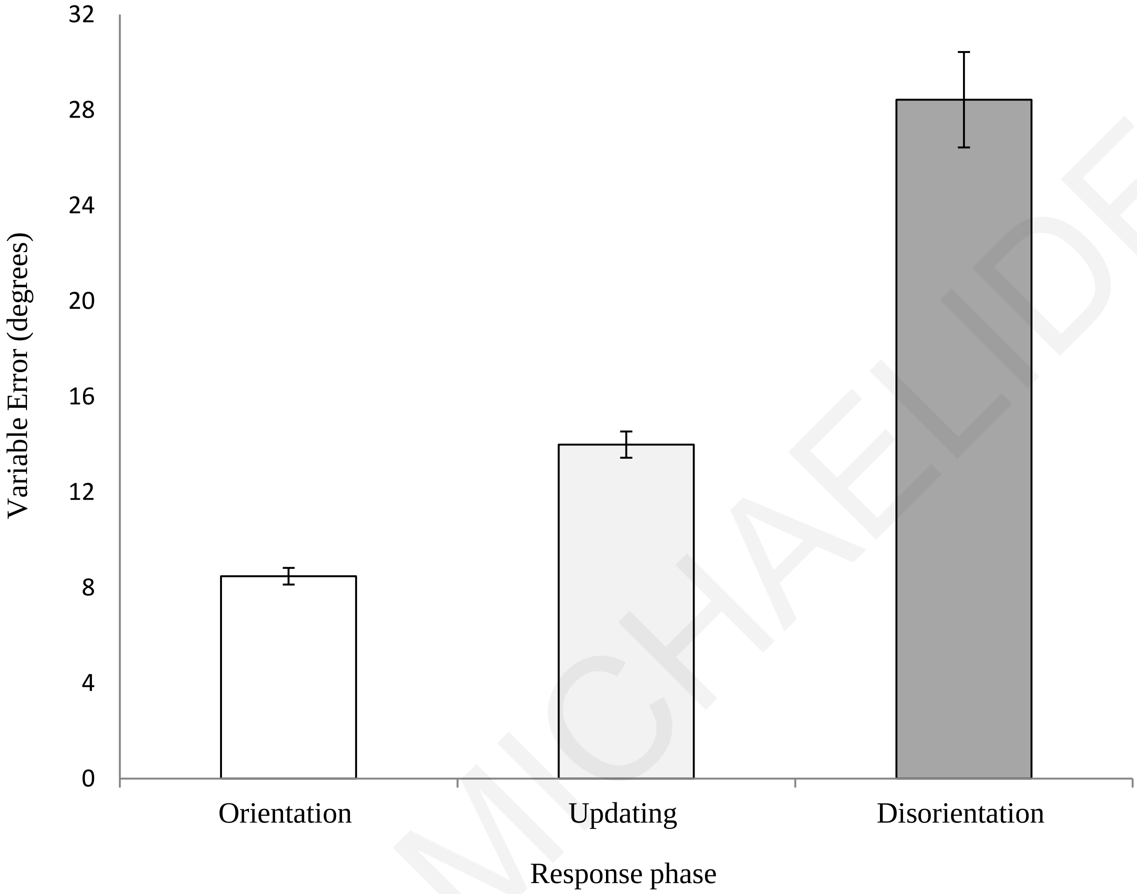


Figure 13. Variable error in the 3 response phases. Error bars represent standard errors of the mean (N=216).

Separate analyses were also conducted for each response phase. First, the analysis for the orientation phase showed an effect of age, $F(8,207) = 3.61$, $p = .001$, $\eta^2 = .12$. Six-year olds were significantly less accurate than 9-year olds (p = .043), 10-year olds (p = .003), 11-year olds (p = .025), 19-year old adults (p = .007), and 35-year old adults (p = .034). Children from the age of 7 and onward showed comparable performance to each other and to adults, all *p's* > .13 (see Table 4 for descriptive statistics).

The analysis in the updating phase also revealed a significant effect of age, $F(8, 207) = 3.86$, $p < .001$, $\eta^2 = .13$. As seen in Figure 15, 6-year olds had significantly larger variable error than 7-year olds (p = .015), 9-year olds (p = .004), 11-year olds (p = .009) and 19-year old (p = .002), 35-year old (p = <.001), and 60-year old adults (p = .04), and marginally larger than 10-year olds, p = .07. Children from the age of 7 and onward had a comparable variable error to each other and to adults, all *p's* = 1, despite the fact that 19-, and 35-year old adults were numerically more accurate than all children groups (Table 4).

Although 60-year old adults had a numerically larger variable error than 7-, 9-, 11-year olds, the difference was not significant, all *p's* =1 (Figure 15).

In the disorientation phase the analysis revealed no effect of age, $F(8, 207) = 1.57$, $p = .13$, $\eta^2 = .057$. Only 6-year olds (M = 43.42, SD = 33.58) had significantly larger variable error compared to 19-year old adults (M = 14.74, SD = 22.2), $p = .03$. Older children and adults showed comparable performance to each other (all *p's* = 1), despite that 19- and 35-year old adults had numerically lower variable error than all children groups (Table 4). It should be noted that 60-year old adults performed (M = 27.6, SD = 31.99) at the levels of 9-year olds (M = 27.59, SD = 31.46).

Table 4. Mean (SD) for variable error in the different age groups and the three response phases of the experiment (N=216)

Age-group	Mean (SD) for each response phase			
	Orientation	Updating	Disorientation	N
6-years old	12.35 (8.21)	21.74 (13.17)	43.42 (33.58)	24
7-years old	9.19 (4.52)	13.33 (6.1)	33.09 (33.81)	24
8-years old	8.62 (4.35)	15.06 (8.02)	28.67 (30.34)	24
9-years old	7.54 (4.37)	12.54 (7.8)	27.59 (31.46)	24
10-years old	6.42 (3.83)	14.37 (9.67)	29.53 (23.33)	24
11-years old	7.31 (3.78)	13.02 (6.84)	26.46 (27.15)	24
19-years old	6.78 (3.15)	11.93 (5.85)	14.74 (22.20)	24
35-years old	7.44 (5.36)	9.97 (4.3)	24.82 (28.25)	24
60-years old	10.7 (6.11)	13.97 (8.17)	27.6 (31.99)	24
Total	8.48 (5.3)	13.99 (8.56)	28.44 (29.71)	216

As seen in table 4, variable error was about double in the disorientation phase than in the updating phase and more than 3 times greater than the orientation phase. Further analyses revealed that this increased in variable error in the disorientation phase was related to participants' reported subjective orientation after the disorientation procedure. Based on their verbal responses about which way they thought they were facing, participants were divided into 3 groups: the learning orientation (0^o), the updating orientation (45^o), and other orientations (e.g., towards one of the objects or other orientations). An ANOVA using subject orientation as a term showed a significant effect in the disorientation phase on variable error, $F(2, 213) = 14.87$, $p < .001$, $\eta^2 = .12$. As seen in Figure 14, participants who reported facing either the learning (M = 11.83, SD = 5.77) or the updating orientation (M = 16.87, SD = 11.69), had significantly lower variable error than those who reported other orientations (M = 35.63, SD = 33.49), p<.001 and p=.005 respectively. Those who adopted one of the two previously experienced orientations had a comparable variable error, *p* =1.

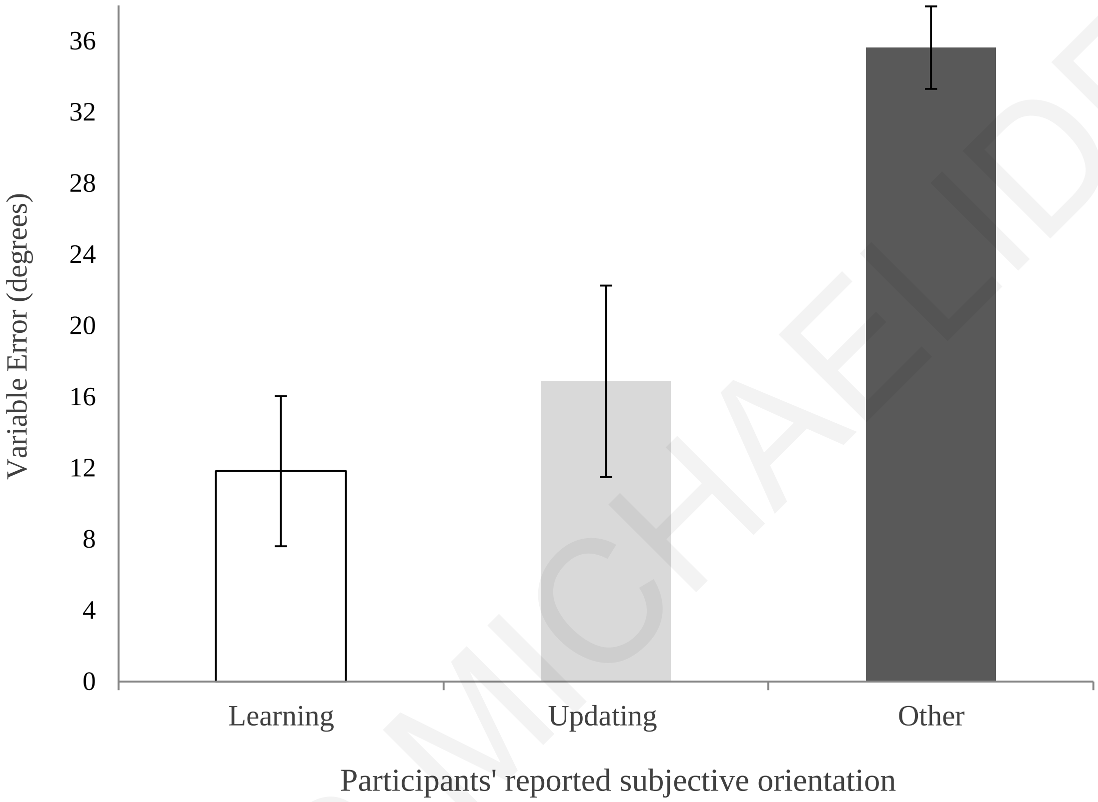


Figure 14. Variable error among the different subjective orientations in the disorientation phase. Error bars represent standard errors of the mean.

In summary, the analysis of variable error documented the presence of progressive increase from phase to phase, with variable error being smaller in the orientation and larger in the disorientation phase. All age-groups exhibited a significant increase in variable error between the orientation and the updating phase (35-year old adults had a marginally significant difference). This increase shows that updating memorized spatial relations is not a perfect process, but instead results in some error. A significant or marginally significant difference was also found between the updating and the disorientation phase in all age-groups, with the exception of the 19-year old adults. Within each experimental phase, some age differences were also observed. In the orientation and the updating phase, 6-year olds had a higher variable error than older children and adults, while participants from the age of 7 and onward showed comparable performance to each other. In the disorientation phase, 6-year olds had again higher variable error than 19-year old adults.

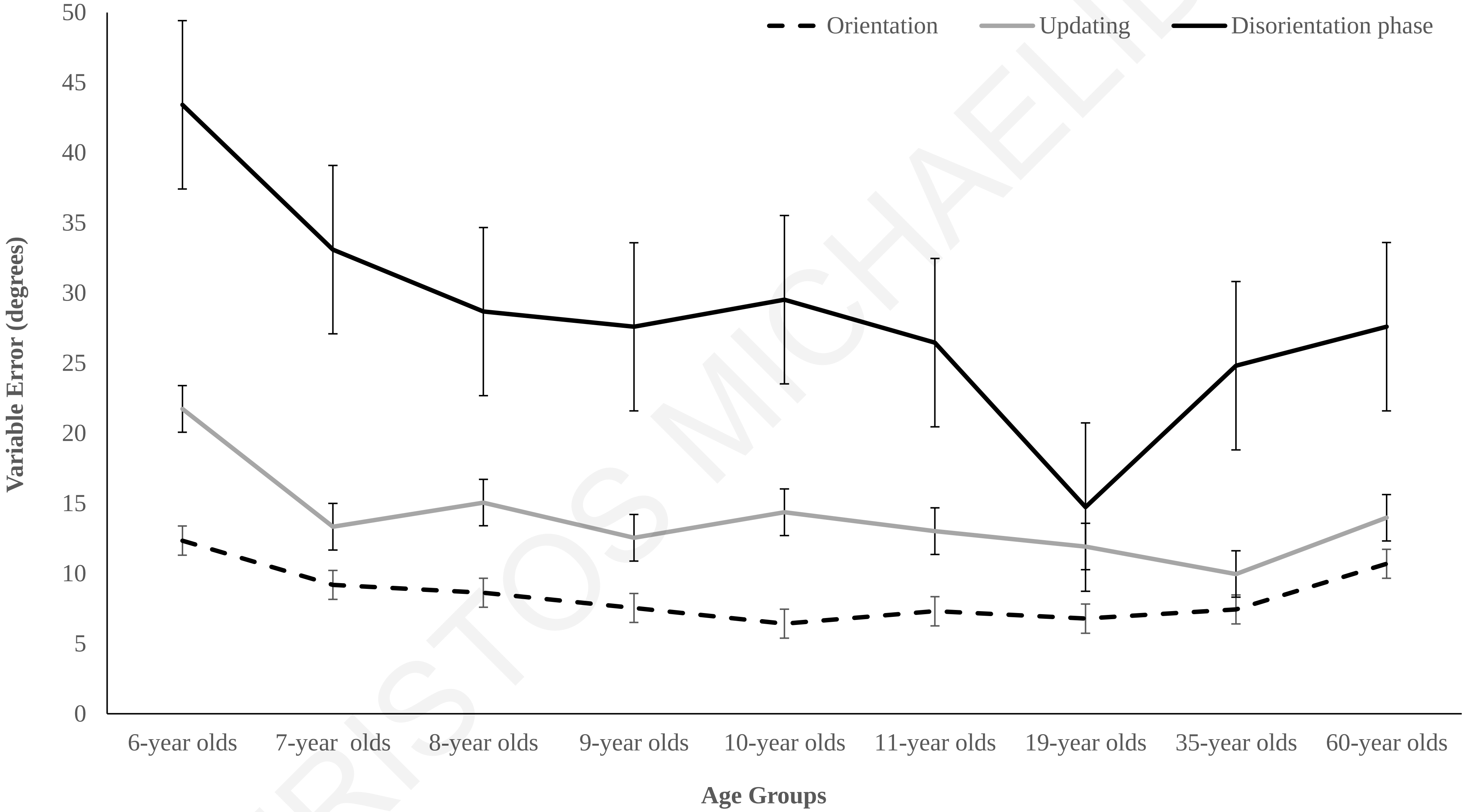


Figure 15. Variable error for the different age-groups in the 3 response phases. Error bars represent standard errors of the mean.

As shown in Figure 15, variable error was overall higher in the disorientation phase (M = 28.44, SD = 29.71) compared to all other experimental phases, all *p's* $< .001$. In fact, variable error increased more than twofold from the updating phase (M = 13.99, SD = 8.56), and more than three times from the orientation phase (M = 8.48, SD = 5.3). A similar pattern was observed for pointing error (Figure 12), although this increase was smaller than the increase of variable error. Pointing error increased from the orientation (M = 11.95, SD = 7.29) to the updating phase (M = 14.54, SD = 8.81) and much further to the disorientation phase (M = 18.27, SD = 13.07), all *p's* $< .001$, indicating that participants were not so consistent in their pointing responses to the same object, particularly in the disorientation phase. In order to examine whether the increase of variable error from the orientation to the updating and from the orientation to the disorientation phase can be entirely accounted for by the increase of pointing variability, two separate ANOVA's were carried out with age as factor and the observed change of variable error and the predicted change based on pointing error as the dependent variables. The analysis revealed that the observed change of variable error from the orientation to the updating phase was significantly greater than the predicted change based on pointing error, $F(1, 207) = 20.68$, $p < .001$, $\eta^2 = .09$ (Figure 16). Similarly, the observed change of variable error from the orientation to the disorientation phase was also significantly greater than the predicted change based on pointing error, $F(1, 207) = 45.93$, $p < .001$, $\eta^2 = .18$ (Figure 17). Thus, the observed increase in variable error in both the updating and the disorientation phase cannot be solely attributed to variability in pointing to the same object.

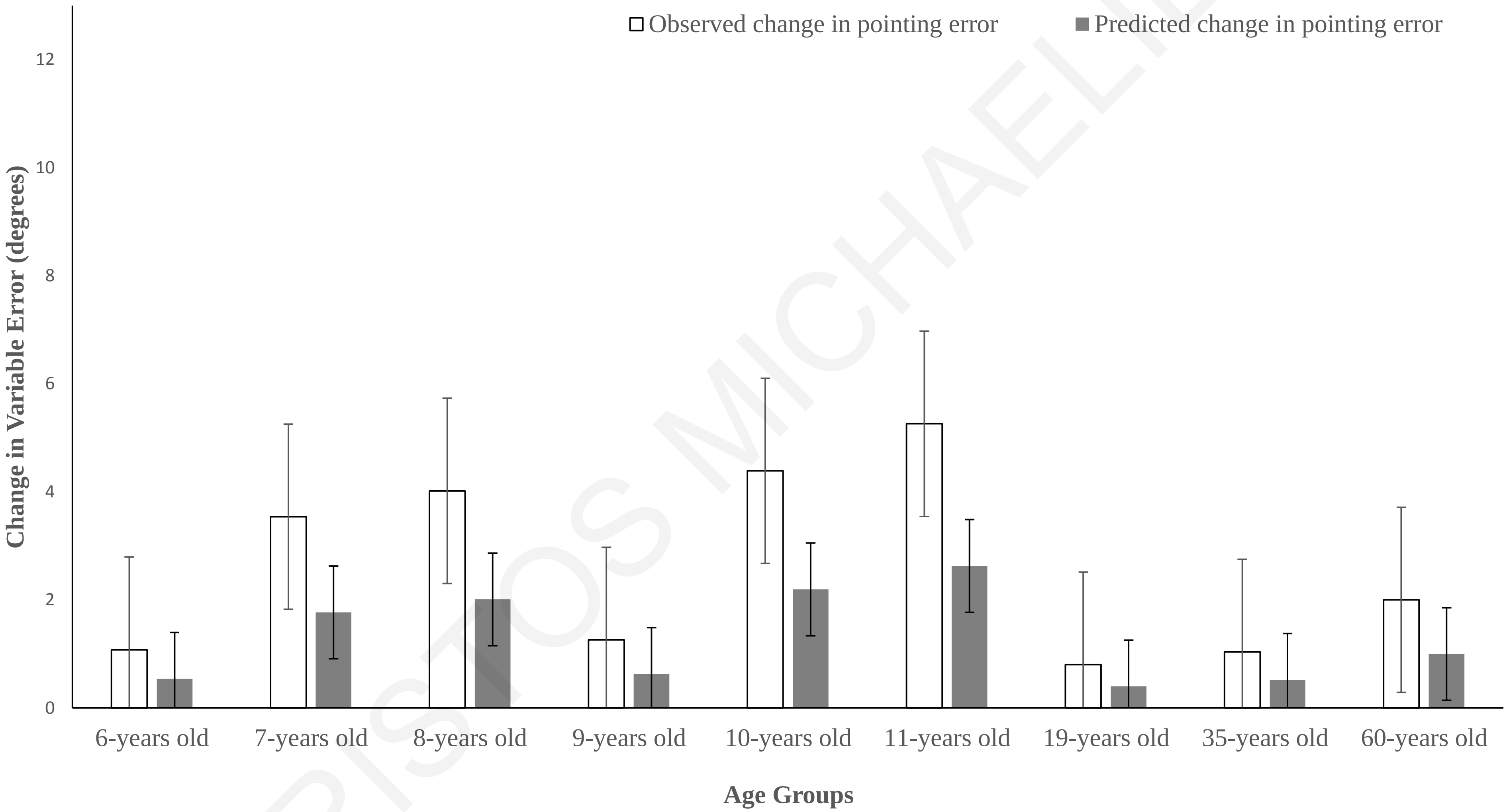


Figure 16. The observed change and the predicted change in variable error based on pointing error between the orientation and the updating phase. Error bars represent standard errors of the mean.

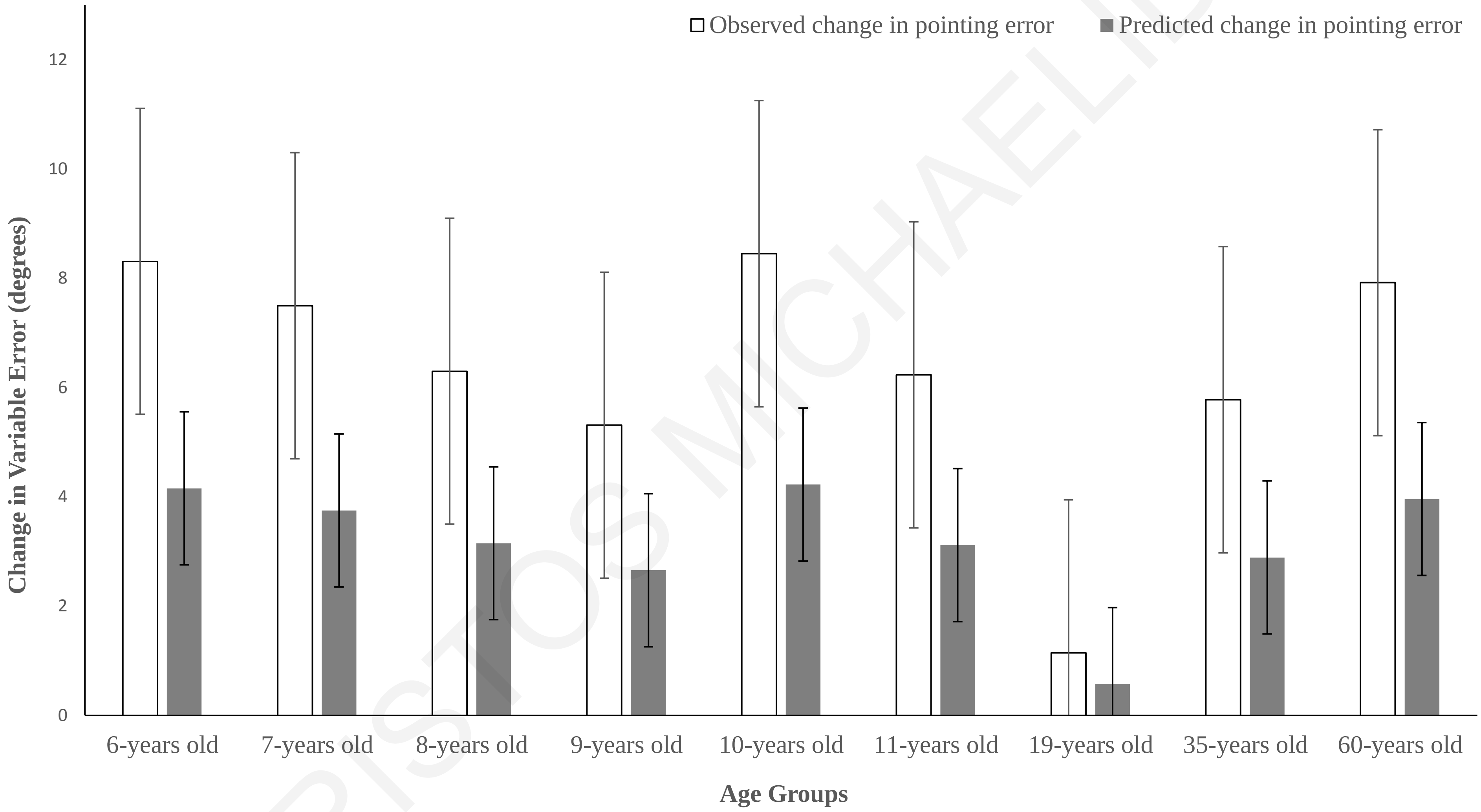


Figure 17. The observed change and the predicted change in variable error based on pointing error between the orientation and the disorientation phase. Error bars represent standard errors of the mean.

Pointing Latency. The ANOVA on pointing latency showed a significant main effect for the experimental phase, $F(2, 414) = 1382.03$, $p < .001$, $\eta^2 = .87$. No significant effect of age and no significant interaction between pointing latency and age were found, $F(8, 207) = 1.25$, $p = .27$, $\eta^2 = .046$, and $F(16, 414) = 1.48$, $p = .105$, $\eta^2 = .054$ respectively.

As seen in Figure 18, pointing latency was significantly shorter in the orientation phase (M = 1011.95, SD = 593.67) than in the disorientation phase (M = 1283.27, SD = 771.54), and nearly four times shorter than the pointing latency in the updating phase (M = 3773.5, SD = 589.19), all *p*'s < .001.

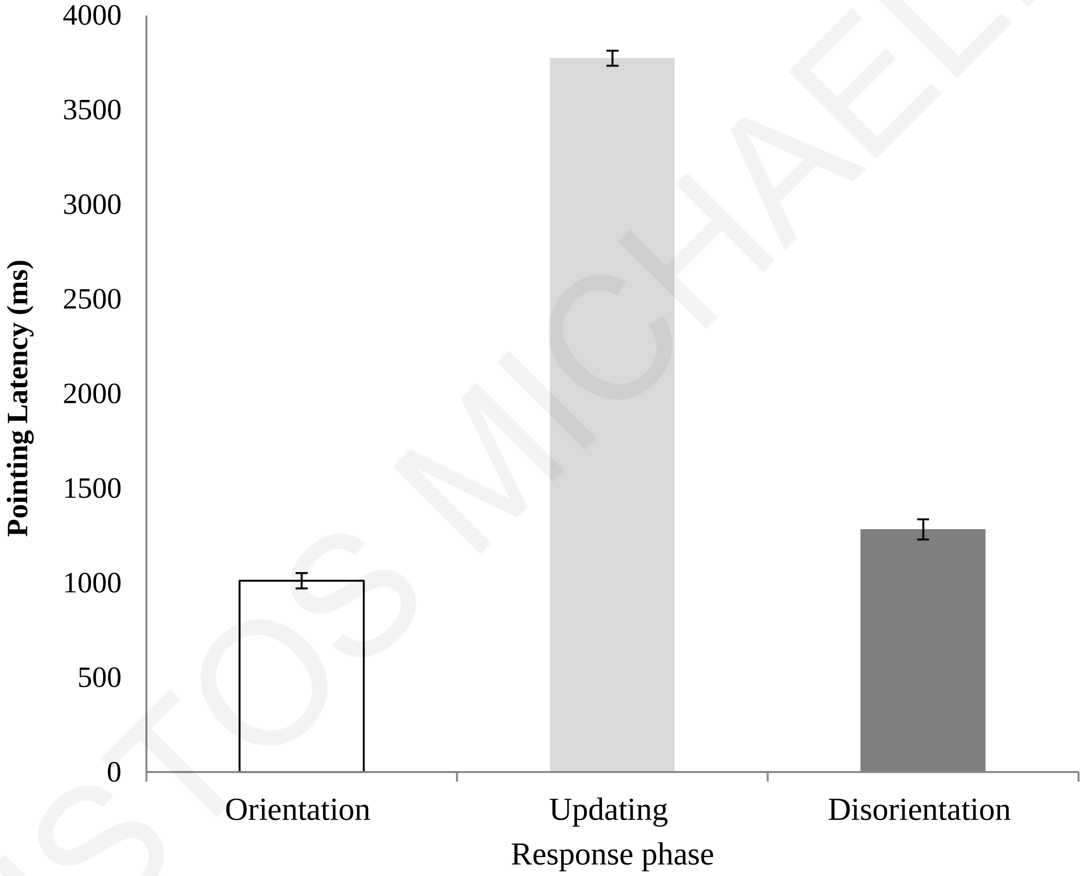


Figure 18. Pointing latency in the 3 response phases. Error bars represent standard errors of the mean.

Pointing latency was significantly lower in the disorientation than in the updating phase, $p < .001$. Further analysis revealed that latency in the disorientation phase was influenced by participants' reported subjective orientation in the disorientation phase. As shown in Figure 19, participants who reported adopting the learning orientation, had lower mean pointing latency (M = 957.34, SD = 441.05) compared to those who adopted the updating (M = 1380.06, SD = 974.37) or the other orientations (M = 1364.15, SD = 786.44). The ANOVA showed that there was a significant difference among participants' subjective orientations, $F(2, 213) = 5.13$, $p = .007$, $\eta^2 = .05$. The learning orientation group had significantly lower pointing latency than the other orientations group, $p = .006$. Although those in the learning orientation group had numerically lower pointing latency than those in the updating orientation group, the difference was not significant, $p = .07$. The updating and the other orientations group had comparable pointing latency, $p = 1$.

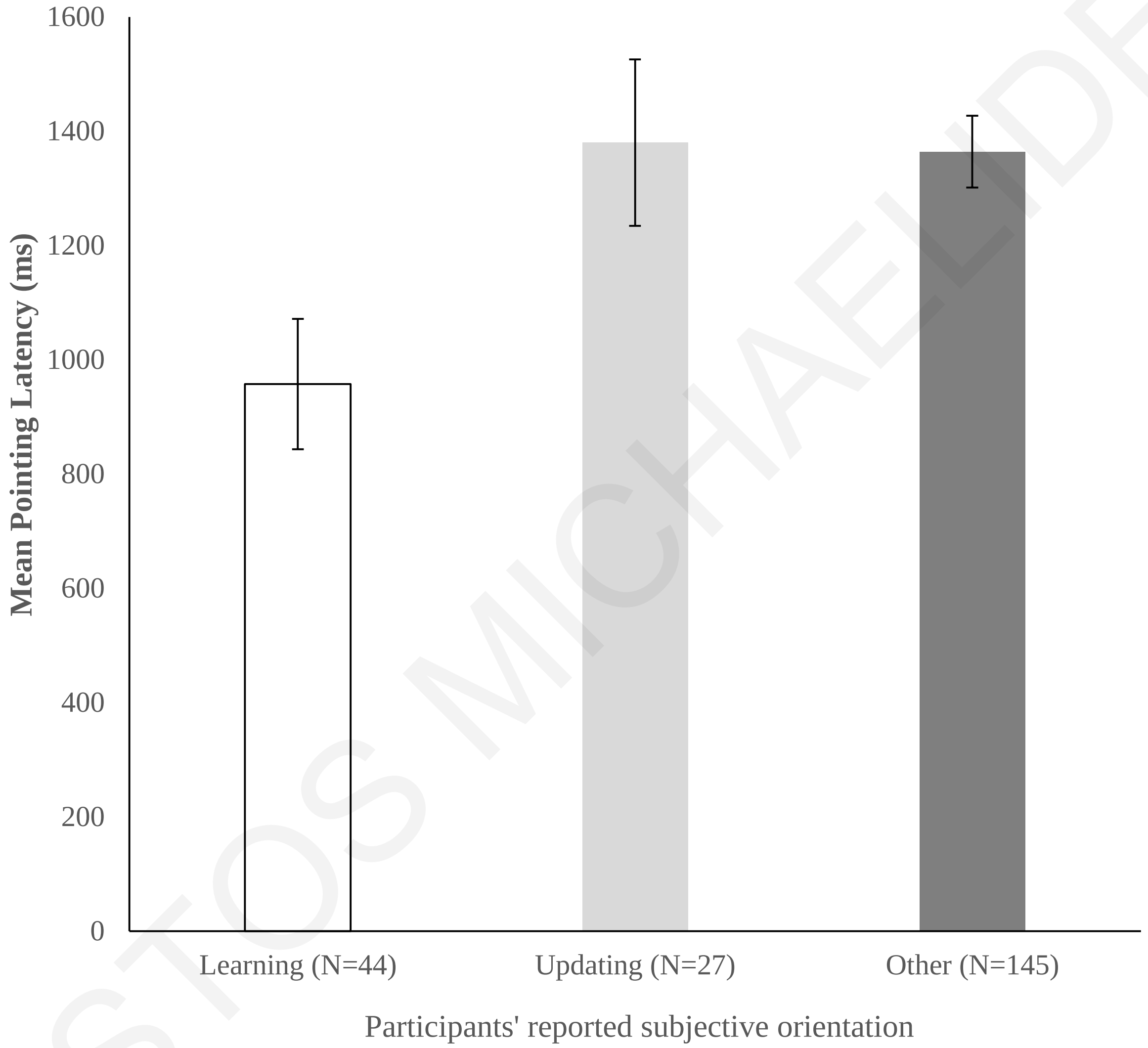


Figure 19. The mean pointing latency (milliseconds) of different subjective orientations in the disorientation phase. Error bars represent standard errors of the mean.

As expected, the simple main effect analysis in the orientation phase did not reveal a significant effect of age, $F(8, 207) = 1.59$, $p = .13$, $\eta^2 = .058$ (see Table 5 for descriptive statistics for each age-group and response phase). All age-groups had comparable pointing latency, all *p's* > .84 (Figure 17). No significant effect of age was present in either the updating phase [$F(8, 207) = .91$, $p = .51$, $\eta^2 = .03$] or the disorientation phase, $F(8, 207) = 1.54$, $p = .15$, $\eta^2 = .06$ (Figure 20).

Table 5. Mean (SD) for pointing latency for each age-group in the 3 response phases.

Age-group	Mean (SD) pointing latency in milliseconds			
	Orientation	Updating	Disorientation	N
6-years old	845.39 (394.23)	3938.46 (601.75)	973.42 (649.57)	24
7-years old	922.54 (476.31)	3751.44 (556.14)	1334.25 (916.55)	24
8-years old	911.68 (527.71)	3703.87 (529.4)	1107.12 (700.23)	24
9-years old	861.8 (349.75)	3766.77 (656.9)	1137.64 (527.68)	24
10-years old	1231.11 (579.58)	3628.63 (661.98)	1556.65 (635.74)	24
11-years old	1055.98 (678.6)	3710.38 (676.4)	1342.63 (760.08)	24
19-years old	1111.03 (554.12)	3985.39 (573.02)	1243.56 (634.53)	24
35-years old	935.99 (467.56)	3758.78 (476.01)	1311.72 (613.69)	24
60-years old	1232.06 (999.59)	3717.76 (548.46)	1542.45 (1208.7)	24
Total	1011.95 (593.67)	3773.5 (589.19)	1283.27 (771.54)	216

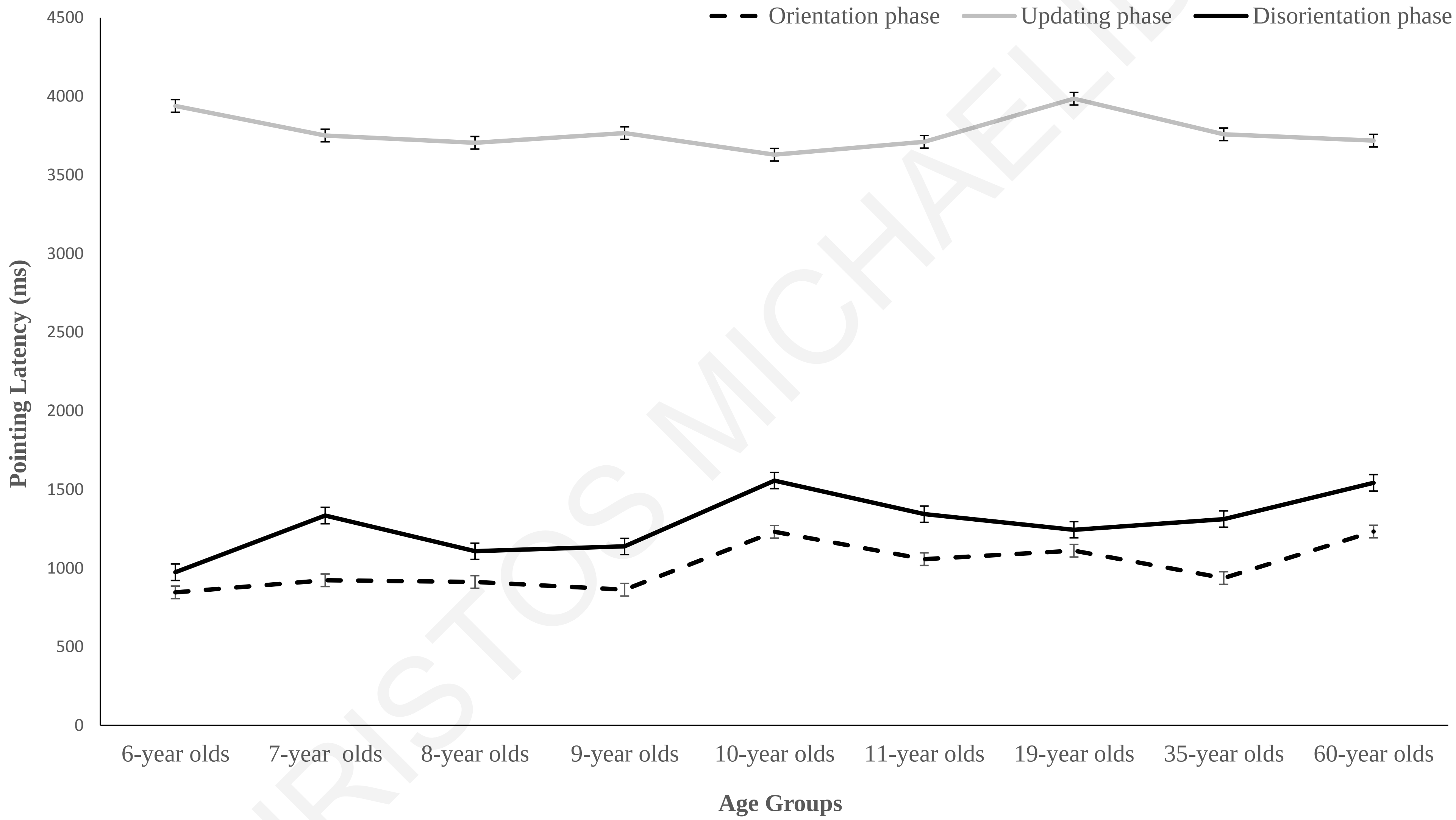


Figure 20. Pointing latency (milliseconds) of each age-group in the 3 response phases. Error bars represent standard errors of the mean.

4.1.2. Spatial short-term memory, gender, and handedness

Separate ANOVAs were conducted with the 3 directional error measures (i.e. constant, pointing and variable error) and pointing latency as the outcome variables, and (a) participants' spatial short-term memory capacity, (b) gender and (c) handedness as the predictor variables.

Based on their individual score on Corsi's Block test, participants were divided into 3 spatial short-term memory groups: low, medium and high. The low spatial memory group (N = 82) consisted of those who scored 4 and below on the test. Participants who scored 5 were designated the medium group (N = 64), while those with a score of 6 and above were in the high group (N = 70). Although there is no established standardization data on the Corsi's Block test, these specific cut-offs used for categorizing participants in the different spatial short-term memory groups were selected based on the results of previous studies with both children and adults. Orsini et al. (1987) provided some initial normative data for spatial short-term memory span, after testing 1355 adults and 1112 children with the Corsi's Block test, and proposed that the average visuospatial span is 4. In a more recent study, Farrell Pagulayan, Busch, Medina, Bartok, and Krikorian (2006) tested both elementary and middle school children and young adults with the Corsi's Block test and found that the lower score was 5 and the maximum 7. Based on these results, I decided to use the score of 5 as the mean score in the current study.

Participants' gender formed 2 groups: males (N = 100) and females (N = 216), while, the administration of the Edinburgh Handedness Inventory –short form led to the formation of 4 groups: right-handers (N = 195), mixed-handers with right-hand preference (N = 6), mixed-handers with left-hand preference (N = 1) and left-handers (N = 14). Due to their small number, in all the following analyses, the 6 mix-handers with right-hand preference and the single one with left-hand preference were included in one group named mixed-handers (see Table 1 for demographic data).

4.1.2.1. Spatial short-term memory

Constant error. No significant differences were found in the distribution of constant error among the different spatial memory groups. In all the experimental phases the Rayleigh test showed that the distribution was not random, all p*'s* $< .001$. The Watson-

Williams F-test showed that the low spatial memory group had larger constant error than the medium and the high group in the orientation phase, and larger error than the medium group in the updating phase, $F(2, 213) = 6.36$, $p = .002$, and $F(2, 213) = 3.004$, $p = .05$ respectively.

Pointing error. The analysis revealed a significant main effect for the different spatial short-term memory groups, $F(2, 213) = 9.1$, $p < .001$, $\eta^2 = .08$. No significant interaction between response phase and spatial memory groups was found. The low spatial memory group had larger pointing error than the other 2 groups in the orientation phase [$F(2, 213) = 5.93$, $p = .003$, $\eta^2 = .05$], and larger error than the high group in both the updating [$F(2, 213) = 4.05$, $p = .02$, $\eta^2 = .04$], and the disorientation phase [$F(2, 213) = 4.88$, $p = .009$, $\eta^2 = .04$].

Pointing latency. No significant differences were found among the three spatial memory groups and pointing latency, in neither experimental phase.

Variable error. The analysis on variable error revealed a significant main effect of spatial short-term memory group, $F(2, 213) = 8.5$, $p < .001$, $\eta^2 = .07$. In the updating phase, participants in the low spatial memory group had significant larger variable error than those in the high group, while in the disorientation phase they had also larger error compared to participants in both the medium and the high spatial group, $F(2, 213) = 4.14$, $p = .02$, $\eta^2 = .04$, and $F(2, 213) = 5.33$, $p = .005$, $\eta^2 = .05$ respectively. More interesting, a significant interaction was found between variable error in the different response phases and the different spatial memory groups, $F(4, 426) = 3.31$, $p = .01$, $\eta^2 = .03$. Variable error increased from the orientation to the updating and from the updating to the disorientation phase, while participants in the low spatial short-term memory group had a higher variable error than those in the medium and the high group (Figure 21).

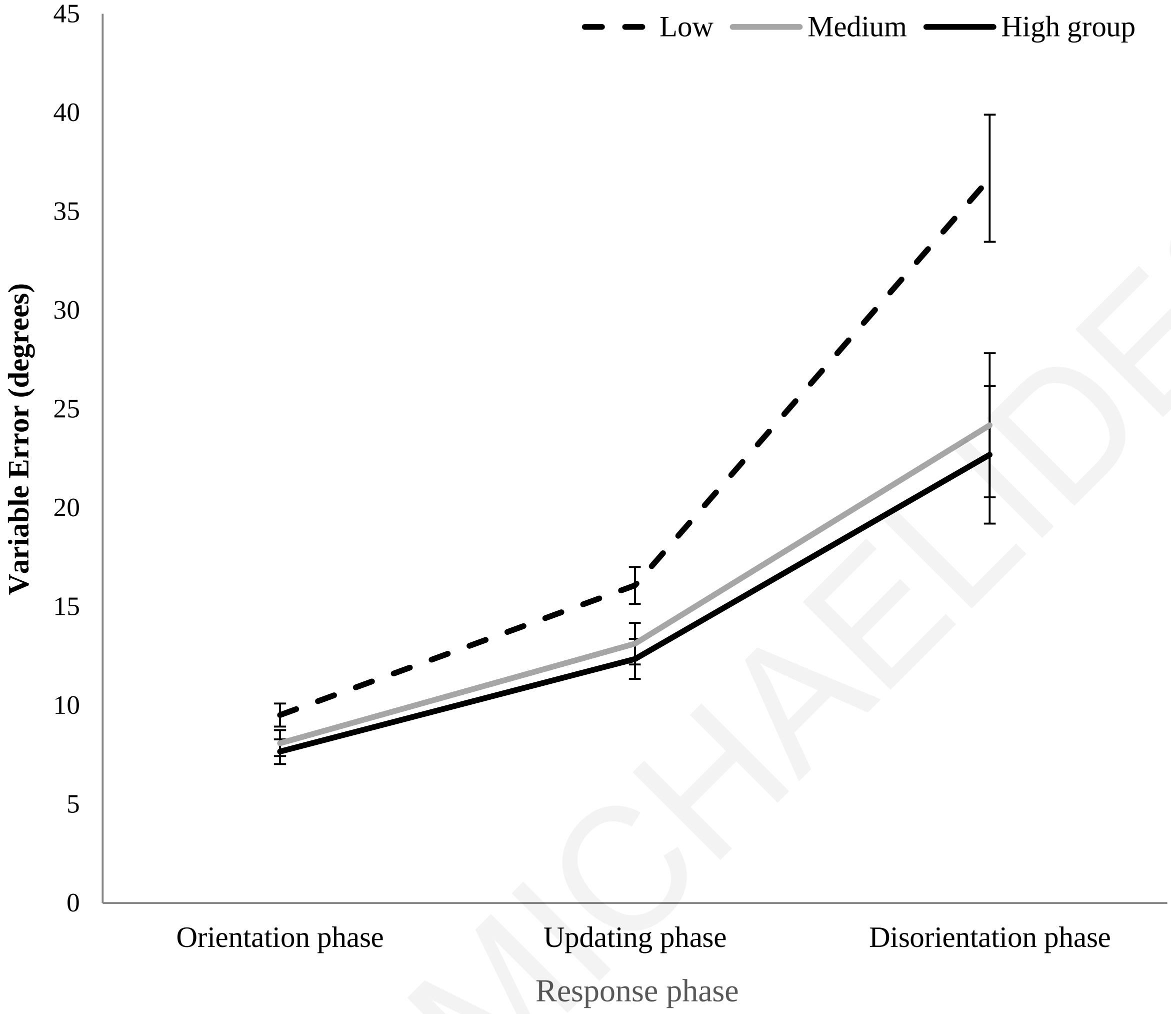


Figure 21. Variable error for each spatial short-term memory group in the 3 response phases. Error bars represent standard errors of the mean.

4.1.2.2. Gender

Constant error. Male and female participants did not differ in the distribution of constant error. In all the experimental phases the Rayleigh test showed that the distribution was not random, all *p's* < .001. In the updating phase, the Watson-Williams F-test showed that males had a lower constant error than females, $F(1, 214) = 6.56$, $p = .011$.

Pointing error. The analysis on pointing error did not reveal any significant gender differences, and no significant interaction between pointing error in the different response phases and gender was found, $F(1, 214) = 2.57$, $p = .11$, $\eta^2 = .01$, and $F(2, 428) = .64$, $p = .53$, $\eta^2 = .003$ respectively. However, the analysis revealed that females had significantly lower pointing error than males in the orientation phase [$F(1, 214) = 3.75$, $p = .05$, $\eta^2 = .02$], and marginally significant lower error in the updating phase, $F(1, 214) = 3.62$, $p =$

.059, η^2= .02. Nevertheless, the magnitude of these significant effects was small, as indicated by eta squared measures.

Variable error. No differences were found between males and females in variable error, neither a significant interaction between variable error in the different response phases and gender, $F(1, 214) = .33$, $p = .57$, η^2= .002, and $F(2, 428) = .45$, $p = .64$, η^2= .002 respectively.

Pointing latency. Although males had overall numerically lower pointing latency than females in all three experimental phases, the analysis did not reveal any significant gender differences, $F(1, 214) = 3.26$, $p = .07$, η^2= .02. No significant interaction between pointing latency in the different response phases and gender was found, $F(2, 428) = 2.06$, $p = .13$, η^2= .01. However, the analysis in the updating phase showed that males had significantly lower pointing latency than females, $F(1, 214) = 9.43$, $p = .002$, η^2= .04.

4.1.2.3. Handedness

Constant error. The constant error was unimodally distributed around zero in both the orientation and the updating phase, regardless of participants' hand preference. In the disorientation phase, mix-handers seemed more disoriented than right- and left-handers, as indicated by a non-significant *p*-value in the Rayleigh test ($p = .068$). However, due to the small number of mix-handers (N = 7), these results may be unreliable. In fact, Rao's Spacing Test (Batschelet, 1981), which also tests the null hypothesis of uniformly distributed data by examining spacing's deviation among points around the circle, yielded a significant value for mix-handers ($p < .05$), and thus the randomness of the data in the disorientation phase can be rejected. The analysis with the Watson-Williams F-test showed that right-handers had lower constant error than left-handers in all the experimental phases: orientation phase [$F(1, 207) = 5.57$, $p = .02$], updating phase [$F(1, 207) = 15.29$, $p < .001$], and disorientation phase [$F(1, 207) = 4.68$, $p = .03$].

Pointing error. The analysis on pointing error revealed a significant effect of handedness, $F(2, 213) = 2.99$, $p = .05$, η^2= .03. Right-handers had lower pointing error than left-handers in both the orientation and the updating phase, $F(2, 213) = 5.01$, $p = .007$, η^2= .05, and $F(2, 213) = 11.06$, $p < .001$, η^2= .09 respectively. More interesting, a significant interaction between pointing error in the different response phases and handedness was found, $F(4, 426) = 4.55$, $p = .001$, η^2= .04. Left- and mix-handers had larger pointing error in all but the disorientation phase. In the orientation phase, right-handers had a lower error than left-handers, who in turn had a numerically lower error than mix-handers. This pattern reversed in the disorientation phase. Nevertheless, the magnitude of these significant effects was small to medium, as indicated by eta squared measures.

Variable error. No differences in variable error were found across the 3 groups (right-left-mix handers), nor a significant interaction between variable error in the different response phases and handedness was found, $F(2, 213) = .37$, $p = .69$, $\eta^2 = .003$, and $F(4, 426) = 1.08$, $p = .37$, $\eta^2 = .01$ respectively.

Pointing latency. Although no differences across the 3 groups in pointing latency were found [$F(2, 213) = 1.38$, $p = .25$, $\eta^2 = .01$], the analysis revealed a significant interaction between pointing latency in the different response phases and handedness, $F(4, 426) = 4.54$, $p = .001$, $\eta^2 = .04$. Mix-handers had lower pointing latency in all but the updating phase, while left-handers had lower pointing latency in the updating phase.

More detail about the analysis on (a) participants' spatial short-term memory, (b) gender, and (c) handedness, can be found in Appendix D.

4.1.3. Age as a continuous variable

In addition to the ANOVAs in which age was treated as a categorical variable, I ran correlational and multiple regression analyses on constant, pointing, and variable error, and pointing latency at the 3 response phases, with age as a continuous variable recorded in months, gender, handedness and spatial short-term memory.

4.1.3.1. Correlational analysis

As shown in Table 6, age correlated positively with spatial short-term memory ($p < .001$), and negatively with constant error in the orientation and the updating phase, $p < .05$ and $p < .01$ respectively. Age also correlated negatively with pointing error in the orientation and the updating phase (both *p's* <.001), and the disorientation phase, $p < .05$. Strong significant negative correlations were found between spatial short-term memory and pointing error in all three response phases, all *p's* <.01. Significant negative correlations between spatial short-term memory and variable error were also found in the orientation ($p < .05$), the updating and the disorientation phase, both *p's* <.01. It is worth mentioning that constant error correlated positively with pointing error in both the orientation and the updating phase, all *p's* < .001.

Table 6

Bivariate Correlations between Age (months), gender, Handedness, Spatial short-term memory, and Measures of Constant, Pointing, and Variable error and Pointing Latency at the Orientation, the Updating, and the Disorientation Phase (N=216)

Measure	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
1. Age (months)	—														
2. Gender	.008	—													
3. Handedness	-.018	-.133	—												
4. Spatial short-term memory	.215***	.105	.034	—											
5. Constant error-Orientation	-.101*	-.142*	.176**	-.106	—										
6. Constant error-Updating	-.186**	.018	.049	-.01	.147*	—									
7. Constant error-Disorientation	.04	-.039	.001	.035	.052	.069	—								
8. Pointing error-Orientation	-.221***	-.131	.205**	-.21**	.569***	.296***	.042	—							
9. Pointing error-Updating	-.251***	-.129	.236***	-.191**	.349***	.282***	.065	.469***	—						
10. Pointing error-Disorientation	-.138*	-.019	-.058	-.206**	.14*	.123	-.039	.201**	.266***	—					
11. Variable error-Orientation	.078	-.099	-.067	-.148*	.102	.096	.003	.251***	.118	.059	—				
12. Variable error-Updating	-.115	.05	.099	-.185**	.09	.15*	.037	.139*	.228***	.124	.36***	—			
13. Variable error-Disorientation	-.086	-.04	-.082	-.201**	-.02	.061	-.121	.03	-.016	.231***	.077	.083	—		
14. Latency-Orientation	.099	.026	-.041	.015	.077	.082	-.055	-.037	.115	.026	-.02	-.036	.082	—	
15. Latency-Updating	-.035	.205**	-.057	-.021	-.183**	.036	.04	-.225***	-.256***	-.144*	.015	.283***	.009	-.154*	—
16. Latency-Disorientation	.092	.029	-.102	.064	.104	.059	.021	-.023	.081	.173*	-.028	-.117	.113	.695***	-.165*

Ns = not significant (p > .05), $p < .05$*, $p < .01$**, $p < .001$***

4.1.3.2. Multiple Regression Analysis

Multiple linear regression analyses were calculated to predict pointing error, variable error and pointing latency in the different response phases, based on participants' age (in months), gender, hand-preference and spatial short-term memory capacity. Although in all the analyses described so far participants were divided into 3 spatial short-term memory groups (i.e., low, medium, and high), for the multiple regression analyses participants were divided into 2 spatial short-term memory groups: low and high. The low group consisted of those who scored 3 or 4 on the Corsi's Block test (82 participants, 38% of the sample), while participants who scored 5 and above were designated in the high group (134 participants, 62%). Based on the administration of the Edinburgh Handedness Inventory –short form, participants were divided into right-handers, mixed-handers-right hand preference, mixed-handers-left hand preference and left-handers (Table 1). Due to their small number, the 6 mix-handers with right-hand preference were included in the right-handed group, while the single mixed-hander-left hand preference participant was included in the left-handed group. In all the following analyses, age was measured in months, gender was coded as 1 = Male, 2 = Female, spatial short-term memory capacity was coded as 1 = low capacity group, 2 = high capacity group, and handedness was coded as 1 = Right-handers, 2 = Left handers.

Pointing error. In regards to pointing error in the orientation phase, a significant regression equation was found, $F(4, 211) = 7.93$, $p < .001$, with an R^2 of .13. Participants' predicted pointing error was equal to 14.12 - .006 (age) - 1.41 (gender) - 2.82 (spatial memory) + 5.56 (handedness). Pointing error decreased .006 degrees for each month of age ($p = .011$), and participants in the low spatial capacity group had 2.82 degrees higher pointing error than participants in the high group, $p = .005$. Left-handers had 5.56 degrees higher pointing error than right-handers, $p = .003$. Pointing error for males and females did not differ, $p = .14$.

A significant regression equation was also found with pointing error in the updating phase, $F(4, 211) = 11.44$, $p < .001$, with an R^2 of .18. Participants' predicted pointing error was equal to 11.87 - .009 (age) - 1.74 (gender) - 2.29 (spatial memory) + 10.4 (handedness). Pointing error decreased .009 degrees for each month of age ($p = .001$), and participants in the low spatial capacity group had 2.29 degrees higher pointing error than participants in the high group, $p = .05$. Left-handers had 10.4 degrees higher pointing error than right-handers, $p < .001$. Again, pointing error did not differ between males and females, $p = .12$.

The analysis on pointing error in the disorientation phase also revealed a significant regression equation, $F(4, 211) = 2.7$, $p = .032$, with an R^2 of .05. Participants' predicted pointing error is equal to 28.23 - .006 (age) + .12 (gender) - 4.71 (spatial memory) - 1.03 (handedness). The only significant difference present was for spatial short-term memory capacity group. Participants in the low spatial capacity group had 4.71 degrees higher pointing error than participants in the high group, $p = .01$.

Variable error. The multiple linear regression analysis on variable error in the orientation phase revealed a significant regression equation, $F(4, 211) = 2.65$, $p = .03$, with an R^2 of .05. Predicted pointing error was equal to 13.64 + .003 (age) - .86 (gender) - 1.77 (spatial memory) - 1.54 (handedness). Only one significant difference was found; participants in the low short-term memory group had 1.77 degrees higher variable error than participants in the high group, $p = .02$.

A significant regression equation was also found with variable error in the updating phase, $F(4, 211) = 2.67$, $p = .03$, $R^2 = .05$. Predicted pointing error was equal to 16.61 - .003 (age) + 1.32 (gender) - 3.28 (spatial memory) + 1.25 (handedness). Again, the only significant difference was between the two spatial short-term memory capacity groups. Participants in the low capacity group had variable error that was 3.28 degrees greater than that of participants in the high group, $p = .008$.

Finally, the analysis also revealed a significant regression equation with variable error in the disorientation phase, $F(4, 211) = 2.72$, $p = .03$, $R^2 = .05$. Predicted pointing error was equal to 53.18 - .006 (age) - .74 (gender) - 12.57 (spatial memory) - 1.85 (handedness). As with the previous two phases, the only significant difference was that participants in the low spatial capacity group had variable error that was greater by 12.57 degrees than participants in the high group, $p = .004$.

Pointing Latency. Multiple linear regression analyses on pointing latency in both the orientation and the disorientation phase did not result in a significant regression equation, $F(4, 211) = .66$, $p = .62$, $R^2 = .01$, and $F(4, 211) = .68$, $p = .61$, $R^2 = .01$ respectively. However, a significant regression equation was found with pointing latency in the updating phase, $F(4, 211) = 6.67$, $p < .001$, $R^2 = .11$. Participants' predicted pointing error was equal to 4180.4 - .07 (age) + 244.72 (gender) - 101.82 (spatial memory) - 562.87 (handedness). Males had lower pointing latency in the updating phase than females (p = .002), and left-handers had lower pointing latency than right-handers, $p < .001$.

CHAPTER 5 – DISCUSSION

The primary goal of the current study was to experimentally examine developmental changes in how children at various ages (6-, 7-, 8-, 9-, 10-, 11-year olds) as well as adults (19-, 35-, 60-year old adults), construct and update spatial representations of multiple objects. More specifically, the experiment was designed to examine at different ages: (1) the accuracy of spatial memories for layouts containing multiple objects, (2) how well the previously formed spatial memories can be updated as a result of self-movement, and (3) how resilient spatial memories are to disorientation. Based on the literature review and the findings from previous studies, 7 hypotheses were formed and examined.

5.1. Hypothesis 1

My first hypothesis was that in the orientation phase, younger children would be less accurate than older children and adults in reconstructing from memory an array of multiple objects. Overall, results showed that participants remained oriented while blindfolded, localized each object from memory with precision, and retained the spatial relations among the different objects. However, 6-year olds were less accurate than older children and adults, in reconstructing from memory the spatial array while being oriented, indicating that mental spatial representations continue to improve and become more accurate during the first school years.

These results are in line with findings from other studies (e.g., Hund & Plumert, 2003; Michaelides & Avraamides, 2017; Plumert, Franzen, Mathews & Violante, 2017), which have documented the improvement in memory for studied locations, after the age of 7. In a recent experiment, we asked 7-, 9-, and 11-year olds and adults to memorize an array of 4 objects that were presented at different locations on the circumference of a circle projected on a large screen. After memorizing the array, participants were asked to recreate it, by placing the location of each object on a handout containing a printed circle (Michaelides & Avraamides, 2017). Results from this simple task showed that, although 7-year olds were able to represent spatial locations in their memory with relative precision, the ability to maintain accurate object-to-object relations was fully mastered only after the age of 7.

One possibility is that the difference in accuracy between the 6-year olds and the older participants was due to less refined motor skills in younger children. The current task required participants to extend their hand without bending it and point to objects so performance could be impaired if one experienced difficulty with the motor aspects of the task. Although it is known that young children have less refined motor skills than older children and adults (Haubenstricker & Seefeldt, 1986), the analysis of pointing error revealed that 6-year olds had higher error than 11-year olds and all adult groups, but they did not differ from 8-, 9-, and 10-year olds. In contrast, 6-year olds' variable error was higher than that of 9-, 10-, 11-year olds and 19-, 35-year old adults. That 6-year olds had comparable pointing errors to older children, indicates that the observed differences in variable error cannot be attributed, at least not fully, to less developed motor skills.

An alternative explanation for the differences in variable error relates to the development of the different cognitive processes involved in the task. Pointing without vision to objects while oriented in the environment may seem a rather simple task. However, the previous literature indicates that it goes through at least three different processing stages (Cestari, Lucidi, Pieroni, & Rossi-Arnaud, 2007; Peebles & Jones, 2014; Postma, Wijnalda, & Kessel, 2001). That is, to complete the orientation phase, participants had to (1) identify and remember the different objects, (2) carry out positional encoding, i.e., encode and maintain the distinct locations occupied by the objects, and (3) associate objects and locations, that is, to process and remember which object was at which location. Past research has shown that binding objects to locations depends on visuospatial memory capacity and requires attention resources (Wheeler & Treisman, 2002); these resources may be underdeveloped at the age of 6. This is corroborated by the finding that spatial short-term memory capacity in the current study was the lowest in 6-year olds compared to all other age-groups. Results revealed a developmental increase in spatial span -from early childhood to early adulthood- reflecting a constant improvement of spatial short-term memory over time. Interestingly, this improvement paralleled a decrease of variable error, from the age of 6 years up to the age of 35 years. Although age and spatial short-term memory were positively correlated, the correlation analysis revealed significant negative correlations only between spatial short-term memory and variable error, but not between age and variable error.

Interestingly, 6-year olds' performance differed from that of older children and younger adults, but not from that of 60-year old adults. In fact, the average 6-year olds' pointing response deviated 12.4^{o} ($\pm$ 8.2^{o}) from the veridical object's position, while the corresponding one for the 60-year old adults was 10.7^{o} (± 6.1^{o}), with these two age-groups having the highest deviation from all the age-groups.

5.2. Hypothesis 2

Hypothesis 2 stated that although self-movement provides useful vestibular and motor efference cues which can be used to update spatial memories accurately, the updating process is not perfect. Updating accumulates error which is problematic for long distances. Although in the present experiment the updating phase involved only a short rotation, I expected that there would be decrements in participants' pointing performance compared to the orientation phase. Results confirmed Hypothesis 2 by showing that both the pointing and the variable error increased from the orientation to the updating phase, for all age-groups.

Previous studies (e.g., Farrell & Thomson, 1998, 1999; Huttenlocher & Presson, 1973; Nardini et al., 2006; Newcombe et al., 1998; Presson & Montello, 1994; Rieser, 1989; Simons & Wang, 1998; Wang and Simons, 1999) provided evidence that when people physically move to a new standpoint, they continuously and effortlessly update self-to-object spatial relations. The current study revealed that blindfolded participants in the updating phase, regardless of their age, maintained a relatively accurate spatial representation of the object-array, although not as accurate as the one in the orientation phase. These findings indicate that the idiothetic cues that accompany physical movement (e.g., vestibular signals, proprioceptive and optic flow information) were sufficient for blindfolded participants to update their orientation relative to the stable environment. An interesting finding from the current study was that even 6-year olds were able to update their orientation relative to the stable environment based solely on idiothetic cues, although their performance was less accurate compared to that of older children and adults. This finding is in line with those of Nardini et al. (2006), who showed that the updating ability continues to improve until at least the age of 6 years. The current findings also add to the existing developmental literature on spatial updating, by revealing that the updating performance continues to improve until the age of 7, the age at which it seems to reach the adult level.

However, the results of the constant, pointing and variable error in the updating phase, suggest that spatial updating is not a perfect process. The analysis of constant error revealed that there was a significant difference in participants' perceived facing direction between the orientation and the updating phase, and not all participants were highly accurate in updating their facing orientation. Moreover, the pointing error increased numerically for all age-groups from the orientation to the updating phase, while this increase was significant for children and older adults. Finally, all age-groups exhibited a significant increase in variable error from the orientation to the updating phase (35-year old adults had a marginally significant increase). These results support the view that spatial updating remains a potential source of error (Meilinger & Vosgerau, 2010), and they are in line with the results of previous studies with adults showing that spatial updating accumulates error over distance (e.g., Wang, 1999; Wang & Spelke, 2000; Xiao, Lian, & Hegarty, 2015). Furthermore, the current study adds to the existing developmental literature on spatial updating, by revealing that the process of updating memorized spatial relations among multiple objects remains a possible source of error throughout the lifespan even with a small physical rotation.

5.3. Hypothesis 3

According to Hypothesis 3, disoriented participants had to adopt a subjective orientation before pointing to the different objects in the disorientation phase. I expected that some participants in the current study would adopt one of the two previously experienced orientations as their subjective orientation (i.e., the learning or the updating orientation). I hypothesized that the participants who would adopt the previously experienced orientations would be more accurate and faster in their pointing responses, than those who would adopt other random orientations. The results partially confirmed Hypothesis 3, as both the experienced orientations resulted in more accurate performance than the other random orientations, although only the learning orientation resulted in lower pointing latency.

First, the results of the current research revealed that blindfolded participants were indeed unaware of their facing direction due to the 30-seconds rotation that preceded the disorientation phase. Participants' disorientation was confirmed by their self-reported subjective orientation at the end of the experiment, as nearly all of them reported an incorrect facing direction. Due to their uncertainty about their facing direction, participants had to adopt a subjective orientation before being able to point to the different objects. As expected, when participants were asked to report the direction they thought they were facing, after completing the disorientation phase, one-third of them (mostly 19- and 35-year old adults) responded as if they were facing either the learning or the updating orientation. These results are in line with previous studies with adults, which showed that when people are disoriented, they tend to adopt the orientation experienced during learning (e.g., He, McNamara, & Kelly, 2018; Holmes & Sholl, 2005; Mou et al., 2004, 2006; Waller et al., 2002). However, the majority of all children's groups and the 60-year old adults selected an orientation towards a specific object of the array or the orientation behind them, as their subjective orientation.

The current results showed that participants who adopted one of the two previously experienced orientations were more accurate in their pointing responses than those who reported facing other random orientations. These findings are in line with previous studies, which showed that individuals could more easily retrieve the locations of different objects when they adopted the previously experienced learning orientation, than when they adopted other orientations (e.g., Holmes & Sholl, 2005; Mou et al., 2004, 2006; Xiao et al., 2015). In the current study, participants who adopted either the learning or the updating orientation might have benefitted from the familiarity with these orientations and simply repeated the pointing responses they executed during learning or updating. In contrast, participants who relied on other random orientations --mostly children and older adults-- were more disadvantaged, as in the disorientation phase they had to compute egocentric vectors based on a previous spatial memory and their subjective orientation. This might have posed a burden on cognitive resources, especially in school-age children and older adults accounting for their lower accuracy.

Although both the learning and the updating orientations resulted in more accurate performance than the other random orientations, these two orientations were not equivalent regarding pointing latency. In the current study, only the learning orientation resulted in lower pointing latency, while participants who adopted either the updating orientation or other random orientations exhibited similar pointing latency. The better performance for the learning orientation, not only in pointing accuracy but in pointing latency as well, indicates that participants in the study may have formed during learning a spatial representation with a specific reference direction. In the orientation phase, participants could rely on this initial representation and point accurately to the different objects. In the updating phase, participants updated self-to-object spatial relations and formed an additional representation that was nevertheless less precise. During the disorientation phase, participants who adopted the learning orientation were able to point to the different objects based on their initial representation. By contrast, participants who adopted the updating orientation used the representation they formed in the updating phase. This less accurate representation could lead to increased pointing latency, indicating prolonged conscious reflection about the response with increasing uncertainty. Another possible explanation might be that participants who adopted the updating orientation, instead of using the updating representation, may have deliberately recalculated the spatial relations between themselves and the different objects based on the initial learning orientation, resulting again to higher pointing latency.

5.4. Hypothesis 4

According to Hypothesis 4, I expected that participants would perform worse in the disorientation phase than in the orientation and the updating phase, either because of switching to a more enduring but coarser allocentric representation or because egocentric vectors would be disturbed by disorientation.

Theories of spatial cognition traditionally tried to characterize spatial behavior based on two distinct spatial frames of reference: egocentric and allocentric. The use of an egocentric frame of reference results to representations which maintain the specific spatial perspective from which an individual encodes information. Thus, accurately accessing and representing these spatial locations depends on the invariable relation between the organism and these locations. At the same time, if an individual relies on an allocentric frame of reference, the derived spatial representations -which are centered on objects and not on the organism itself- will be equally accessible despite any changes of the spatial relations between the individual and the locations of different objects. In the current experiment, if participants had encoded each object-location in an egocentric manner, then the encoded spatial information would be expected to change from the orientation to the disorientation phase, as the disorientation process would disturb the egocentric vectors (Wang & Spelke, 2000). In contrast, if participants encoded the different object locations in an allocentric manner, this coding and the resulting representation would remain unaffected the participant's position in space, and both accuracy and pointing latency in the disorientation phase would be comparable to the corresponding measures in the orientation phase of the experiment.

The findings of my study confirmed Hypothesis 4. In the disorientation phase, participants were not only more disoriented, but they also had higher pointing and variable error than in the orientation and the updating phase, regardless of their age, gender or spatial short-term memory group. More specifically, variable error in the disorientation phase was about 2 times greater than in the updating phase and more than 3 times greater than in the orientation phase. This performance decrement in the disorientation phase can be interpreted by two possible explanations, each of which assumes a different type of spatial representation. The first explanation is that disoriented participants switched from a precise but transient egocentric representation to a more enduring but coarser allocentric representation, and this less precise representation accounts for the performance decrement. An alternative explanation may be that participants in the disorientation phase continued to rely on their initial egocentric representation of the object array, and the disorientation procedure disturbed the egocentric vectors resulting in worse performance than in the orientation and the updating phase. Results from previous studies (e.g., Holmes & Sholl, 2005; Mou et al., 2006; Waller & Hodgson, 2006; Xiao, Mou, & McNamara, 2009) are ambiguous, with Waller and Hodgson arguing for an egocentric to allocentric switch, and Wang and Spelke (2000) arguing for the egocentric account. Although no definitive conclusion about which explanation holds can be derived from the current study, the inclusion of participants in different age-groups allows making some more informed speculation.

Specifically, if the disorientation procedure switches reliance from an egocentric to an allocentric representation, the decrement should have been more prominent in younger children and older adults than in the other age-groups. According to past research with children (e.g., Nardini et al., 2009), allocentric representations develop late in childhood or at least are selected for action at a later developmental stage. As shown by a large body of experimental research, the ability of using allocentric representations seems to emerge somewhere between 6- and 8-years of age (e.g., Bullens et al., 2010; Lehnung et al., 2003; Leplow et al., 2003; Nardini et al., 2006, 2009), with the ability undergoing significant development until adolescence when specific brain regions reach full maturation (Pine et al., 2002). Furthermore, previous studies revealed that older adults also had difficulties with the allocentric spatial coding. These studies revealed that older adults were less accurate and needed more time than the younger ones, in tasks that require allocentric representations (e.g., Harris et al., 2012; Jansen et al., 2010; Kirasic, 1991; Lester et al., 2017; Montefinese et al., 2015; Wiener et al., 2012, 2013). Therefore, a switch from an egocentric to an allocentric representation would result in less accurate performance for both the younger children and the older adults than the other age-groups. If however, in the disorientation phase people continue to rely on egocentric vectors for their spatial representations, there is no reason to expect that the decrement would differ across age-groups.

The current results are more in line with the egocentric account. Participants, regardless of their age, seem to encode spatial relations among multiple objects using an egocentric representation, rather than switching to an allocentric representation. The analysis of the variable error in the disorientation phase revealed no effect of age, with children from the age of 7 and onwards showing comparable performance to each other and adults. Further analysis revealed that only the 6-year olds had significantly larger variable error compared to the 19-year old adults. Despite that the 19-year old adults had a numerically lower variable error than all other age-groups, this difference was not statistically significant. The finding that the older participants in the current study showed comparable performance to the younger ones is in line with the findings of Montefinese et al. (2015), who also found no differences between older and younger adults in a task that required egocentric coding. The current findings do not support Waller and Hodgson's (2006) interpretation that disorientation results in the replacement of one's accurate but transient egocentric representation with a more enduring but coarser allocentric representation. In contrast, my findings support further Wang and Spelke's theory for the primacy of an online, transient representational system, which is accurate as far as individuals stay oriented, but becomes unreliable as a result of disorientation. Furthermore, the current findings, in conjunction with the findings of previous studies offer support for the retrogenesis hypothesis. According to this hypothesis, cognitive changes in healthy aging reverse the order of acquisition in mental development (Reisberg et al., 1999). More specifically, the current study revealed that egocentric representations which are believed to develop early in the developmental pathway, remain intact at least until the age of 60. The current and previous findings strengthen the view for the primacy of egocentric representations and further supports the assumption that allocentric representations develop gradually during childhood.

5.5. Hypothesis 5

According to Hypothesis 5, blindfolded participants had to rely on previously formed mental spatial representations to point to the different objects, as they did not have the opportunity to refresh their memory for the object array during the experiment. I expected that participants with high spatial short-term memory capacity would be more accurate in their pointing performance in all the response phases, than those with low spatial short-term memory capacity. The results only partially supported Hypothesis 5, as participants in the high spatial memory group were more accurate than those in the low group, only in the updating and the disorientation phase.

To be more explicit, in the orientation phase, although participants in the high spatial memory group were numerically more accurate than those in the medium and the low group, no significant differences were found among the different groups. However, in the updating phase, participants in the low spatial memory group were as expected less accurate in their pointing responses than those in the high spatial memory group. Similarly, in the disorientation phase, participants in the low spatial memory group were also less accurate compared to participants in both the medium and the high spatial memory group. These findings indicate that although limited spatial short-term memory capacity may not influence participants' performance when oriented in space, it may be related to performance decrements when individuals have to update their position in space, and more so when they become disoriented. Interestingly, a significant interaction was found in variable error between the different response phases and the three spatial memory groups. Although no significant differences were found among spatial memory groups in the orientation phase, there were differences in the updating phase that grew bigger in the disorientation phase. In both updating and disorientation, participants in the low group were less accurate than those in either the medium or the high spatial memory group. No significant interaction was found when age was used as a predictor variable, suggesting that it may not be age per se that differentiates pointing performance, but the ability to retain and recall more information from memory, as a consequence of aging. This assumption is further supported by the results of the correlation analysis, which showed that although age and spatial short-term memory were positively correlated, variable error was negatively correlated only with spatial short-term memory, and not with age.

The finding that in the updating phase participants in the low spatial short-term memory group were less accurate than those in the high group, indicates that spatial short term memory influences participants' performance. However, this finding also suggests that spatial updating might not be as automatic as previous studies proposed. The non-automatic spatial updating assumption is further supported by the analysis of pointing latency. Participants regardless of their age needed more time to point to the objects in the updating than in the other two response phases. On average, in both the orientation and the disorientation phase, participants were ready to point towards the announced object within

1-1.5 second, following the 2.5 seconds pre-recorded auditory instruction message. In contrast, in the updating phase participants' pointing latency was nearly four times longer than in the other response phases, indicating prolonged conscious reflection about the response with increasing uncertainty. This increased latency suggests that participants tried consciously to compute egocentric relations that were altered by self-movement. The current findings suggest that spatial updating might be a process that is subjected to memory decay, has capacity limitations and requires cognitive resources.

Another interesting finding resulting from the scores on the Corsi's Blocks test is a developmental increase in the spatial span from early childhood to early adulthood. There was a considerable increase in children's performance from the age of 6 to the age of 8, and an even more substantial increase between the ages of 10 to 11-years, followed by a period of nugatory changes until the age of 19 and some less marked changes up to the age of 35. The fact that the spatial memory span seems to reach the adult level at the age of 11, further supports Belmonti, Cioni, and Berthoz's view (2015) that between 6 and 10 years of age, different cognitive achievements take place. Although the basic working memory structure is present at the age of 6, it seems that it undergoes significant change throughout the childhood years (Gathercole, Pickering, Ambridge, & Wearing, 2004). According to Nichelli et al. (2001), this impressive improvement in memory performance of children might be determined by the interaction of biological and socio-educational maturation factors. Throughout childhood, significant developmental changes in the morphological and functional organization of the brain (for a review see Tau & Peterson, 2010), in conjunction with the cognitive strengthening and automatization of different strategies due to formal education, result in the improvement of children's spatial performance (Nichelli et al., 2001). Despite the fact that spatial span seems to remain stable from late childhood through mid-adulthood, it showed a significant decrement around the age of 60, possibly as a result of overall physiological and cognitive decline observed in old age. Since the current task was resource-demanding, the observed reduced performance of both young children and the elderly could be ascribed to a developmental or age-related decrease in cognitive resources (e.g., memory capacity, processing speed, deployment of strategies). The current results are in line with those of other studies (e.g., Belmonti et al., 2015; Orsini et al., 1987; Farrell Pagulayan et al., 2006) and reflect the underlying changes in the spatial brain from childhood to old age.

5.6. Hypothesis 6

Despite the fact that there is still a controversy about the conditions under which gender differences are observed in spatial ability, scientists agree that they depend largely on the type of spatial task used (Iachini et al., 2008; Voyer et al., 1995). According to Hypothesis 6, I did not expect to find any gender differences on pointing accuracy and latency, based on previous findings from studies that used Wang and Spelke's (2000) paradigm with adults.

Although there is a consensus that there are no gender differences in what is called general intelligence (Halpern & LaMay, 2000; Reilly, Neumann, & Andrews, 2017), studies in the last half century have reported gender differences for different cognitive abilities. In fact, the most substantial gender differences have repeatedly been found in spatial ability (Reilly et al., 2017; Voyer et al., 1995; Voyer, Voyer, & Saint-Aubin, 2017). In the majority of these studies, men outperformed women in tasks that require spatial perception and visualization, mental rotation, the ability to generate and transform a spatial image, aiming at and tracking objects, or navigating large-scale outdoor environments (Halpern & LaMay, 2000; Iachini, Ruotolo, & Ruggiero, 2009; Kaufman, 2007; Linn & Petersen, 1985; Silverman, Choi, & Peters, 2007; Voyer et al., 2017). However, in some other studies, women were found to perform better than men, especially in tasks that involved object location memory (Duff & Hampson, 2001; Eals & Silverman, 1994; Silverman et al., 2007; Voyer et al., 2017). Other studies, however, underlined the absence of gender differences in spatial tasks that involved object location memory (Dabbs, Chang, Strong, & Milun, 1998; Janzen & Van Turennout, 2004; Rahman, Bakare, & Serinsu, 2011) or the use of different navigational strategies in virtual mazes (Harris et al., 2012; Wiener et al., 2012, 2013; Wiener, Carroll, Juthapan, Bibi, Ivanova, & Wolbers, 2017).

The results of the current study only partially supported Hypothesis 6. More specifically, some gender differences were found regarding the constant and pointing error and pointing latency. On the one hand, although blindfolded participants maintained a sense of orientation in the different experimental phases, males were faster and more accurate in updating their orientation than females. Waller et al. (2002) found similar results in a study that required adult participants to learn different paths from a specific viewpoint and later make judgments of relative directions based on specific orientations on each path, after updating their representations. On the other hand, female participants were more accurate than males in their pointing responses in the orientation and the updating phase of the current experiment. This finding is in line with previous results which showed an advantage for females on different visual memory tasks. Silverman et al. (2007) compared data from 40 different countries and more than 247 000 participants from 7 ethnic groups on an object location memory task and found that women performed better than men in 35 of the 40 countries. Additionally, Eals and Silverman (1994) found that women were more accurate than men in recalling the locations of multiple objects (but see Rahman et al., 2011).

However, the analysis of variable error, which was the primary measure of interest in the current study, did not reveal any differences across genders. These results are in line with previous findings, in which gender had no effect on the variable error when adult participants were examined (e.g., Holmes & Sholl, 2005; Waller & Hodgson, 2006). Moreover, they extend these findings by underlining the absence of gender differences in a task that examines object localization ability during self-movement, from childhood to old age.

Furthermore, although some studies (e.g., Capitani, Laiacona, & Ciceri, 1991; Orsini et al., 1987; see Voyer et al., 2017 for a meta-analysis review) reported a larger spatial memory span favouring men –at least at specific age-groups-, the current study did not find any significant gender differences in spatial short-term memory capacity. The current results corroborate findings reported by other studies which also did not find any significant differences between men and women in spatial span capacity (e.g., Nichelli et al., 2001; Farrell Pagulayan et al., 2006). In a recent meta-analysis, Voyer et al. (2017) observed shrinkage in the reported magnitude of gender differences in the Corsi's Block test, presumably due to social changes in the last years.

Past findings, along with those from the current study, support the notion that spatial cognition is not a single, unitary structure but it consists of several interrelated abilities, which according to Iachini et al. (2008), may produce different outcomes for males and females, depending on the task.

5.7. Hypothesis 7

Hypothesis 7 stated that although hand-preference might influence accuracy while pointing to a target with vision available, pointing to different objects when blindfolded would not have any effect on pointing accuracy and latency. The current results only partially confirmed the hypothesis. Despite the fact that the analysis of variable error did not reveal any significant handedness-related differences, the analyses of the constant and pointing error and pointing latency revealed some differences between right- and left-handers.

More specifically, although participants -regardless of their hand preference- remained oriented while blindfolded, the analysis of the constant error revealed that right-handers were more oriented than left-handers in all the experimental phases. Right-handers were also more accurate in their pointing responses than left-handers, in the orientation and the updating phase of the experiment. These results are in line with the conclusions of a recent systematic review and meta-analyses of 16 studies examining the relationship of spatial ability and handedness (Somers, Shields, Boks, Kahn, & Sommer, 2015). Somers et al. found that right-handers had a small but significant advantage on overall spatial ability, although the reasons for this remain unclear. The authors proposed that this small advantage may have a neurobiological basis (e.g., smaller corpus callosum, decreased white matter integrity and increased bilateral lateralization of spatial functions in left-handers). In an even more recent meta-analysis of 36 studies that examined the relationship of IQ and handedness, Ntolka and Papadatou-Pastou (2018) also found a small but significant advantage of right-handers over left-handers, although according to the authors these differences were marginal in magnitude and practically negligible in the general population. The only difference favoring the left-handers in my study was found on pointing latency, where left-handers were able to update their representation and point to the different objects significantly faster -- but not more accurately -- than the right- and the mix-handers.

5.8. Conclusions

The current study examined, using a developmental approach, how well spatial locations are encoded and updated, as well as how resilient spatial representations are to disorientation. Having this information would help us understand better the mechanisms that support spatial memory in both the childhood and in the aging.

Several interesting findings were obtained: (a) Participants, regardless of age, remained oriented while blindfolded in all the experimental phases. (b) Participants were less oriented in the updating than in the orientation phase, and their orientation decreased further in the disorientation phase as a result of the 30-seconds rotation. (c) In the orientation phase, blindfolded participants were able to localize each object from memory with precision, and retained the spatial relations among the different objects. However, 6-year olds' performance was not as accurate as that of older children and adults, indicating that spatial representations continue to improve during the first school years. (d) In the updating phase, participants maintained a relatively accurate spatial representation of the object-array, although not as accurate as that of the orientation phase. (e) Idiothetic cues were sufficient, even for 6-year olds, to update their orientation relative to the stable environment, in the absence of any visual cues. Nevertheless, some participants were less accurate than others in updating their facing orientation. (f) Regardless of participants' age group, pointing latency was significantly higher in the updating phase than in the orientation or the disorientation phase. The latter two phases also differed between them, with pointing latency being lower in the orientation than the disorientation phase. (g) Spatial updating continues to develop until the age of 7. The updating process is not as accurate as previously suggested but instead seems to be subjected to memory decay and require cognitive resources. (h) Participants' performance was better in the orientation phase, intermediate in the updating and worse in the disorientation phase. (i) Participants seem to rely on an enduring egocentric representation to code the spatial relations among multiple objects, rather than switching to an allocentric representation. (j) Following the disorientation procedure, participants who adopted one of the previously experienced orientations (either the learning or the updating orientation), were more accurate in their pointing responses than those who adopted other random orientations. (k) Regardless of their age-group, participants performed equally worse in the disorientation phase. This equally worse performance for all age-groups suggests that participants made their pointing judgments based on an egocentric spatial representation, which was disturbed as a result of the disorientation procedure. (l) Participants with high spatial short-term memory capacity were more accurate in their pointing judgments in both the updating and the disorientation phase than those with low spatial short-term memory capacity. (m) Both males and females were equally able to localize an object relative to the other objects of the spatial array, as no gender differences were found on variable error. (n) No differences were found on variable error across the right-, left-, and mix handers.

A limitation of the study is related to the sample composition. The oldest age-group included in the study was that of the 60-year old adults. Previous studies with older participants (e.g., Harris et al., 2012; Iachini et al., 2009; Jansen et al., 2010; Ruggiero et al., 2016; Wiener et al., 2012, 2013) reported an age-related decline in selective spatial abilities in terms of both accuracy and latency, which starts between 60 and 70 years of age. Including older participants in the current study could lead to a more comprehensive understanding of how older people construct and update spatial representations for layouts containing multiple objects. However, the experimental procedures followed in the current experiment did not allow the inclusion of older participants in the study. Participants stood and were blindfolded through the experiment, and before the disorientation phase, they were spun for 30 seconds. This procedure could be proven problematic for older participants as it could lead to vestibular and somatosensory disturbance. A different experiment -possibly a stationary one- can include older participants and examine furthermore the possible effects of aging on spatial representations.

The assessment of different spatial abilities can become a useful diagnostic tool for both typical and atypical aging (Wiener et al., 2017), albeit this presupposes the existence of normative data across the lifespan. The current study provides some preliminary data and extends our understanding of the nature of spatial representations used when individuals are oriented and disoriented in space, and when they update their orientation in their environment. However, more research is needed to provide a detailed description of the developmental paths and psychological mechanisms adopted by children and adults.

REFERENCES

Acredolo, L. P. (1987). Early development of spatial orientation in humans. In P. Ellen & C. Thinus-Blanc (Eds.), *Cognitive Processes and Spatial Orientation in Animal and Man, NATO ASI Series* (Series D: Behavioural and Social Sciences), Vol 37. Dordrecht: Springer. doi:10.1007/978-94-009-3533-4_17

Annett, M. (1970). The growth of manual preference and speed. *British Journal of Psychology, 61*(4), 545-558. doi:10.1111/j.2044-8295.1970.tb01274.x

Annett, M. (2002). *Handedness and brain asymmetry: The right shift theory*. Hove, East Sussex: Psychology Press.

Avraamides, M. N. (2003). Spatial updating of environments described in texts. *Cognitive Psychology, 47*(4), 402-431. doi:10.1016/S0010-0285(03)00098-7

Avraamides, M. N., & Kelly, J. W. (2005). Imagined perspective-changing within and across novel environments. In C. Freksa, B. Nebel, M. Knauff, & B. Krieg-Bruckner (Eds.), *Lecture Notes in Artificial Intelligence: Spatial Cognition IV. Reasoning, action, interaction* (pp. 245–258). Berlin: Springer. doi:10.1007/978-3-540-32255-9_15

Avraamides, M. N., & Kelly, J. W. (2008). Multiple systems of spatial memory and action. *Cognitive Processing, 9*(2), 93-106. doi:10.1007/s10339-007-0188-5

Barca, L., Pezzulo, G., & Castelli, E. (2010). Egocentric and allocentric spatial references in children with cerebral palsy. In S. Ohlsson & R. Catrambone (Eds.), *Proceedings of the 32nd Annual Conference of the Cognitive Science Society* (pp. 831–835). Austin, TX. Retrieved from https://escholarship.org/ uc/item/2p10v5v0

Batschelet E (1981). *Circular Statistics in Biology*. London: Academic Press.

Belmonti, V., Cioni, G., & Berthoz, A. (2015). Switching from reaching to navigation: differential cognitive strategies for spatial memory in children and adults. *Developmental Science, 18*(4), 569-586. doi:10.1111/desc.12240

Bennett, C. R., Loomis, J. M., Klatzky, R. L., & Giudice, N. A. (2017). Spatial updating of multiple targets: Comparison of younger and older adults. *Memory & Cognition, 45*(7), 1240-1251. doi:10.3758/s13421-017-0725-0

Berch, D. B., Krikorian, R., & Huha, E. M. (1998). The Corsi block-tapping task: Methodological and theoretical considerations. *Brain and Cognition, 38*(3), 317-338. doi: 10.1006/brcg.1998.1039

Bullens, J. (2009). *How children learn to deal with space: Developmental studies on spatial memory* (Doctoral dissertation, Utrecht University). Retrieved from https://dspace.library.uu.nl/handle/1874/32080

Bullens, J., Iglói, K., Berthoz, A., Postma, A., & Rondi-Reig, L. (2010). Developmental time course of the acquisition of sequential egocentric and allocentric navigation strategies. *Journal of Experimental Child Psychology, 107*(3), 337-350. doi: 10.1016/j.jecp.2010.05.010

Burgess, N. (2006). Spatial memory, how egocentric and allocentric combine. *Trends in Cognitive Science*, *10*(12), 551-557. doi:10.1016/j.tics.2006.10.005

Burgess, N. (2008). Spatial cognition and the brain. Annals of the New York Academy of Sciences, 1124(1), 77-97. doi:10.1196/annals.1440.002

Burgess, N., Spiers, H. J., & Paleologou, E. (2004). Orientational manoeuvres in the dark: dissociating allocentric and egocentric influences on spatial memory. *Cognition, 94*(2), 149-166. doi:10.1016/j.cognition.2004.01.001

Byrne, P., Becker, S., & Burgess, N. (2007). Remembering the past and imagining the future: a neural model of spatial memory and imagery. *Psychological Review*, *114*(2), 340-375. doi:10.1037/0033-295X.114.2.340

Capitani, E., Laiacona, M., & Ciceri, E. (1991). Sex differences in spatial memory: a reanalysis of block tapping long-term memory according to the short-term memory level. *The Italian Journal of Neurological Sciences, 12*(4), 461-466. doi:10.1007/

BF02335507

Cestari, V., Lucidi, A., Pieroni, L., & Rossi-Arnaud, C. (2007). Memory for object location: A span study in children. *Canadian Journal of Experimental Psychology, 61*(1), 13-20. doi:10.1037/cjep2007002

Corsi, P. (1972). Human *memory and the medial temporal region of the brain* (Doctoral dissertation, McGill University). Retrieved from http://digitool.library.mcgill.ca/webclient/StreamGate?folder_id=0&dvs=1520083436910~911

Cowan, N., Naveh-Benjamin, M., Kilb, A., & Saults, J. S. (2006). Life-span development of visual working memory: When is feature binding difficult? *Developmental Psychology*, *42*(6), 1089-1102. doi:10.1037/0012-1649.42.6.1089

Dabbs, J. M., Chang, E. L., Strong, R. A., & Milun, R. (1998). Spatial ability, navigation strategy, and geographic knowledge among men and women. *Evolution and Human Behavior*, *19*(2), 89-98. doi:10.1016/S1090-5138(97)00107-4

Duff, S. J., & Hampson, E. (2001). A sex difference on a novel spatial working memory task in humans. *Brain and Cognition*, *47*(3), 470-493. doi:10.1006/brcg.2001.1326

Eals, M., & Silverman, I. (1994). The hunter-gatherer theory of spatial sex differences: Proximate factors mediating the female advantage in recall of object arrays. *Ethology and Sociobiology, 15*(2), 95-105. doi:10.1016/0162-3095(94)90020-5

Farrell, M. J., & Robertson, I. H. (1998). Mental rotation and automatic updating of body-centered spatial relationships. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*(1), 227-233. doi:10.1037/0278-7393.24.1.227

Farrell, M. J., & Thomson, A. (1998). Automatic spatial updating during locomotion without vision. *The Quarterly Journal of Experimental Psychology: Section A, 51*(3), 637-654. doi:10.1080/713755776

Farrell, M. J., & Thomson, A. (1999). On-line updating of spatial information during locomotion without vision. *Journal of Motor Behavior, 31*(1), 39–53. doi:10.1080/00222899909601890

Farrell Pagulayan, K., Busch, R. M., Medina, K. L., Bartok, J. A., & Krikorian, R. (2006). Developmental normative data for the Corsi block-tapping task. *Journal of Clinical and Experimental Neuropsychology, 28*(6), 1043-1052. doi:10.1080/ 13803390500350977

Filimon, F. (2015). Are all spatial reference frames egocentric? Reinterpreting evidence for allocentric, object-centered, or world-centered reference frames. *Frontiers in Human Neuroscience, 9*. doi:10.3389/fnhum.2015.00648

Finlay, C. A., Motes, M. A., & Kozhevnikov, M. (2007). Updating representations of learned scenes. *Psychological Research, 71*(3), 265-276. doi:10.1007/s00426-006-0082-2

Friedman, A. (2005). Examining egocentric and allocentric frames of reference in virtual space systems. *Sprouts Working Papers on Information Systems, 5*(16), 50-63. Retrieved from http://sprouts.aisnet.org/5-16

Galati, G., Pelle, G., Berthoz, A., & Committeri, G. (2010). Multiple reference frames used by the human brain for spatial perception and memory. *Experimental Brain Research, 206*(2), 109-120. doi:10.1007/s00221-010-2168-8

Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology, 40*(2), 177-190. doi:10.1037/0012-1649.40.2.177

Giudice, N. A., Bennett, C. R., Klatzky, R. L., & Loomis, J. M. (2017). Spatial updating of haptic arrays across the life span. *Experimental Aging Research, 43*(3), 274-290. doi:10.1080/0361073X.2017.1298958

Halpern, D. F., & LaMay, M. L. (2000). The smarter sex: A critical review of sex differences in intelligence. *Educational Psychology Review, 12*(2), 229-246. doi:10.1023/A:1009027516424

Harris, M. A., Wiener, J. M., & Wolbers, T. (2012). Aging specifically impairs switching to an allocentric navigational strategy. *Frontiers in Aging Neuroscience, 4*,29. doi:10.3389/fnagi.2012.00029

Haubenstricker, J., & Seefeldt, V. (1986). Acquisition of motor skills during childhood. In: V. Reston (Ed), *Physical Activity and Well-Being* (pp. 41-92). Reston, VA.

He, Q., & McNamara, T. P. (2017). Spatial updating strategy affects the reference frame in path integration. Psychonomic Bulletin & Review. doi:10.3758/s13423-017-1307-7

He, Q., McNamara, T. P., & Kelly, J. W. (2018). Reference frames in spatial updating when body-based cues are absent. *Memory & Cognition*, *46*(1), 32-42. doi:10.3758/s13421-017-0743-y

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence, 32*(2), 175-191. doi:10.1016/j.intell.2003.12. 001

Holmes, M. C., & Sholl, M. J. (2005). Allocentric coding of object-to-object relations in overlearned and novel environments. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*(5), 1069-1087. doi:10.1037/0278-7393.31.5.1069

Hund, A. M., & Foster, E. K. (2008). Understanding developmental changes in the stability and flexibility of spatial categories based on object relatedness. *Developmental Psychology, 44*(1), 218-232. doi:10.1037/0012-1649.44.1.218

Hund, A. M., & Plumert, J. M. (2003). Does information about what things are influence children's memory for where things are? *Developmental Psychology, 39*(6), 939-948. doi:10.1037/0012-1649.39.6.939

Huttenlocher, J., & Presson, C. C. (1973). Mental rotation and the perspective problem.

Cognitive Psychology, *4*(2), 277-299. doi:10.1016/0010-0285(73)90015-7

Iachini, T., Poderico, C., Ruggiero, G., & Iavarone, A. (2005). Age differences in mental scanning of locomotor maps. *Disability & Rehabilitation*, *27*(13), 741-752. doi:10.1080/09638280400014782

Iachini, T., & Ruggiero, G. (2006). Egocentric and allocentric spatial frames of reference: A direct measure. *Cognitive Processing*, *7*, 126-127. doi:10.1007/s10339-006-0100-8

Iachini T., Ruggiero G., Ruotolo F. (2009). The effect of age on egocentric and allocentric spatial frames of reference. *Cognitive Processing*, *10*(2), 222-224. doi:10.1007/s10339-009-0276-9.

Iachini, T., Ruggiero, G., Ruotolo, F., and Pizza, R. (2008). Age and gender differences in some components of spatial cognition. In H. T. Benninghouse & A. G. Rosset (Eds.), *Women and Aging: New Research* (pp. 365-388). New York: Nova Science Publishers Inc. Retrieved from https://www.researchgate.net/publication/229598227

Iachini, T., Ruotolo, F., & Ruggiero, G. (2009). The effects of familiarity and gender on spatial representation. *Journal of Environmental Psychology*, *29*(2), 227-234. doi:10.1016/j.jenvp.2008.07.001

Iglói, K., Zaoui, M., Berthoz, A., & Rondi-Reig, L. (2009). Sequential egocentric strategy is acquired as early as allocentric strategy: Parallel acquisition of these two navigation strategies. *Hippocampus*, *19*(12), 1199-1211. doi:10.1002/hipo.20595

Ittyerah, M., Gaunet, F., & Rossetti, Y. (2007). Pointing with the left and right hands in congenitally blind children. *Brain and Cognition*, *64*(2), 170-183. doi:10.1016/j.bandc.2007.02.002

Jansen, P., Schmelter, A., & Heil, M. (2010). Spatial knowledge acquisition in younger and elderly adults. *Experimental Psychology, 57*(1), 54–60. doi:10.1027/1618-3169/a000007

Janzen, G., & Van Turennout, M. (2004). Selective neural representation of objects relevant for navigation. *Nature Neuroscience, 7*(6), 673-677. doi:10.1038/nn1257

Johnston, D. W., Nicholls, M. E., Shah, M., & Shields, M. A. (2009). Nature's experiment? Handedness and early childhood development. *Demography, 46*(2), 281-301. doi:10.1353/dem.0.0053

Kaufman, S. B. (2007). Sex differences in mental rotation and spatial visualization ability: Can they be accounted for by differences in working memory capacity? *Intelligence, 35*(3), 211-223. doi:10.1016/j.intell.2006.07.009

Kelly, J. W., Avraamides, M. N., & McNamara, T. P. (2010). Reference frames influence spatial memory development within and across sensory modalities. In *Spatial Cognition VII* (pp. 222-233). Springer Berlin Heidelberg. doi:10.1007/978-3-642-14749-4_20

Kirasic, K. C. (1991). Spatial cognition and behaviour in young and elderly adults: Implications for learning environments. *Psychology and Aging, 6*(1), 10–18. doi:10.1037/0882-7974.6.1.10

Klatzky, R. L. (1998). Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections. In C. Freksa, C. Habel, & K. F. Wender (Eds.), *Spatial Cognition: An interdisciplinary approach to representation and processing of spatial knowledge* (pp. 1-17). Berlin: Springer. doi:10.1007/3-540-69342-4_1

Klatzky, R. L., Loomis, J. M., Beall, A. C., Chance, S. S., & Golledge, R. G. (1998). Spatial updating of self-position and orientation during real, imagined, and virtual locomotion. *Psychological Science, 9*(4), 293-298. doi:10.1111/1467-9280.00058

Kovach Computing Services. (2011). *Oriana, Version 4. Users' Manual*. Retrieved from http://www.kovcomp.co.uk/oriana/

Krüger, M., & Jahn, G. (2015). Children’s spatial representations: 3-and 4-year-olds are affected by irrelevant peripheral references. *Frontiers in Psychology, 6*, 1677. doi:10.3389/fpsyg.2015.01677

Lehnung, M., Leplow, B., Ekroll, V.R., Benz, B., Ritz, A., Mehdorn, M., & Ferstl, R. (2003). Recovery of spatial memory and persistence of spatial orientation deficits after traumatic brain injury during childhood. *Brain Injury, 17*(10), 855-869. doi:10.1080/0269905031000089369

Leplow, B., Lehnung, M., Pohl, J., Herzog, A., Ferstl, R., & Mehdorn, M. (2003). Navigational place learning in children and young adults as assessed with a standardized locomotor search task. *British Journal of Psychology, 94*(3), 299-317. doi:10.1348/000712603767876244

Lester, A. W., Moffat, S. D., Wiener, J. M., Barnes, C. A., & Wolbers, T. (2017). The aging navigational system. *Neuron, 95*(5), 1019-1035. doi:10.1016/j.neuron. 2017.06.037

Lew, A. R., Bremner, J. G., & Lefkovitch, L. P. (2000). The development of relational landmark use in six-to twelve-month-old infants in a spatial orientation task. *Child Development, 71*(5), 1179-1190. doi:10.1111/1467-8624.00222

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development, 56*(6), 1479-1498. doi:10.2307/1130467

May, M., & Klatzky, R. L. (2000). Path integration while ignoring irrelevant movement. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*(1), 169-186. doi:10.1037/0278-7393.26.1.169

McCullough, M., Xu, H., Michelson, J., Jackoski, M., Pease, W., Cobb, W., ... & Williams,

B. (2015). Myo arm: Swinging to explore a VE. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception* (pp. 107-113). doi:10.1145/ 2804408.2804416

McKeever, W. F., Rich, D. A., Deyo, R. A., & Conner, R. L. (1987). Androgens and spatial ability: Failure to find a relationship between testosterone and ability measures. *Bulletin of the Psychonomic Society*, *25*(6), 438-440. doi:10.3758/BF03334734

McNamara, T. P., Rump, B., & Werner, S. (2003). Egocentric and geocentric frames of reference in memory of large-scale space. *Psychonomic Bulletin & Review*, *10*(3), 589-595. doi:10.3758/BF03196519

McNamara, T. P., & Valiquette, C. M. (2004). Remembering where things are. In G. L. Allen (Ed.), *Human Spatial Memory: Remembering where* (pp. 251–285). Mahwah, NJ: Lawrence Erlbaum Associates.

Meilinger, T., & Vosgerau, G. (2010). Putting egocentric and allocentric into perspective. In C. Hölscher, T. F. Shipley, M. O. Belardinelli, J. A.Bateman, & N. S. Newcombe (Eds.), *Lecture Notes in Computer Science: Vol. 6222. Spatial Cognition VII* (pp. 207–221). Berlin: Springer. doi:10.1007/978-3-642-14749-4_19

Michaelides, C. S., & Avraamides, M. N. (2017). Developmental changes in the mental transformation of spatial arrays. *Journal of Experimental Child Psychology*, *164*, 152-162. doi:10.1016/j.jecp.2017.07.013

Millar, S. (1994). *Understanding and representing space: Theory and evidence from studies with blind and sighted children*. Oxford: Oxford University Press, Clarendon Press.

Milner, A. D. & Goodale, M. A. (2008). Two visual systems re-viewed. *Neuropsychologia*, *46*(3), 774-785. doi:10.1016/j.neuropsychologia.2007.10.005

Moffat, S. D. (2009). Aging and spatial navigation: what do we know and where do we go?

Neuropsychology Review, 19(4), 478-489. doi:10.1007/s11065-009-9120-3

Montefinese, M., Sulpizio, V., Galati, G., & Committeri, G. (2015). Age-related effects on spatial memory across viewpoint changes relative to different reference frames. *Psychological Research, 79*(4), 687-697. doi:10.1007/s00426-014-0598-9.

Moraleda, E., Broglio, C., Rodríguez, F., & Gómez, A. (2013). Development of different spatial frames of reference for orientation in small-scale environments. *Psicothema, 25*(4), 468-475. doi:10.7334/psicothema2013.29

Motes, M. A., Finlay, C. A., & Kozhevnikov, M. (2006). Scene recognition following locomotion around a scene. *Perception, 35*(11), 1507-1520. doi:10.1068/p5459

Mou, W., & McNamara, T. P. (2002). Intrinsic frames of reference in spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*(1), 162-170. doi:10.1037//0278-7393.28.1.162

Mou, W., McNamara, T. P., Rump, B., & Xiao, C. (2006). Roles of egocentric and allocentric spatial representations in locomotion and reorientation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*(6), 1274. doi:10.1037/0278-7393.32.6.1274

Mou, W., McNamara, T. P., Valiquette, C. M., & Rump, B. (2004). Allocentric and egocentric updating of spatial memories. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*(1), 142-157. doi:10.1037/0278-7393.30.1.142142

Nadel, L., & Hardt, O. (2004). The spatial brain. *Neuropsychology, 18*(3), 473-476. doi:10.1037/0894-4105.18.3.473473

Nardini, M., Burgess, N., Breckenridge, K., Atkinson, J. (2006). Differential developmental trajectories for egocentric, environmental and intrinsic frames of reference in spatial memory. *Cognition, 101*(1), 153-172. doi:10.1016/j.cognition. 2005.09.005

Nardini, M., Jones, P., Bedford, R., & Braddick, O. (2008). Development of cue integration in human navigation. *Current Biology, 18*(9), 689-693. doi:10.1016/ j.cub.2008.04.021

Nardini, M., Thomas, R. L., Knowland, V. C., Braddick, O. J., & Atkinson, J. (2009). A viewpoint-independent process for spatial reorientation. *Cognition,112*(2), 241-248. doi:10.1016/j.cognition.2009.05.003

Negen, J., & Nardini, M. (2015). Four-year-olds use a mixture of spatial reference frames. *PloS One, 10*(7), e0131984. doi:10.1371/journal.pone.0134973

Negen, J., Heywood-Everett, E., Roome, H. E., & Nardini, M. (2017). Development of allocentric spatial recall from new viewpoints in virtual reality. *Developmental Science, 21*(1). doi:10.1111/desc.12496

Newcombe, N. S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education, 4*(3), 102-111. doi:10.1111/j.1751-228X.2010.01089.x

Newcombe, N. S. & Huttenlocher, J. (2000). *Making space: The development of spatial representation and reasoning.* Cambridge, MA: MIT Press.

Newcombe, N. S., & Huttenlocher, J. (2006). Development of spatial cognition. In D. Kuhn & R. S. Siegler (Eds.), *Handbook of child psychology: Cognition, perception, and language,* Vol. 2 (6th ed., pp. 734–776). New York: Wiley. doi: 10.1002/ 9780470147658.chpsy0217

Newcombe, N., Huttenlocher, J., Drummey, A. B., & Wiley, J. G. (1998). The development of spatial location coding: Place learning and dead reckoning in the second and third years. *Cognitive Development, 13*(2), 185-200. doi:10.1016/S0885-2014(98)90038-7

Newcombe, N.S., Uttal, D.H. & Sauter, M. (2013). Spatial development. In P. D. Zelazo

(Ed.), *Oxford Handbook of Developmental Psychology, Vol. 1: Body and Mind* (pp. 564-590). New York: Oxford University Press.

Nichelli, F., Bulgheroni, S., & Riva, D. (2001). Developmental patterns of verbal and visuospatial spans. *Neurological Sciences, 22*(5), 377-384. doi:10.1007/s100720100068

Ntolka, E., & Papadatou-Pastou, M. (2018). Right-handers have negligibly higher IQ scores than left-handers: Systematic review and meta-analyses. *Neuroscience & Biobehavioral Reviews, 84*, 376-393. doi:10.1016/j.neubiorev.2017.08.007

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia, 9*(1), 97-113. doi:10.1016/0028-3932(71)90067-4

Orsini, A., Grossi, D., Capitani, E., Laiacona, M., Papagno, C., & Vallar, G. (1987). Verbal and spatial immediate memory span: normative data from 1355 adults and 1112 children. *The Italian Journal of Neurological Sciences, 8*(6), 537-548. doi:10.1007/BF02333660

Paillard, J. (1991). Motor and representational framing of space. In J. Paillard (Ed.), *Brain and Space* (pp. 163-182). New York: Oxford University Press. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.199.2257&rep=rep1&type=pdf

Peebles, D., & Jones, C. (2014). A model of object location memory. In *Proceedings of the Annual Meeting of the Cognitive Science Society*. Austin, TX: Cognitive Science Society. Retrieved from https://cloudfront.escholarship.org/dist/prd/content/qt34f5d9d1/qt34f5d9d1.pdf

Perelle, I. B., & Ehrman, L. (1994). An international study of human handedness: the data. *Behavior Genetics, 24*(3), 217-227. doi:10.1007/BF01067189

Piaget, J., & Inhelder, B. (1967). *The Child's Conception of Space.* New York: W.W. Norton.

Piccardi, L., Iaria, G., Ricci, M., Bianchini, F., Zompanti, L., & Guariglia, C. (2008). Walking in the Corsi test: which type of memory do you need? *Neuroscience Letters, 432*(2), 127-131. doi:10.1016/j.neulet.2007.12.044

Pine, D. S., Grun, J., Maguire, E. A., Burgess, N., Zarahn, E., Koda, V., Fyer, A., Szeszko, P. R., & Bilder, R. M. (2002). Neurodevelopmental aspects of spatial navigation: a virtual reality fMRI study. *Neuroimage, 15*(2), 396-406. doi:10.1006/nimg.2001.0988

Plumert, J. M., Franzen, L. J., Mathews, M. M., & Violante, C. (2017). Linking "what" and "where" information: How the strength of object categories influences children's memory for object locations. *Journal of Experimental Child Psychology, 157,* 95-110. doi:10.1016/j.jecp.2016.12.012

Pontillo, T. M. (2010). *Spatial ability and handedness as potential predictors of space teleoperation performance* (MS Thesis, Massachusetts Institute of Technology). Retrieved from https://dspace.mit.edu/handle/1721.1/59564

Postma, A., Wijnalda, E. M., & Kessel, R. P. C. (2001). Object-location memory in primary school children: A preliminary study. *Cognitive Processing*, 2, 221-233.

Presson, C. C., & Montello, D. R. (1994). Updating after rotational and translational body movements: Coordinate structure of perspective space. *Perception, 23*(12), 1447-1455. doi:10.1068/p231447

Rahman, Q., Bakare, M., & Serinsu, C. (2011). No sex differences in spatial location memory for abstract designs. *Brain and Cognition, 76*(1), 15-19. doi:10.1016/j.bandc.2011.03.012

Recker, K. M., & Plumert, J. M. (2009). How do opportunities to view objects together in time influence children's memory for location? *Journal of Cognition and Development, 9*(4), 434-460. doi:10.1080/15248370802678331

Reilly, D., Neumann, D. L., & Andrews, G. (2017). Gender differences in spatial ability:

Implications for STEM education and approaches to reducing the gender gap for parents and educators. In M. S. Khine (Ed.), *Visual-Spatial Ability: Transforming Research into Practice* (pp. 195-224). Switzerland: Springer International. doi:10.1007/ 978-3-319-44385-0_10

Reio, T., Czarnolewski, M., & Eliot, J. (2004). Handedness and spatial ability: Differential patterns of relationships. *Laterality: Asymmetries of Body, Brain and Cognition, 9*(3), 339-358. doi:10.1080/13576500342000220

Reisberg, B., Kenowsky, S., Franssen, E. H., Auer, S. R., & Souren, L. E. (1999). Towards a science of Alzheimer's disease management: a model based upon current knowledge of retrogenesis. *International Psychogeriatrics, 11*(1), 7-23. doi:10.1017/S1041610299005554

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*(6), 1157-1165. doi:10.1037/0278-7393.15.6.1157

Rieser, J. J., Ashmead, D. H., Talor, C. R., & Youngquist, G. A. (1990). Visual perception and the guidance of locomotion without vision to previously seen targets. *Perception, 19*(5), 675-689. doi:10.1068/p190675

Ruggiero, G., D'Errico, O., & Iachini, T. (2016). Development of egocentric and allocentric spatial representations from childhood to elderly age. *Psychological Research, 80*(2), 259-272. doi:10.1007/s00426-015-0658-9

Ruggiero, G., Iachini, T., Ruotolo, F. & Senese, V. P. (2009). Spatial memory: The role of egocentric and allocentric frames of reference. In J. B. Thomas (Ed.), *Spatial Memory: Visuospatial processes, cognitive performance and developmental effective* (pp. 51–75). United States: Nova Science Publishers.

Sholl, M. J., & Nolin, T. L. (1997). Orientation specificity in representations of place.

Journal of Experimental Psychology: Learning, Memory, and Cognition, 23(6), 1494-1507.

Shusterman, A. & Li, P. (2016). A framework for work on frames of reference. In D. Barner, & A. Baron (Eds.), *Core knowledge & conceptual change* (pp. 188–202). Oxford, UK: Oxford University Press.

Silverman, I., Choi, J., & Peters, M. (2007). The hunter-gatherer theory of sex differences in spatial abilities: Data from 40 countries. *Archives of Sexual Behavior, 36*(2), 261-268. doi:10.1007/s10508-006-9168-6

Simons, D. J., & Wang, R. F. (1998). Perceiving real-world viewpoint changes. *Psychological Science, 9*(4), 315-320. doi:10.1111/1467-9280.00062

Snyder, P. J., & Harris, L. J. (1993). Handedness, sex, familial sinistrality effects on spatial tasks. *Cortex, 29*(1), 115-134. doi:10.1016/S0010-9452(13)80216-X

Somers, M., Shields, L. S., Boks, M. P., Kahn, R. S., & Sommer, I. E. (2015). Cognitive benefits of right-handedness: a meta-analysis. *Neuroscience & Biobehavioral Reviews, 51*, 48-63. doi:10.1016/j.neubiorev.2015.01.003

Tau, G. Z., & Peterson, B. S. (2010). Normal development of brain circuits. *Neuropsychopharmacology, 35*(1), 147-168. doi:10.1038/npp.2009.115

Uttal, D. H., Miller, D. I., & Newcombe, N. S. (2013). Exploring and enhancing spatial thinking: Links to achievement in science, technology, engineering, and mathematics? *Current Directions in Psychological Science, 22*(5), 367-373. doi:10.1177/0963721413484756

Vasilyeva, M., & Lourenco, S. F. (2012). Development of spatial cognition. *Wiley Interdisciplinary Reviews: Cognitive Science, 3*(3), 349–362. doi:10.1002/wcs.1171

Veale, J. F. (2014). Edinburgh handedness inventory–short form: A revised version based on confirmatory factor analysis. *Laterality: Asymmetries of Body, Brain and Cognition, 19*(2), 164-177. doi:10.1080/1357650X.2013.783045

Vlachos, F., Avramidis, E., Dedousis, G., Katsigianni, E., Ntalla, I., Giannakopoulou, M. & Chalmpe, M. (2013). Incidence and gender differences for handedness among Greek adolescents and its association with familial history and brain injury. *Research in Psychology and Behavioral Sciences,1*(1), 6-10. doi:10.12691/rpbs-1-1-2

Vogel, J. J., Bowers, C. A., & Vogel, D. S. (2003). Cerebral lateralization of spatial abilities: a meta-analysis. *Brain and Cognition, 52*(2), 197-204. doi:10.1016/S0278-2626(03)00056-3

Voyer, D. (1996). On the magnitude of laterality effects and sex differences in functional lateralities. *Laterality: Asymmetries of Body, Brain and Cognition, 1*(1), 51-84. doi:10.1080/713754209

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: a meta-analysis and consideration of critical variables. *Psychological Bulletin, 117*(2), 250-270. doi:10.1037/0033-2909.117.2.250

Voyer, D., Voyer, S. D., & Saint-Aubin, J. (2017). Sex differences in visual-spatial working memory: a meta-analysis. *Psychonomic Bulletin & Review, 24*(2), 307-334. doi:10.3758/s13423-016-1085-7

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101*(4), 817-835. doi:10.1037/a0016127

Waller, D. (2006). Egocentric and nonegocentric coding in memory for spatial layout: Evidence from scene recognition. *Memory & Cognition, 34*(3), 491-504. doi:10.3758/BF03193573

Waller, D., & Hodgson, E. (2006). Transient and enduring spatial representations under disorientation and self-rotation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*(4), 867-882. doi:10.1037/0278-7393.32.4.867

Waller, D., Montello, D. R., Richardson, A. E., & Hegarty, M. (2002). Orientation specificity and spatial updating of memories for layouts. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*(6), 1051-1063. doi:10.1037//0278-7393.28.6.1051

Wang, R. F. (1999). Representing a stable environment by egocentric updating and invariant representations. *Spatial Cognition and Computation, 1*(4), 431-445. doi:10.1023/A:1010043814328

Wang, R. F. (2004). Between reality and imagination: When is spatial updating automatic? *Perception & Psychophysics, 66*(1), 68-76. doi:10.3758/BF03194862

Wang, R. F. (2007). Spatial processing and view-dependent representations. In F. Mast & L. Jancke (Eds.), *Spatial Processing in Navigation, Imagery, and Perception* (pp. 49-65). Springer Science + Business Media, Inc. doi:10.1007/978-0-387-71978-8_4

Wang, R. F. (2012). Theories of spatial representations and reference frames: What can configuration errors tell us? *Psychonomic Bulletin & Review, 19*(4), 575-587. doi:10.3758/s13423-012-0258-2

Wang, R. F. (2016). Building a cognitive map by assembling multiple path integration systems. *Psychonomic Bulletin & Review, 23*(3), 692-702. doi:10.3758/s13423-015-0952-y

Wang, R. F. (2017). Spatial updating and common misinterpretations of spatial reference frames. *Spatial Cognition & Computation, 17*(3), 222-249. doi:10.1080/13875868.2017.1304394

Wang, R. F., & Brockmole, J. R. (2003). Simultaneous spatial updating in nested environments. *Psychonomic Bulletin & Review, 10*(4), 981-986. doi:10.3758/BF03196562

Wang, L., & Carr, M. (2014). Working memory and strategy use contribute to gender differences in spatial ability. *Educational Psychologist, 49*(4), 261-282. doi: 10.1080/00461520.2014.960568

Wang, R. F., Crowell, J. A., Simons, D. J., Irwin, D. E., Kramer, A. F., Ambinder, M. S., ... & Hsieh, B. B. (2006). Spatial updating relies on an egocentric representation of space: Effects of the number of objects. *Psychonomic Bulletin & Review, 13*(2), 281-286. doi:10.3758/BF03193844

Wang, R. F., & Simons, D. J. (1999). Active and passive scene recognition across views. *Cognition, 70*(2), 191-210. doi:10.1016/S0010-0277(99)00012-8

Wang, R. F., & Spelke, E. S. (2000). Updating egocentric representations in human navigation. *Cognition, 77*(3), 215-250. doi:10.1016/S0010-0277(00)00105-0

Wang, R. F., & Spelke, E. S. (2002). Human spatial representation: insights from animals. *Trends in Cognitive Sciences, 6*(9), 376-382. doi:10.1016/S1364-6613(02)01961-7

Weiskrantz, L. (1990). Problems of learning and memory: one or multiple memory systems? *Philosophical Transactions of the Royal Society of London B, 329*, 99–108. doi:10.1098/rstb.1990.0154

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General, 131*(1), 48-64. doi:10.1037//0096-3445.131.1.48

Whitehouse, A. J., & Bishop, D. V. (2009). Hemispheric division of function is the result of independent probabilistic biases. *Neuropsychologia, 47*(8-9), 1938-1943. doi: 10.1016/j.neuropsychologia.2009.03.005

Wiener, J., Carroll, D., Juthapan, S., Bibi, I., Ivanova, D., & Wolbers, T. (2017). Assessing the effects of cognitive ageing on navigation: a novel navigation test battery.

Retrieved from https://psyarxiv.com/z96v7/

Wiener, J. M., de Condappa, O., Harris, M. A., & Wolbers, T. (2013). Maladaptive bias for extrahippocampal navigation strategies in aging humans. *Journal of Neuroscience, 33*(14), 6012-6017. doi:10.1523/JNEUROSCI.0717-12.2013

Wiener, J. M., Kmecova, H., & de Condappa, O. (2012). Route repetition and route retracing: Effects of cognitive aging. *Frontiers in Aging Neuroscience, 4*(7). doi: 10.3389/fnagi.2012.00007

Willems, R. M., Van der Haegen, L., Fisher, S. E., & Francks, C. (2014). On the other hand: Including left-handers in cognitive neuroscience and neurogenetics. *Nature Reviews Neuroscience*, *15*(3), 193-201. doi:10.1038/nrn3679

Wolbers, T., Hegarty, M., Büchel, C., & Loomis, J. M. (2008). Spatial updating: How the brain keeps track of changing object locations during observer motion. *Nature Neuroscience*, *11*(10), 1223-1230. doi:10.1038/nn.2189

Wolbers, T., & Wiener, J. M. (2014). Challenges for identifying the neural mechanisms that support spatial navigation: the impact of spatial scale. *Frontiers in Human Neuroscience, 8*, 571. doi:10.3389/fnhum.2014.00571

Xiao, C., Lian, Y., & Hegarty, M. (2015). Spatial updating of map-acquired representation. *Memory & cognition*, *43*(7), 1032-1042. doi:10.3758/s13421-015-0520-8

Xiao, C., Mou, W., & McNamara, T. P. (2009). Use of self-to-object and object-to-object spatial relations in locomotion. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(5), 1137-1147. doi:10.1037/a0016273

Zaehle, T., Jordan, K., Wüstenberg, T., Baudewig, J., Dechent, P., & Mast, F. W. (2007). The neural basis of the egocentric and allocentric spatial frame of reference. *Brain Research, 1137*, 92-103. doi:10.1016/j.brainres.2006.12.044

Zhong, J. Y., & Kozhevnikov, M. (2016). Relating allocentric and egocentric survey-based representations to the self-reported use of a navigation strategy of egocentric spatial updating. *Journal of Environmental Psychology*, *46*, 154-175. doi:10.1016/j.jenvp.2016.04.007

APPENDIX A

Edinburgh Handedness Inventory - Short Form

Please indicate your preferences in the use of hands in the following activities or objects:

	Always right	Usually right	Both equally	Usually left	Always left
Writing					
Throwing					
Toothbrush					
Spoon					

Scoring:

For each item: Always right = 100; Usually right = 50; Both equally = 0; Usually left = -50; Always
left = -100

To calculate the Laterality Quotient add the scores for the four items in the scale and divide this by four:

Writing score	
Throwing score	
Toothbrush score	
Spoon score	
Total	
Total ÷ 4 (Laterality Quotient)	

Classification:	Laterality Quotient score:
Left handers	-100 to -61
Mixed handers	-60 to 60
Right handers	61 to 100

Reprinted from " Edinburgh Handedness Inventory–Short Form: a revised version based on confirmatory factor analysis." by J. F. Veale, 2014, *Laterality: Asymmetries of Body, Brain and Cognition*, *19*(2), p.177.

APPENDIX B

The tapping sequences used in the Corsi's Block Test (string length in brackets)

5-6	**4-7-2**
4-7	**8-1-5**
9-5 (2)	**3-6-1 (3)**
5-7	**4-1-5**
4-6	**9-5-8**
9-3-1-5	**8-5-4-1-9**
6-5-4-8	**2-3-5-4-1**
4-9-8-7 (4)	**3-4-1-7-2 (5)**
1-6-5-3	**7-9-3-4-1**
6-2-3-7	**8-1-9-2-6**
5-3-2-4-6-7	**5-9-1-7-4-2-8**
9-8-1-4-6-5	**4-1-7-9-3-8-6**
2-3-1-5-9-4 (6)	**5-8-1-9-2-6-4 (7)**
2-4-6-3-5-1	**3-8-2-9-5-1-7**
2-3-6-4-9-5	**6-1-9-4-7-3-8**
1-7-6-4-8-3-2-5	**2-6-5-7-9-3-4-8-1**
5-8-3-2-6-7-1-9	**8-2-3-4-1-7-9-6-5**
7-1-2-3-4-6-8-5 (8)	**3-4-6-7-5-8-9-2-1 (9)**
9-4-7-3-1-8-2-5	**8-6-7-3-4-9-5-2-1**
7-6-9-1-2-3-8-4	**4-3-1-8-7-5-6-2-9**

Adapted from "Verbal and spatial immediate memory span: normative data from 1355 adults and 1112 children" by A. Orsini, D. Grossi, E. Capitani, M. Laiacona, C. Papagno, and G. Vallar, 1987, *The Italian Journal of Neurological Sciences, 8*(6), p.547.

APPENDIX C

Table 1. The reported subjective orientation in each age-group (N=24) following the disorientation phase

Subjective orientation (degrees)	Age groups 6-year olds	7-year olds	8-year olds	9-year olds	10-year olds	11-year olds	19-year olds	35-year olds	60-year olds	Total
Orientation position (0^o)	3	2	3	4	4	5	12	5	6	44
Updating position (45^o)	2	3	2	1	4	3	4	6	2	27
Towards “duck” (30^o)	3	4	2	3	2	0	0	1	1	16
Towards “dog” (80^o)	3	5	4	4	5	5	2	4	1	33
Towards “cat” (290^o)	3	2	6	5	4	3	2	1	4	30
Towards “rabbit” (340^o)	5	4	1	2	1	4	1	1	5	24
Behind them (180^o)	4	3	5	5	4	2	2	5	4	34
Disorientation position (315^o)	1	1	1	0	0	2	1	1	1	8

Table 2. Hotelling's paired test statistics for constant error among response phases for the different age-groups, Corsi's block scores, gender, and handedness

	Pairwise comparisons between different response phases					
	Orientation & Updating		Orientation & Disorientation		Updating & Disorientation	
	F	*p*	*F*	*p*	*F*	*p*
Age-group						
6-year olds (N=24)	4.45	.024	10.55	<.001	5.76	.01
7-year olds (N=24)	4.59	.022	7.55	.003	2.55	.1
8-year olds (N=24)	3.45	.05	14.85	<.001	14.7	<.001
9-year olds (N=24)	5.28	.013	12.69	<.001	6.75	.005
10-year olds (N=24)	6.92	.005	6.08	.008	2.03	.16
11-year olds (N=24)	4.05	.032	11.44	<.001	5.3	.01
19-year olds (N=24)	12.67	<.001	17.44	<.001	7.98	.002
35-year olds (N=24)	0.82	.45	7.48	.003	6.83	.005
60-year olds (N=24)	2.31	.123	21.44	<.001	12.81	<.001
Spatial memory group						
Low (N=82)	9.76	<.001	35.34	<.001	20.34	<.001
Medium (N=64)	5.98	.004	27.04	<.001	19.36	<.001
High (N=70)	12.41	<.001	37.31	<.001	17.24	<.001
Gender						
Males (N=100)	10.21	<.001	49.17	<.001	33.97	<.001
Females (N=116)	17.05	<.001	48.83	<.001	23.69	<.001
Handedness						
Right-handers (N=195)	24.13	<.001	89.38	<.001	49.23	<.001
Left-handers (N=14)	2.29	.143	5.4	.021	3.74	.05
Mix-handers (N=7)	2.31	.123	21.44	<.001	12.81	<.001

Table 3. Paired samples t-test statistics for variable error among the different response phases in each age-group

Age-group (N=24)	Pairwise comparisons between different response phases					
	Orientation & Updating		Updating & Disorientation		Orientation & Disorientation	
	t	*p*	*t*	*p*	*t*	*p*
6-year olds	-3.35	.003	-2.97	.007	-4.48	<.001
7-year olds	-2.66	.014	-2.63	.015	-3.41	.002
8-year olds	-4.38	<.001	-1.99	.059	-3.14	.005
9-year olds	-3.07	.005	-2.72	.012	-3.07	.005
10-year olds	-4.17	<.001	-3.16	.004	-5.21	<.001
11-year olds	-4.77	<.001	-2.45	.022	-3.46	.002
19-year olds	-3.83	.001	-0.58	.57	-1.73	.098
35-year olds	-1.95	.063	-2.53	.019	-3.02	.006
60-year olds	-2.48	.021	-1.97	.06	-2.49	.021

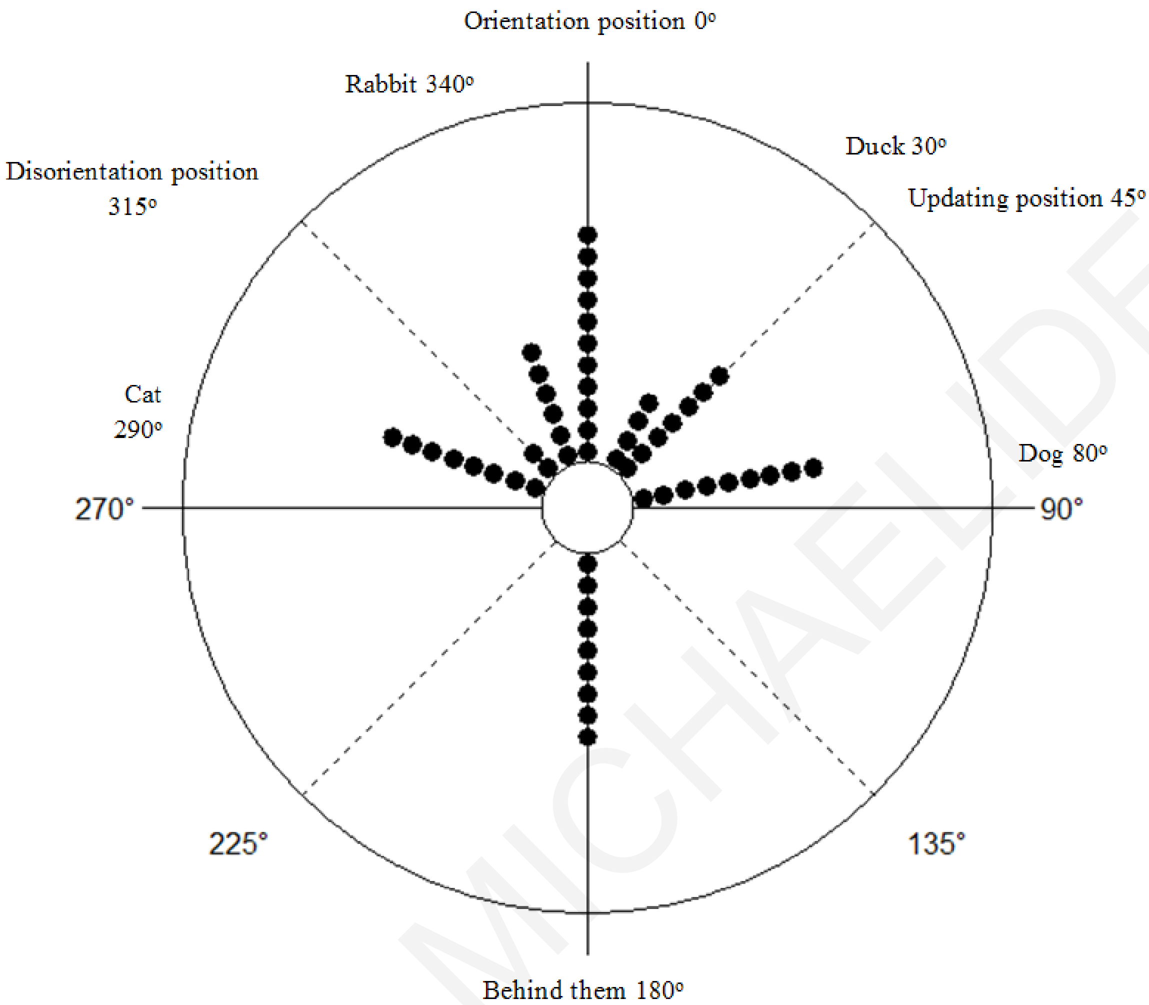


Figure 1. The reported subjective orientation for all participants after the disorientation phase. Each dot represents the subjective orientation of 4 participants (N=216).

APPENDIX D

1. Spatial short-term memory – Corsi's Block score

Spatial short-term memory was assessed with the Corsi's Block test. The lowest score obtained was 3 and the highest 8. As seen in Figure 1, the mean Corsi's score differed among the different age-groups, with 6-year olds having the lowest mean score and 11-year olds and 19-year old adults sharing the highest. Results revealed a developmental increase in spatial span -from early childhood to early adulthood- reflecting a constant improvement of spatial short-term memory over time. There is a considerable increase in children's performance from the age of 6 to the age of 8, and an even larger increase between the ages of 10 to 11, followed by a period of nugatory changes until the age of 19. Spatial memory span seems to reach the adult level at the age of 11, as from the age of 35 years a small decrement is observed. Spatial memory span seems to remain unchangeable from late childhood through mid-adulthood, although it shows a significant decrement around the age of sixties -the oldest age-group participated in the current study.

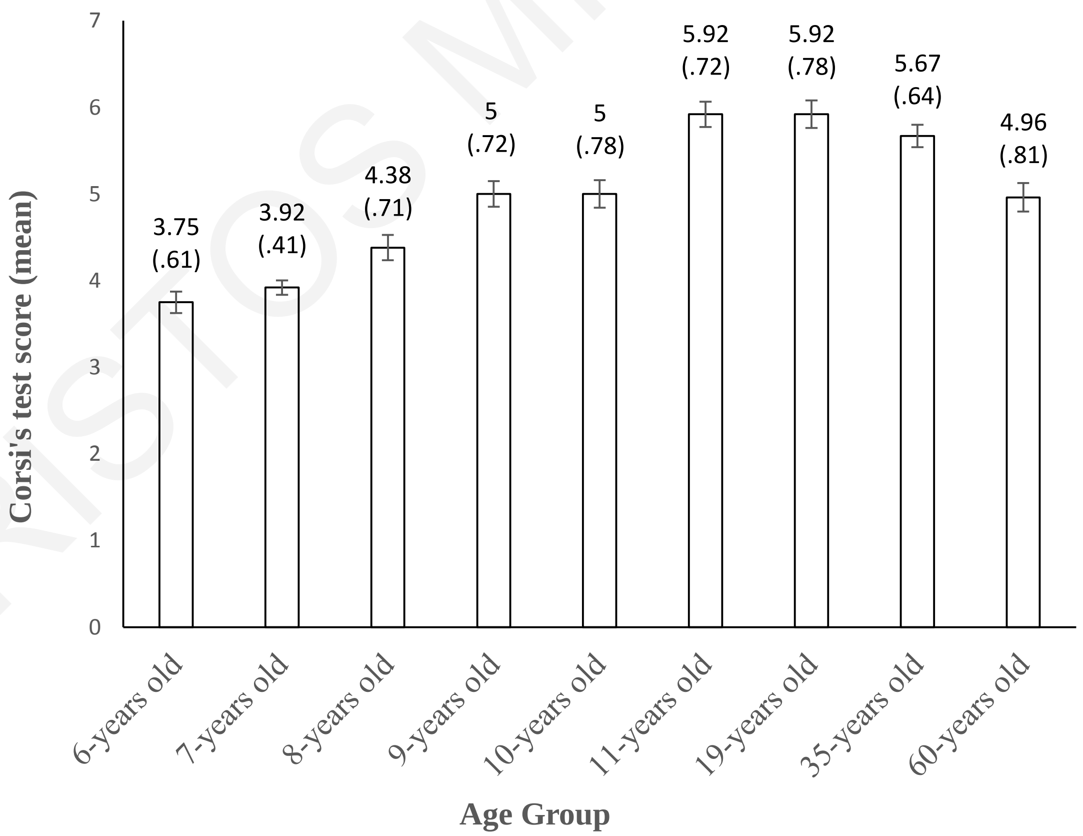


Figure 1. Mean score (SD) in the Corsi's Block test for each age-group. Error bars represent standard errors of the mean.

Overall, as seen in Figure 2, 12 participants (5.6%) received a score of 3 on Corsi's Block test, 70 participants scored 4 (32.4%), 64 participants scored 5 (29.6%), 59 scored 6 (27.3%), 10 participants got a score of 7 (4.6%), and one 19-year old female scored 8 (0.5%).

A simple linear regression analysis was calculated to predict Corsi's Block score based on participant's age. Data met all the assumptions which are required for linear regression analysis. There was a linear relationship between the variables; there were no significant outliers; the observations were independent; the data showed homoscedasticity; and the residuals of the regression line were normally distributed. A significant regression equation was found, $F(1, 214)=116.29$, $p <.001$, with an R^2 of .35. Based on the analysis, age is a significant predictor of Corsi's score (b = .24, β = .59, t = 10.78, $p < .001$). Participants' predicted Corsi's score is equal to 3.77 + .24 units when age is measured in years. More specifically, Corsi's score is increased .24 units for each year of age. Besides age, the analysis was also conducted to predict Corsi's Block score based on participant's gender. Although male participants had a slightly lower mean Corsi's score (M = 4.84, SD = 1.06) than females (M = 5.03, SD = 0.99), the analysis did not reveal any significant effect of gender, $F(1, 214)=1.95$, $p = .16$, $R^2 = .004$. Therefore gender is not consider as a significant predictor of Corsi's score (b = .19, β = .1, t = 1.4, $p = .16$).

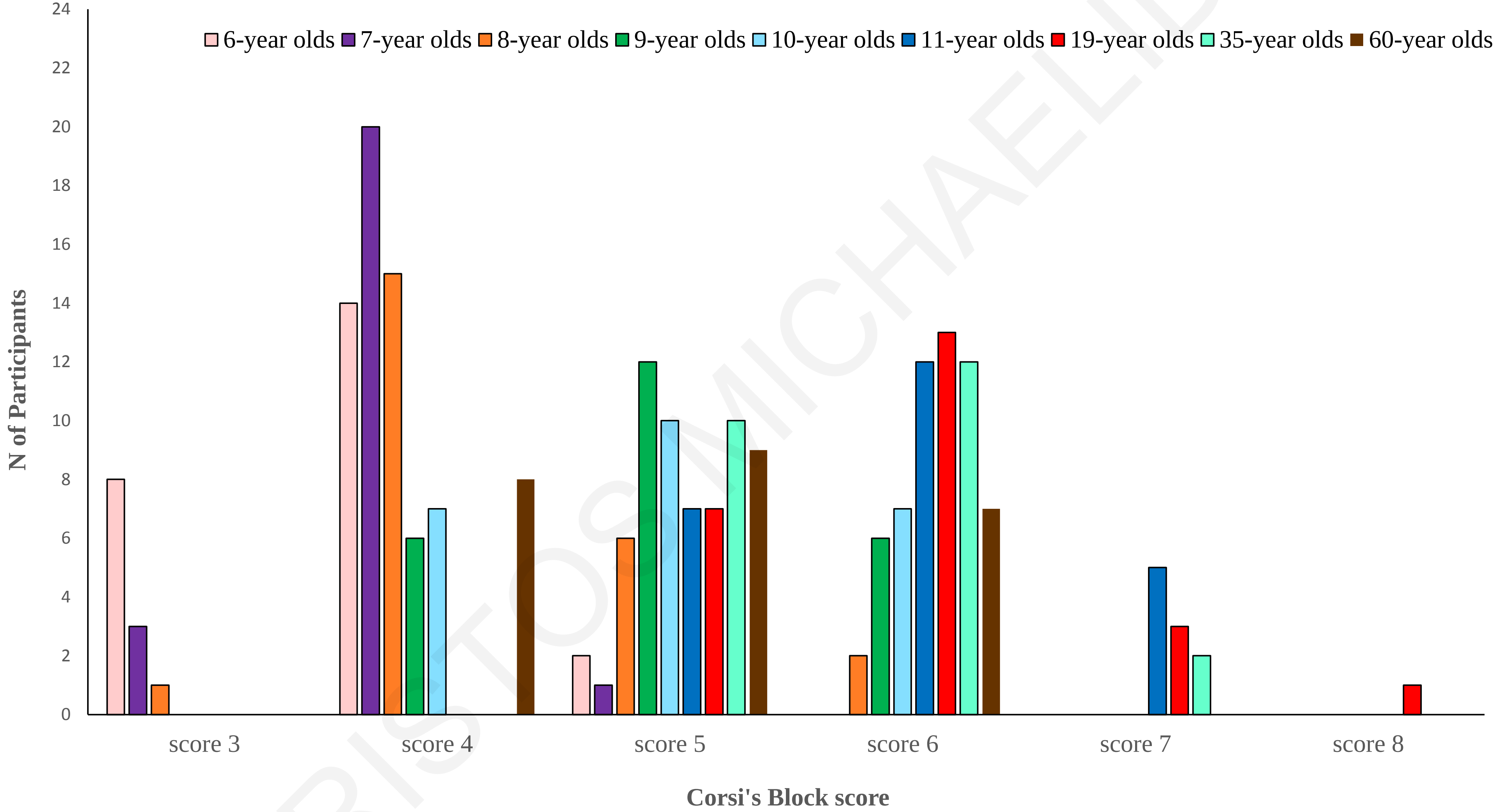


Figure 2. Distribution of the Corsi's Block score among the different age groups (N = 216).

For further analyses, participants were divided into 3 different groups based on their individual Corsi's Block score: low, medium and high spatial short-term memory group. The low spatial short-term memory group consisted of those who scored 4 and below on Corsi's Block test (82 participants, 38% of the sample). Participants who scored 5 were designated to the medium group (64 participants, 29.6%), while those with a score of 6 and above were in the high spatial short-term memory group (70 participants, 32.4%).

Constant error. Regardless of participants' spatial short-term memory group, the constant error was unimodally distributed around the mean direction in both the orientation and the updating phase, indicating that all participants remained oriented while blindfolded (Figure 3).

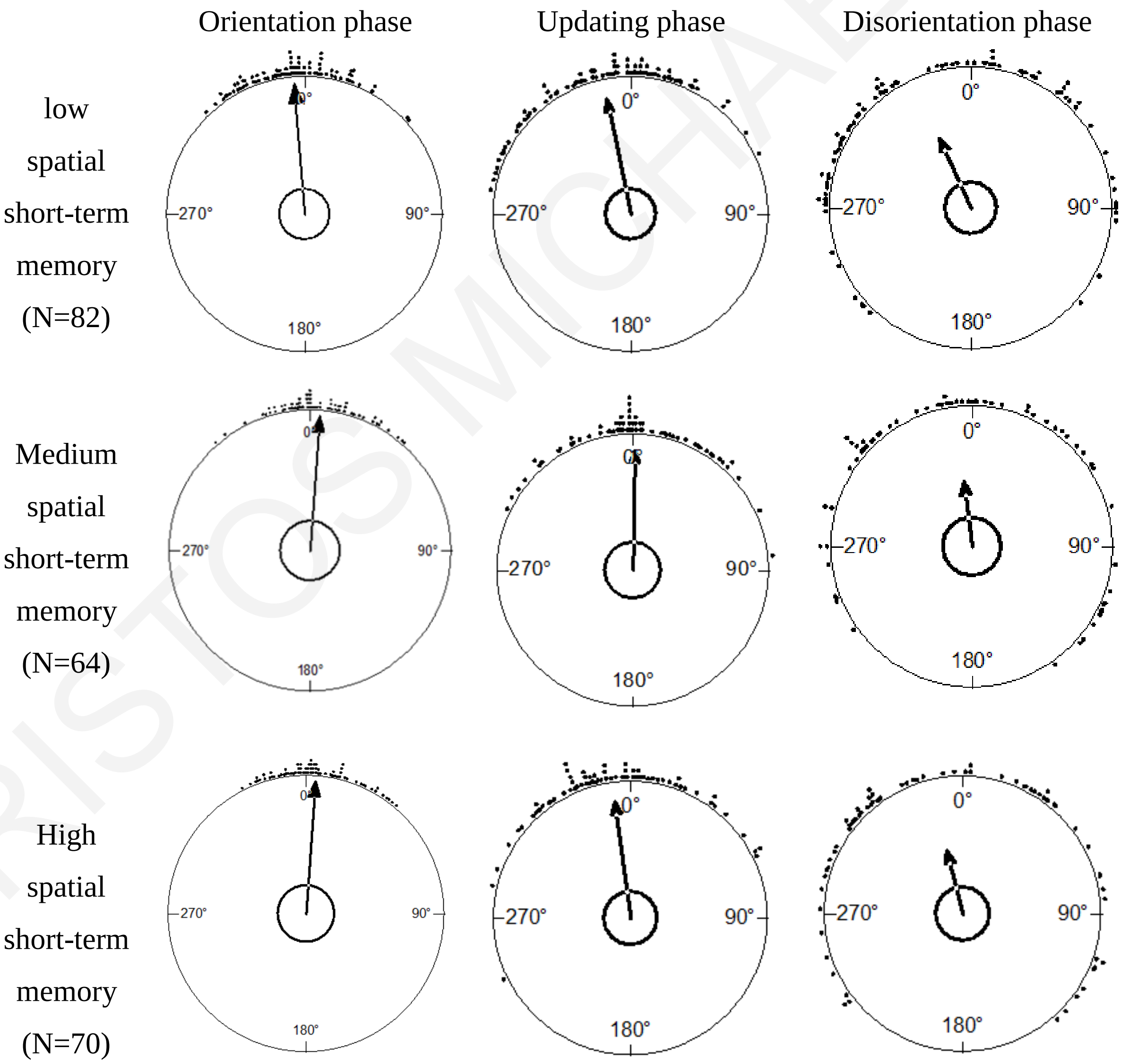


Figure 3. Constant error with the mean vector length (r) in the different spatial short-term memory groups, in the 3 response phases. Each dot represents a single participant.

In the orientation phase, participants' constant error was restricted in less than a quadrant of the circle, while in the updating phase it spanned to one-third of the circle. The distribution of constant error in the updating phase suggests that participants were quite accurate in updating their facing orientation, although this process results in some error. In both experimental phases and all the spatial short-term memory groups, the resultant length of the mean vector (r) was close to 1 (all *r's* > .85) and the circular variance close to zero (see Table 1 for the exact statistics). In the disorientation phase, even though the circular deviation of constant error was widely dispersed and the length of the mean vector (r) was respectively smaller in comparison with the orientation and the updating phase (Table 1), the Rayleigh test showed that the distribution was not random, $p < .001$.

To examine whether the observations from the same spatial memory group differed among the orientation, the updating, and the disorientation phase, I used the Hotelling's paired test. Results showed that within each group, the observations differed significantly among the experimental phases, all *p's* < .01 (see Table 2, Appendix C for the exact statistics for different pairwise comparisons). Within each group, the constant error was significantly larger in the disorientation phase and smaller in the orientation phase.

To determine whether the lengths of the mean angles for each spatial memory group were equal within each experimental phase, data were analyzed with the Watson-Williams F-test (Batschelet, 1981). In the orientation phase, the analysis showed a significant difference among the different groups, $F(2, 213) = 6.36$, $p = .002$. The low spatial memory group had higher constant error than both the medium and the high group, $F(1, 144) = 8.36$, $p = .004$ and $F(1, 150) = 9.29$, $p = .003$ respectively. A significant difference was also found in the updating phase, $F(2, 213) = 3.004$, $p = .05$. The low group had again higher error than the medium group, $F(1, 144) = 5.96$, $p = .016$. No differences were found among the 3 groups in the disorientation phase, $F(2, 213) = 0.97$, $p = .38$.

Table 1. Basic statistics for constant error at the 3 experimental phases and the different spatial short-term memory groups

	Spatial short-term memory group								
	Low (N=82)			Medium (N=64)			High (N=70)		
Phase	Orientation	Updating	Disorientation	Orientation	Updating	Disorientation	Orientation	Updating	Disorientation
Mean vector (degrees)	355.4	348.2	336	4.07	0.5	352.5	4.1	351.7	345.3
Length mean vector (r)	.95	.86	.54	.96	.88	.46	.96	.86	.47
Circular Variance	.05	.14	.46	.04	.12	.54	.04	.14	.53
Circular SD (degrees)	18.8	31.6	63.6	16.8	28.8	71.4	15.9	31.7	70.2
SE of Mean (degrees)	2.1	3.5	7.6	2.1	3.6	10.4	1.9	3.8	9.6
Rayleigh Test (Z)	73.62	60.5	23.9	58.75	49.68	13.55	64.84	51.5	15.63
Rayleigh Test (p)	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001

Pointing error. An ANOVA was carried out for pointing error with response phase (orientation, updating, disorientation) and spatial short-term memory group (low, medium, high) as factors. The analysis revealed a significant main effect for both the response phase, and the spatial memory group, $F(2, 426) = 28.54$, $p = <.001$, $\eta^2 = .12$, and $F(2, 213) = 9.1$, $p < .001$, $\eta^2 = .08$ respectively. No significant interaction was found, $F(4, 426) = .74$, $p = .57$, $\eta^2 = .007$.

The analysis for the orientation phase showed a significant effect of spatial memory group, $F(2, 213) = 5.93$, $p = .003$, $\eta^2 = .05$. The low spatial short-term memory group (M = 14.07, SD = 8.57) had larger pointing error than both the medium (M = 10.81, SD = 5.88) and the high group (M = 10.49, SD = 6.25) [$p = .02$ and $p = .007$ respectively], who exhibited comparable performance to each other, $p = 1$ (Figure 4).

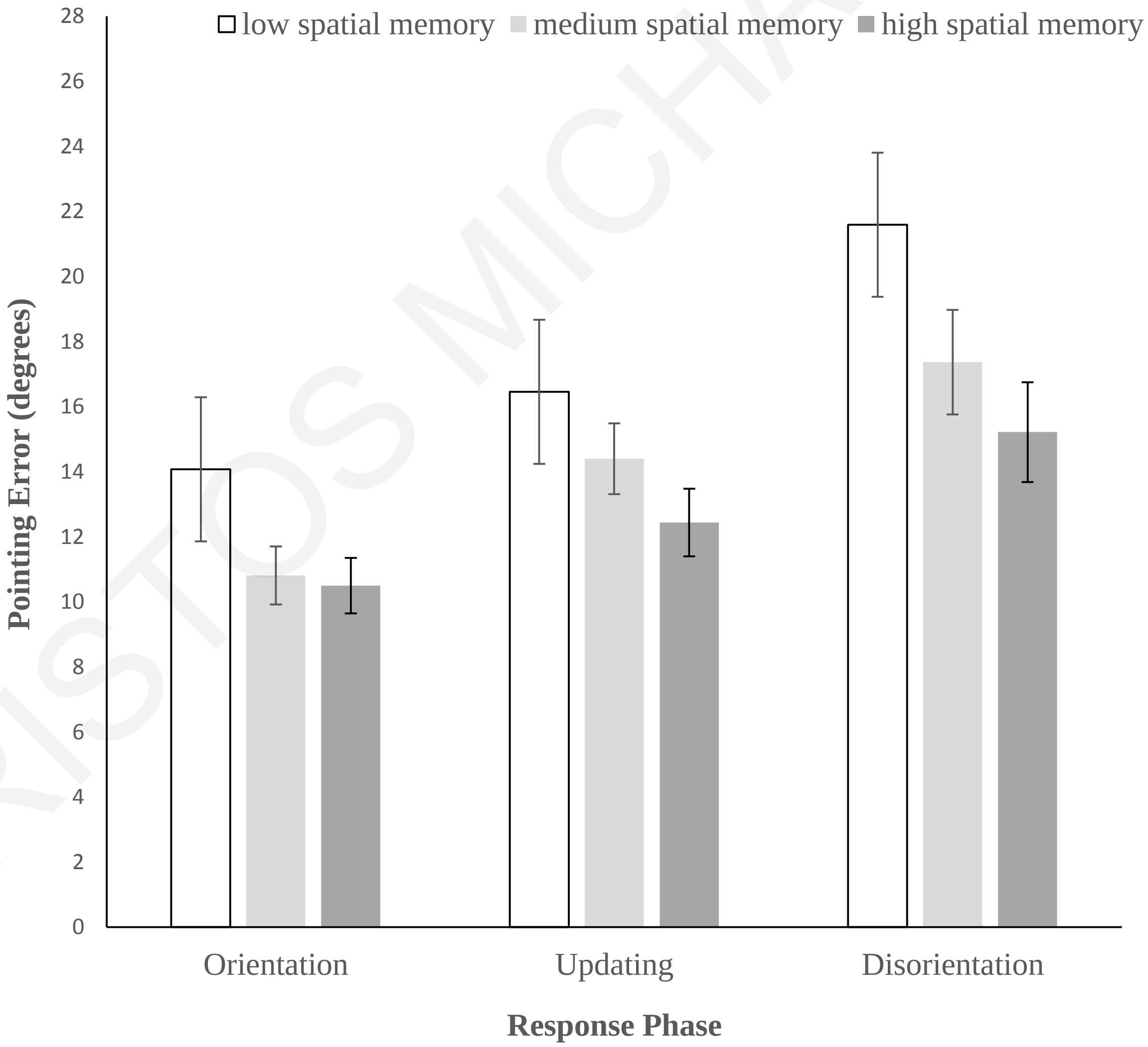


Figure 4. Pointing error for each spatial short-term memory group in the 3 response phases. Error bars represent standard errors of the mean.

A significant difference was also observed in the updating phase, $F(2, 213) = 4.05$, $p = .02$, $\eta^2 = .04$. The low spatial memory group (M = 16.46, SD = 9.42) had larger pointing error than the high group (M = 12.44, SD = 7.14), $p = .02$. A significant difference was also found in the disorientation phase $F(2, 213) = 4.88$, $p = .009$, $\eta^2 = .04$. Again, the low group (M = 21.59, SD = 14.74) had larger error than the high group (M = 15.21, SD = 10.07), $p = .008$ (Figure 4).

Variable error. The analysis revealed not only a significant increase in variable error from the orientation (M = 8.48, SD = 5.3), to the updating (M = 13.99, SD = 8.56) and to the disorientation phase (M = 28.44, SD = 29.71), $F(2, 426) = 70.45$, $p < .001$, $\eta^2 = .25$, but also a significant main effect of spatial short-term memory group, $F(2, 213) = 8.5$, $p < .001$, $\eta^2 = .07$. More interesting, a significant interaction was found between variable error in the different response phases and the spatial short-term memory groups, $F(4, 426) = 3.31$, $p = .01$, $\eta^2 = .03$. Variable error increased from the orientation to the updating and from the updating to the disorientation phase, while participants in the low spatial short-term memory group had higher variable error than those in the medium and the high group (Figure 5).

The analysis for the orientation phase showed that although participants in the high spatial memory group (M = 7.65, SD = 4.9) had numerically lower variable error than those in the medium (M = 8.09, SD = 4.93), and the low group (M = 9.5, SD = 5.79), this difference was not significant, $F(2, 213) = 2.59$, $p = .08$, $\eta^2 = .02$. A significant difference was found in the updating phase, $F(2, 213) = 4.14$, $p = .02$, $\eta^2 = .04$. The low spatial memory group (M = 16.07, SD = 10.28) had larger variable error than the high group (M = 12.35, SD = 6.22), $p = .02$. Finally, a significant difference was also found in the disorientation phase, $F(2, 213) = 5.33$, $p = .005$, $\eta^2 = .05$. Again, the low spatial memory group (M = 36.68, SD = 34.58) had larger error than both the medium (M = 24.18, SD = 24.69) and the high spatial memory group (M = 22.68, SD = 25.67), $p = .03$ and $p = .01$ respectively. In both the updating and the disorientation phase, the medium and the high group showed comparable performance to each other, $p = 1$.

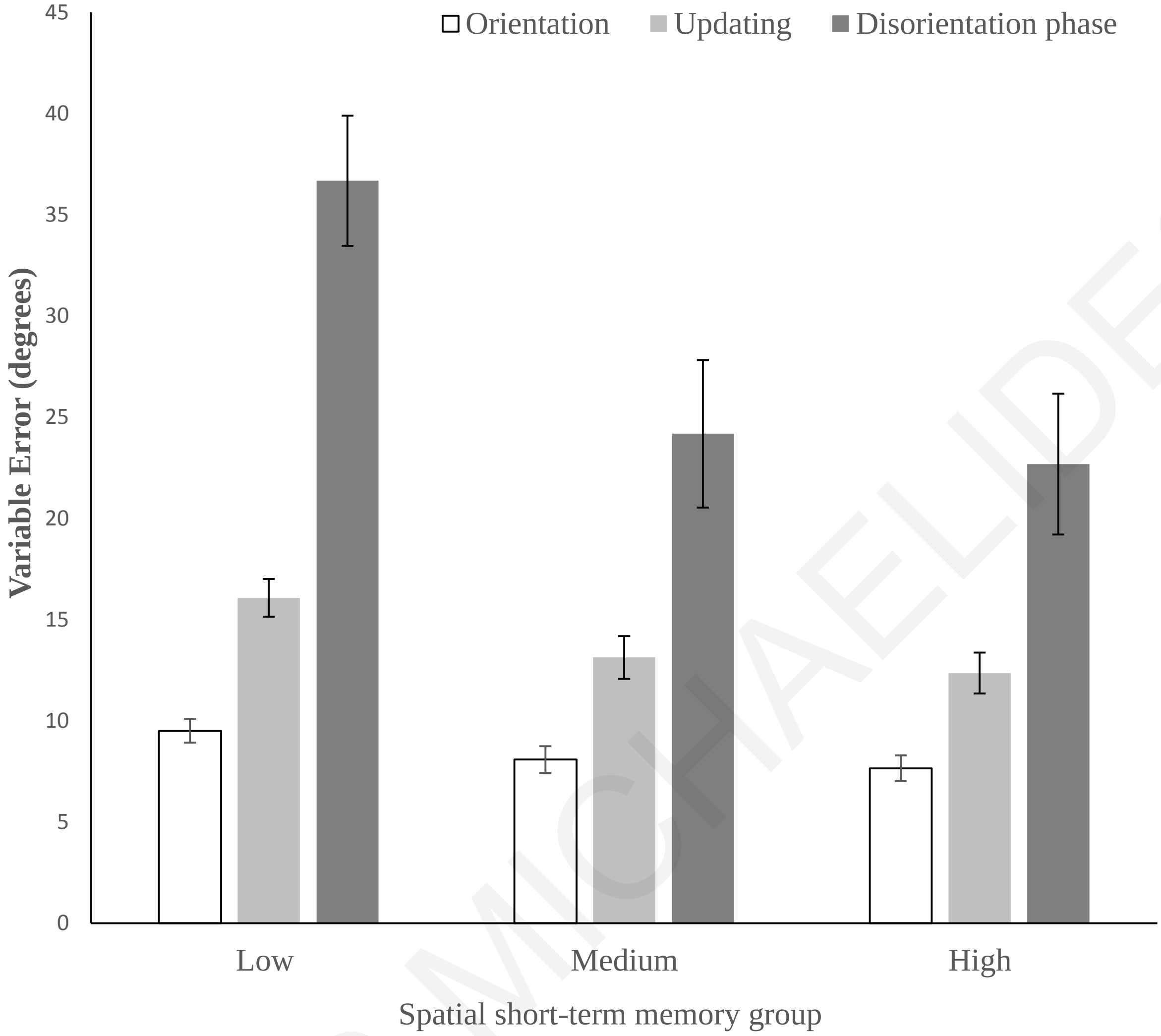


Figure 5. Variable error for each spatial short-term memory group in the 3 response phases. Error bars represent standard errors of the mean.

Pointing latency. Although the analysis showed a significant difference in pointing latency among the different response phases, $F(2, 426) = 1338.81$, $p < .001$, $\eta^2 = .86$, it did not reveal neither a significant effect of spatial short-term memory group, $F(2, 213) = .14$, $p = .87$, $\eta^2 = .001$, nor a significant interaction between pointing latency and spatial memory groups, $F(4, 426) = 1.52$, $p = .2$, $\eta^2 = .01$.

As seen in Figure 6, the pointing latency in the updating phase (M = 3773.5, SD = 589.19) was significantly higher than in the orientation (M = 1011.95, SD = 593.67) and the disorientation phase (M = 1283.27, SD = 771.54), all *p's* < .001. The pointing latency in the disorientation phase was also significantly higher than in the orientation phase, $p < .001$.

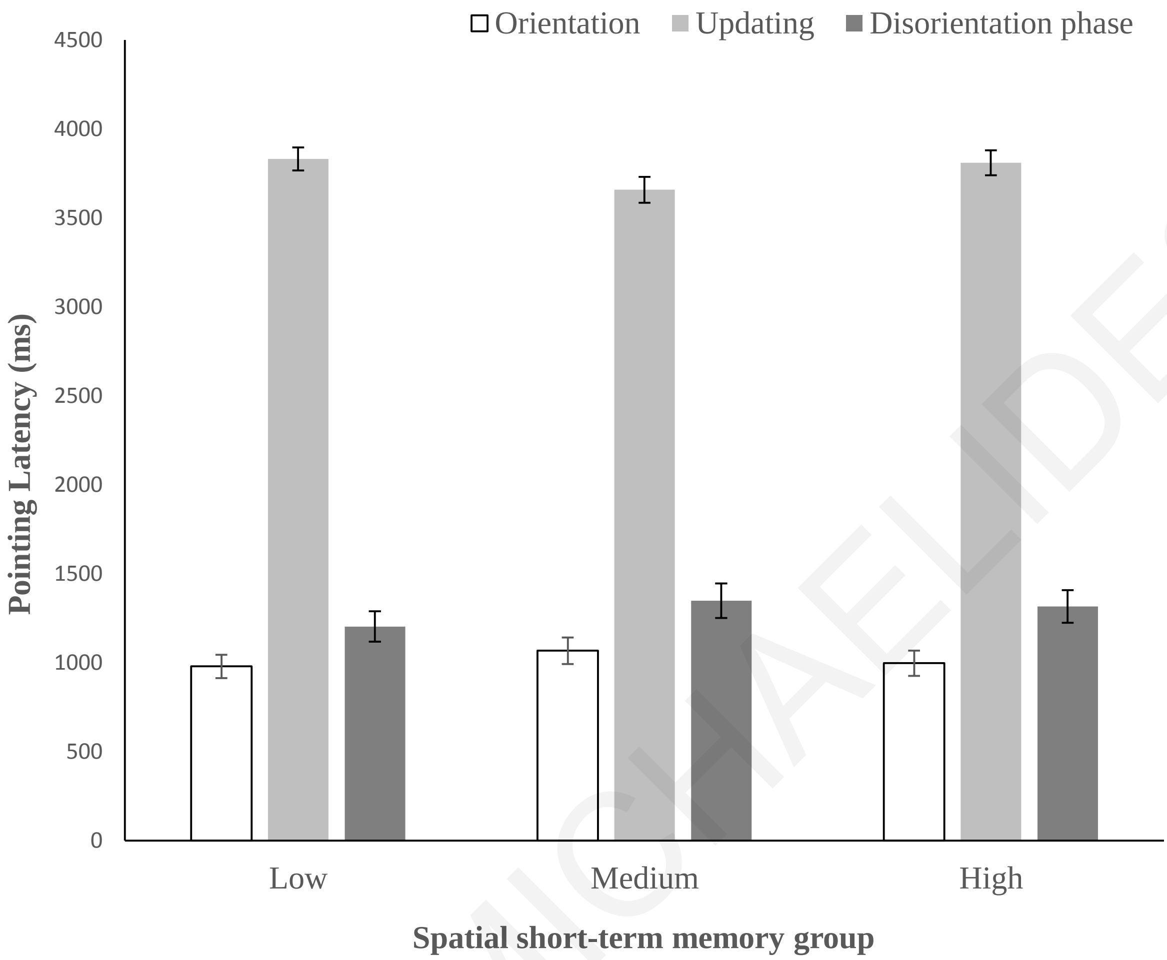


Figure 6. Pointing latency (milliseconds) for each spatial short-term memory group in the 3 response phases. Error bars represent standard errors of the mean.

2. Gender

The gender of the participants (male-female) was also recorded and used in the analysis as a between-subjects factor. As with the spatial short-term memory described above, the relation between gender and the 3 directional error measures (i.e., constant, variable and pointing error) and on pointing latency was examined and is analyzed below.

Constant error. Male participants did not differ from females in the distribution of constant error, which showed that the data were distributed in a uniform manner in both the orientation (males r = .94, females r = .96), the updating (males r = .87, females r =.86) and the disorientation phase (males r = .47, females r =.51), all *p's* <.001. As can be seen in Figure 7, although in the disorientation phase the data were widely dispersed around the circle and the length of the mean vector r was respectively smaller than in the orientation and the updating phase, the Rayleigh test showed that this distribution was not random, $p < .001$.

Hotelling's Paired Test showed that all participants' observations, regardless of their gender, differed significantly among the orientation, the updating and the disorientation phase (all *p's* < .001), with constant error being larger in the disorientation phase and smaller in the orientation (see Table 2, Appendix C for pairwise comparisons between the different response phases and the exact statistics).

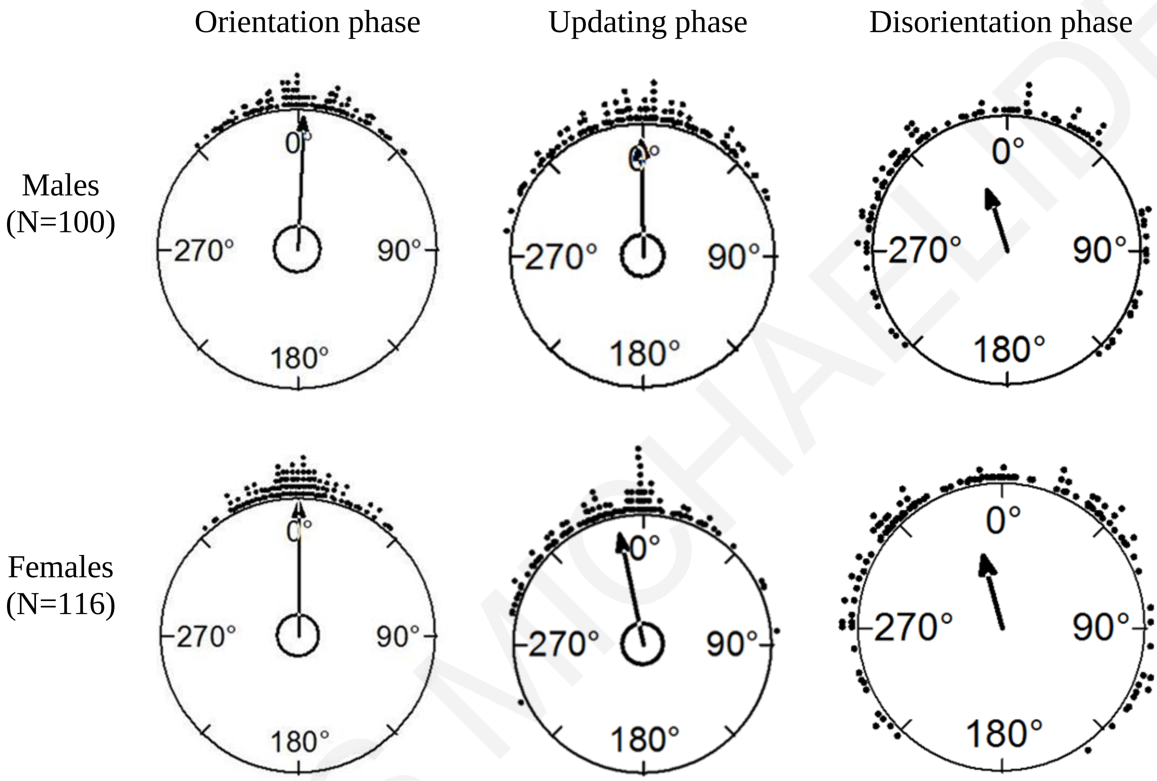


Figure 7. The constant error of male and female participants in the 3 response phases. Each dot represents a single participant.

The Watson-Williams F-test showed that males and females were similarly oriented in both the orientation and the disorientation phase, $F(1, 214) = 0.91$, $p = .34$, and $F(1, 214) = 0.13$, $p = .72$ respectively. The only difference was found in the updating phase, in which males had lower constant error than females, $F(1, 214) = 6.56$, $p = .011$.

Pointing error. The analysis on pointing error revealed a significant main effect for the different response phases, $F(2, 428) = 28.82$, $p = <.001$, $\eta^2 = .12$, Although females had numerically lower pointing error than males in all experimental phases (Figure 8), the analysis did not reveal any significant gender differences, $F(1, 214) = 2.57$, $p = .11$, $\eta^2 = .01$. No significant interaction between pointing error in the different response phases and gender was found, $F(2, 428) = .64$, $p = .53$, $\eta^2 = .003$.

The analysis revealed that in the orientation phase, females (M = 11.06, SD = 6.8) had lower pointing error than males (M = 12.97, SD = 7.72), $F(1, 214) = 3.75$, $p = .05$, $\eta^2 = .02$. Females (M = 13.49, SD = 7.76) had also marginally lower error than males (M = 15.76, SD = 9.79) in the updating phase, $F(1, 214) = 3.62$, $p = .059$, $\eta^2 = .02$. Nevertheless, the magnitude of these significant effects was small, as indicated by eta squared measures. No significant difference was found between males (M = 18.54, SD = 11.46) and females (M = 18.04, SD = 14.36) in the disorientation phase, $F(1, 214) = .08$, $p = .78$, $\eta^2 = .000$ (Figure 8).

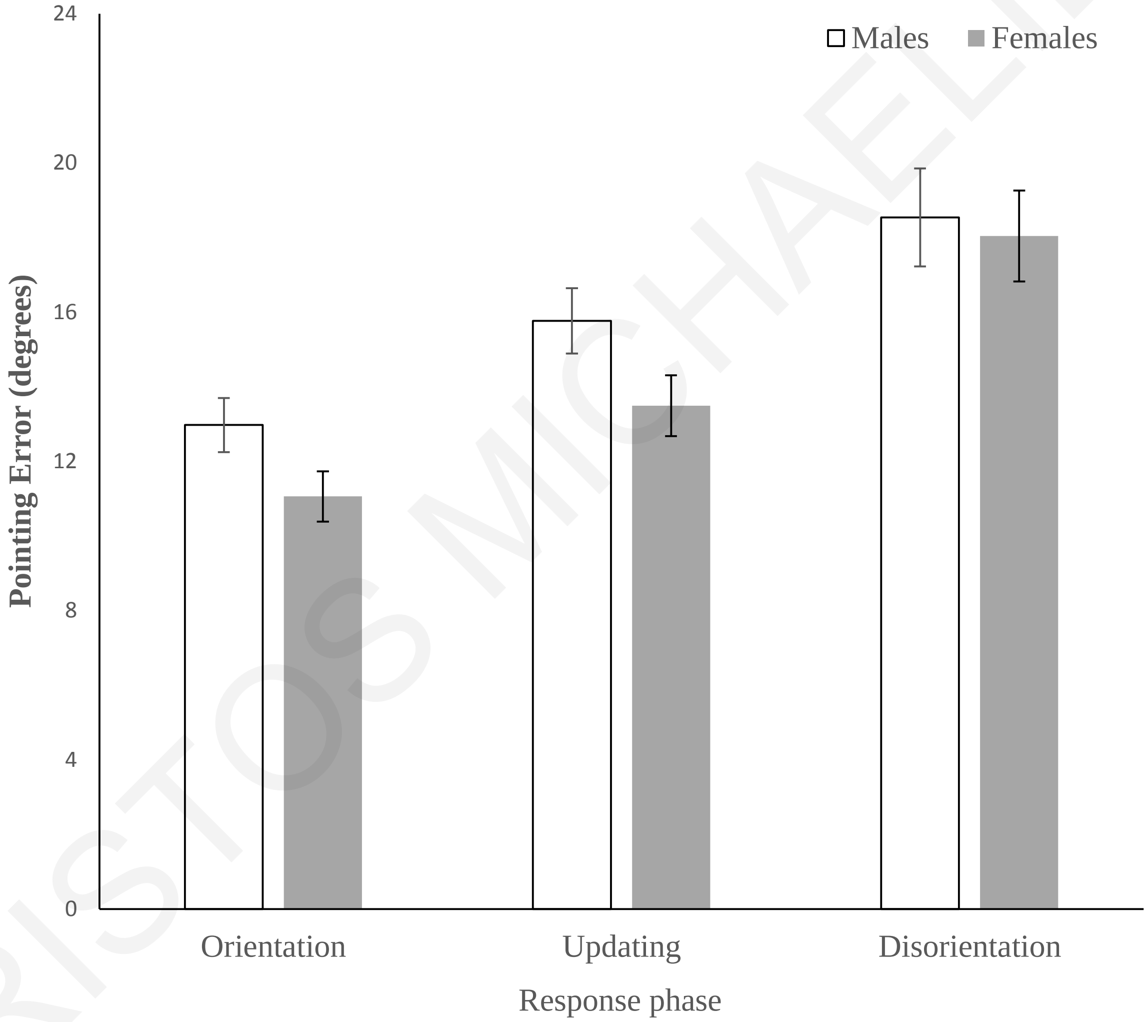


Figure 8. Pointing error in the 3 response phases by gender. Error bars represent standard errors of the mean.

Variable error. The only significant difference in variable error was found in regard with the different response phases, $F(2, 428) = 73.58$, $p = <.001$, $\eta^2 = .26$. The analysis did not reveal any significant gender differences, $F(1, 214) = .33$, $p = .57$, $\eta^2 = .002$. No significant interaction between variable error in the different response phases and gender was found, $F(2, 428) = .45$, $p = .64$, $\eta^2 = .002$.

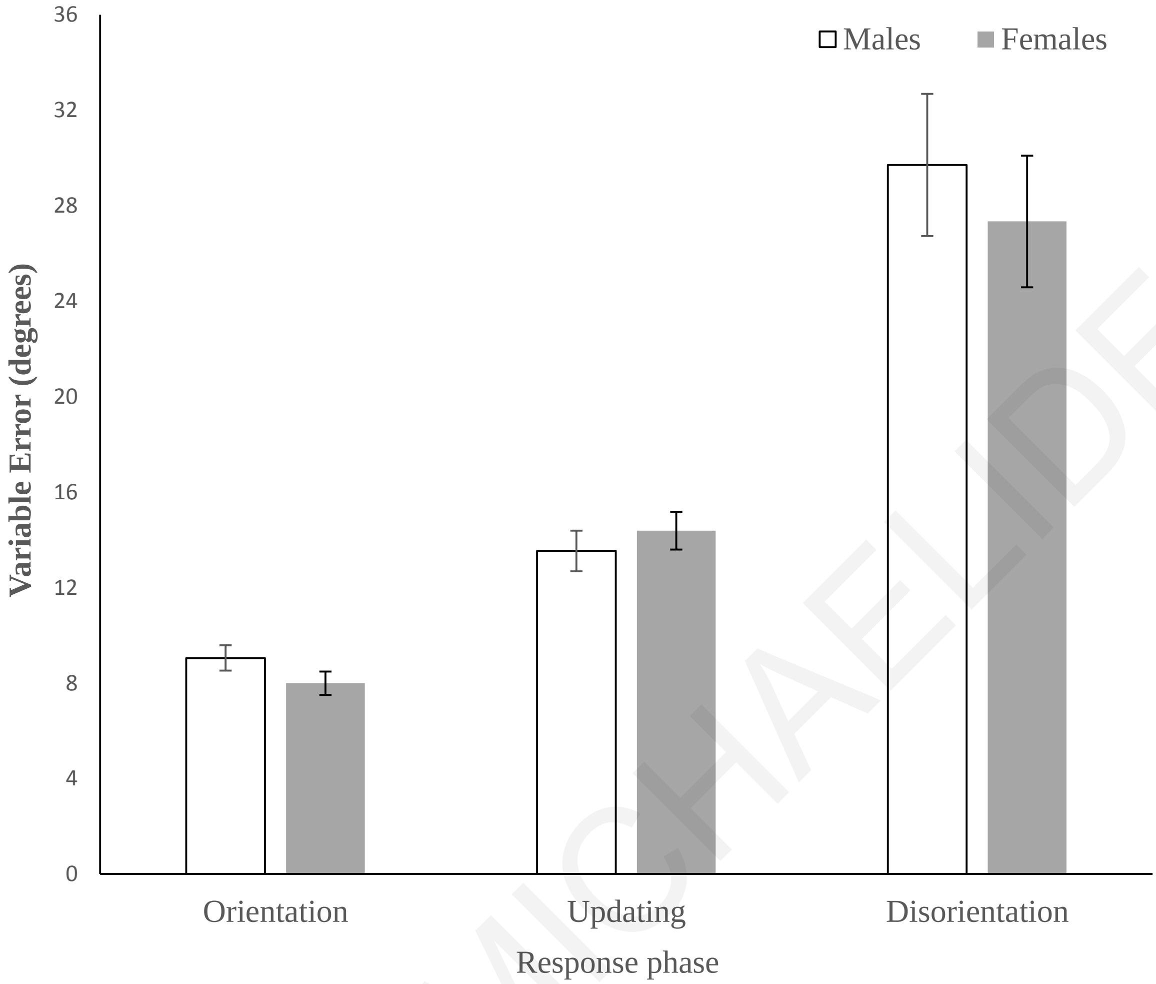


Figure 9. Variable error for male and female participants in the 3 response phases. Error bars represent standard errors of the mean.

Pointing latency. The analysis revealed a significant difference in pointing latency among the different response phases, $F(2, 428) = 1349.33$, $p < .001$, $\eta^2 = .86$. Although males had overall numerically lower pointing latency than females in all three experimental phases (Figure 10), the analysis did not reveal any significant gender differences in pointing latency, $F(1, 214) = 3.26$, $p = .07$, $\eta^2 = .02$. No significant interaction between pointing latency in the different response phases and gender was found, $F(2, 428) = 2.06$, $p = .13$, $\eta^2 = .01$.

Although the analysis did not reveal any significant gender differences in the orientation [$F(1, 214) = .14$, $p = .71$, $\eta^2 = .001$] and the disorientation phase [$F(1, 214) = .18$, $p = .68$, $\eta^2 = .001$], in the updating phase, males (M = 3643.42, SD = 638.57) had significantly lower pointing latency than females (M = 3885.64, SD = 520.16), $F(1, 214) = 9.43$, $p = .002$, $\eta^2 = .04$ (Figure 10).

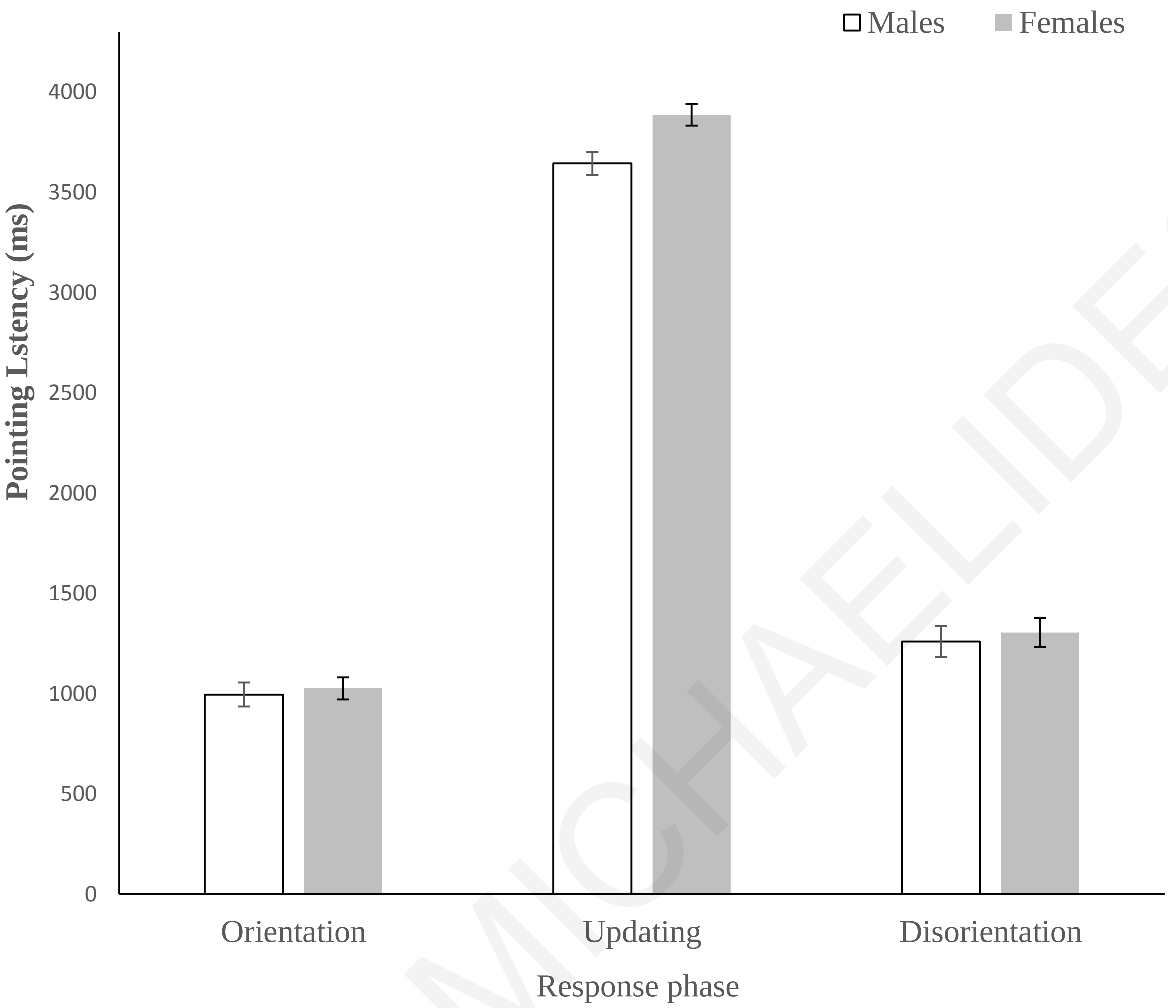


Figure 10. Pointing latency in the 3 response phases by gender. Error bars represent standard errors of the mean.

The relation between gender and spatial short-term memory was also examined. As seen in Table 2, although some minimal differences among average Corsi's scores were observed, with female participants having overall slightly higher mean Corsi's score (M = 5.03, SD = .96) than males (M = 4.84, SD = 1.06), the analysis showed that these differences were not significant, $t(214) = 1.35$, $p = .18$. However, separate analysis for each age-group revealed that 7-year old girls (M = 4.08, SD = .29) had significantly higher spatial short-term memory score than 7-year old boys (M = 3.75, SD = .45), $t(22) = 2.15$, $p = .04$, and 60-year old women (M = 5.2, SD = .78) had marginally significant higher spatial short-term memory score than 60-year old men (M = 4.56, SD = .73), $t(22) = 2.02$, $p = .056$ (see Table 2 for the mean Corsi's score and SD of male and female participants in each age-group).

Table 2. Spatial short-term memory score for males and females participants in each age-group

Age-group	Gender	Spatial short-term memory - Corsi Block's Score					Mean (SD)
		Score 3	Score 4	Score 5	Score 6	Score 7	
6-years old	Male	4	8	---	---	---	3.67 (.49)
	Female	4	6	2	---	---	3.83 (.72)
7-years old	Male	3	9	---	---	---	3.75 (.45)
	Female	---	11	1	---	---	4.08 (.29)
8-years old	Male	---	9	3	1	---	4.38 (.65)
	Female	1	6	3	1	---	4.36 (.81)
9-years old	Male	---	3	3	4	---	5.1 (.88)
	Female	---	3	9	2	---	4.93 (.62)
10-years old	Male	---	4	5	2	---	4.82 (.75)
	Female	---	3	5	5	---	5.15 (.8)
11-years old	Male	---	---	5	5	2	5.75 (.75)
	Female	---	---	2	7	3	6.08 (.67)
19-years old	Male	---	---	2	5	2	6 (.71)
	Female	---	---	5	8	2	5.8 (.68)
35-years old	Male	---	---	4	6	2	5.83 (.72)
	Female	---	---	6	6	0	5.50 (.52)
60-years old	Male	---	5	3	1	---	4.56 (.73)
	Female	---	3	6	6	---	5.2 (.78)
Total	Male	7	38	25	24	6	4.84 (1.06)
	Female	5	32	39	35	5	5.03 (.96)

3. Handedness

The last between-subjects factor to be examined was handedness. Based on the administration of the Edinburgh Handedness Inventory –short form, participants were divided into four groups (Table 1, main text, p.24): right-handers, mixed-handers-right hand preference, mixed-handers-left hand preference and left-handers. Overall, 90.3% of the participants (N = 195) had a right-hand preference, 6.5% (N = 14) were left-handers, while 2.8% (N = 6) and 0.5% (N = 1) were mix-handers with right- and left-hand preference respectively (Figure 11).

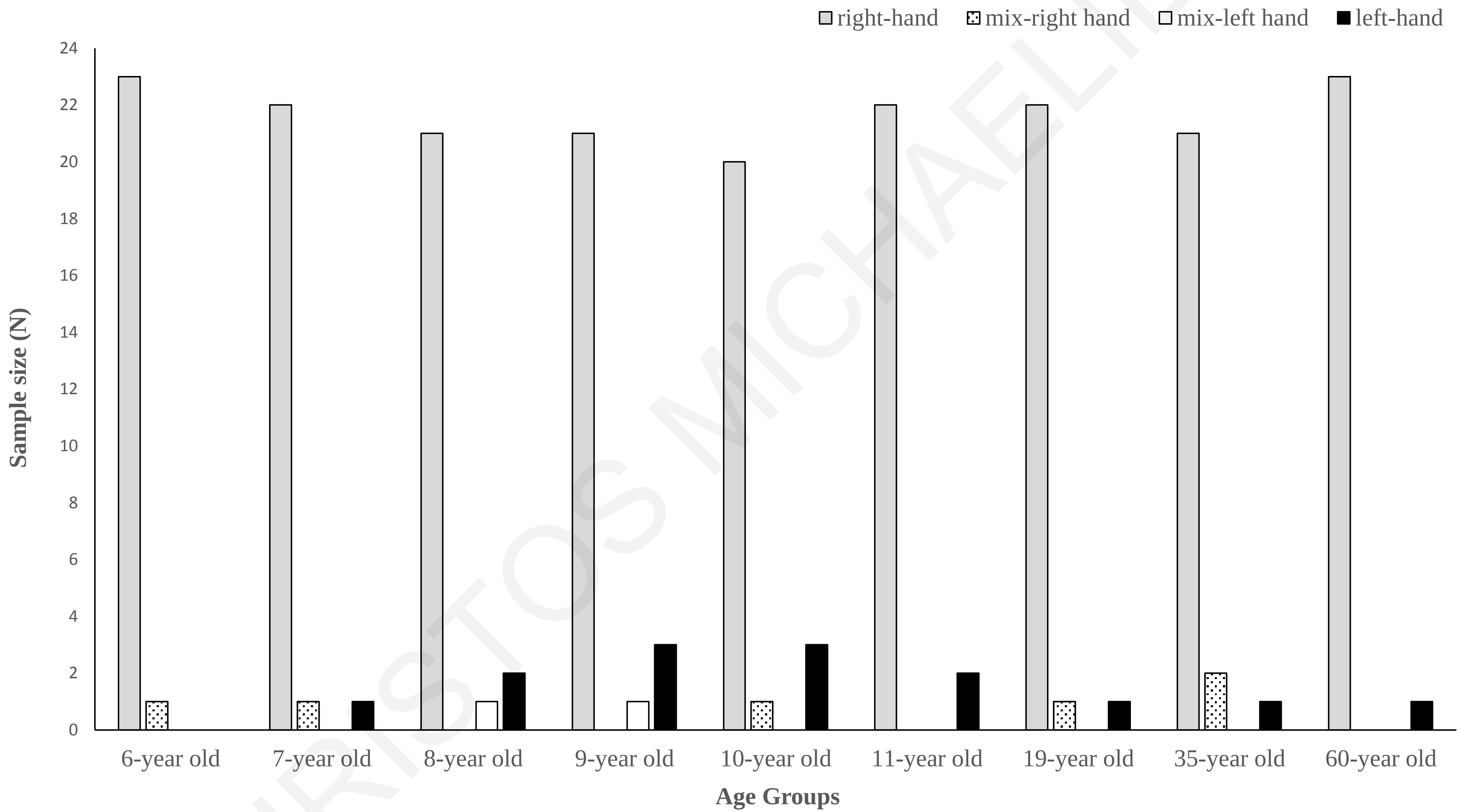


Figure 11. Hand-preference in the different age groups (N = 216).

The proportion of left-handers participating in the current study resembles the one reported in a relevant study in Greece (7.3% left-handed) involving 634 secondary school students (Vlachos, Avramidis, Dedousis, Katsigianni, Ntalla, Giannakopoulou, & Chalmpe, 2013), and is close enough to the commonly accepted historical proportion of 10%. Due to their small number, in all the following analyses, the 6 mix-handers with right-hand preference and the single one with left-hand preference were included in one group, named mixed-handers.

Constant error. As expected, the constant error was unimodally distributed around zero in both the orientation and the updating phase, regardless of participants' hand preference (Figure 12). In the disorientation phase, mix-handers seemed more disoriented than right and left-handers, as indicated by a non-significant *p*-value in the Rayleigh test ($p = .068$). However, due to the small number of mix-handers (N = 7), these results may be unreliable. In fact, Rao's Spacing Test (Batschelet, 1981), which also tests the null hypothesis of uniformly distributed data by examining spacing's deviation among points around the circle, gave a significant value for mix-handers ($p < .05$), and thus the randomness of the data in the disorientation phase is rejected.

Table 3. Circular statistics for constant error and handedness among the different response phases

	Mean vector (°)	Length mean vector -r	Circular Variance	Circular SD (°)	Standard Error of Mean (°)	Rayleigh Test (Z)	Rayleigh Test (p)
				Orientation phase			
Right-handers	0.02	.96	.04	17.01	1.22	178.55	< .001
Left-handers	11.29	.95	.05	19.15	5.73	12.52	< .001
Mix-handers	2.75	.89	.11	27.51	13.21	5.56	< .001
				Updating phase			
Right-handers	350.78	.87	.13	30.21	2.16	147.69	< .001
Left-handers	23.37	.88	.12	28.46	8.5	10.94	< .001
Mix-handers	357.1	.84	.16	33.98	16.25	4.92	= .003
				Disorientation phase			
Right-handers	340.75	.50	.50	67.74	5.45	48.19	< .001
Left-handers	25.24	.47	.53	70.15	23.01	3.13	= .041
Mix-handers	345.38	.61	.39	56.79	23.61	2.62	= .068

The analysis with the Watson-Williams F-test showed that, right-handers had lower constant error than left-handers in all the experimental phases: orientation phase [$F(1, 207) = 5.57$, $p = .02$], updating phase [$F(1, 207) = 15.29$, $p < .001$] and disorientation phase [$F(1, 207) = 4.68$, $p = .03$]. For the circular statistics concerning handedness in the different response phases, see Table 3.

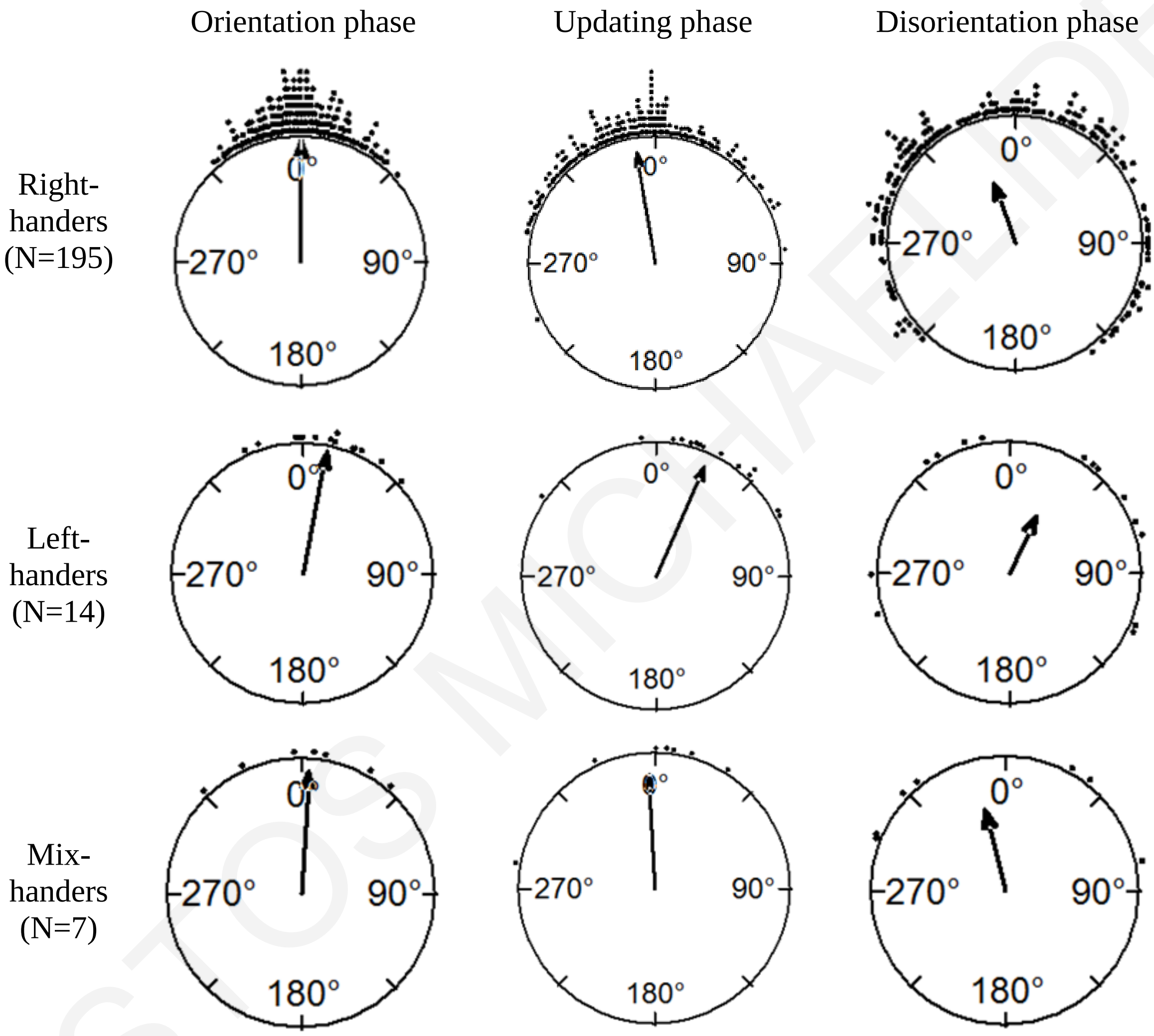


Figure 12. Constant error at the different response phases based on participants' handedness. Each dot represents a single participant.

Hotelling's Paired Test showed that the observations of right-handers differed significantly among the orientation, the updating and the disorientation phase (all *p's* < .001), while left- and mix-handers had significant different observations between the disorientation and the orientation phase ($p = .021$ and $p < .001$ respectively), and between the disorientation and the updating phase, ($p = .05$ and $p < .001$ respectively). All the pairwise comparisons among the different experimental phases and the exact statistics are shown in Table 2 (Appendix C). Overall, the analysis of constant error indicates that although all participants, regardless of their hand preference, remained oriented while blindfolded in all the experimental phases, right-handers were significantly more oriented than left-handers.

Pointing error. Although the analysis in pointing error did not reveal significant differences among the different experimental phases [$F(2, 426) = 2.02$, $p = .13$, $\eta^2 = .009$], it revealed a significant effect of handedness, $F(2, 213) = 2.99$, $p = .05$, $\eta^2 = .03$. More interesting, the analysis showed a significant interaction between pointing error in the different response phases and handedness, $F(4, 426) = 4.55$, $p = .001$, $\eta^2 = .04$. Left- and mix-handers had larger pointing error than right-handers in all but the disorientation phase. In the orientation phase, right-handers had a significantly lower error than left-handers, who in turn had a numerically lower error than mix-handers. This pattern reversed in the disorientation phase (Figure 13).

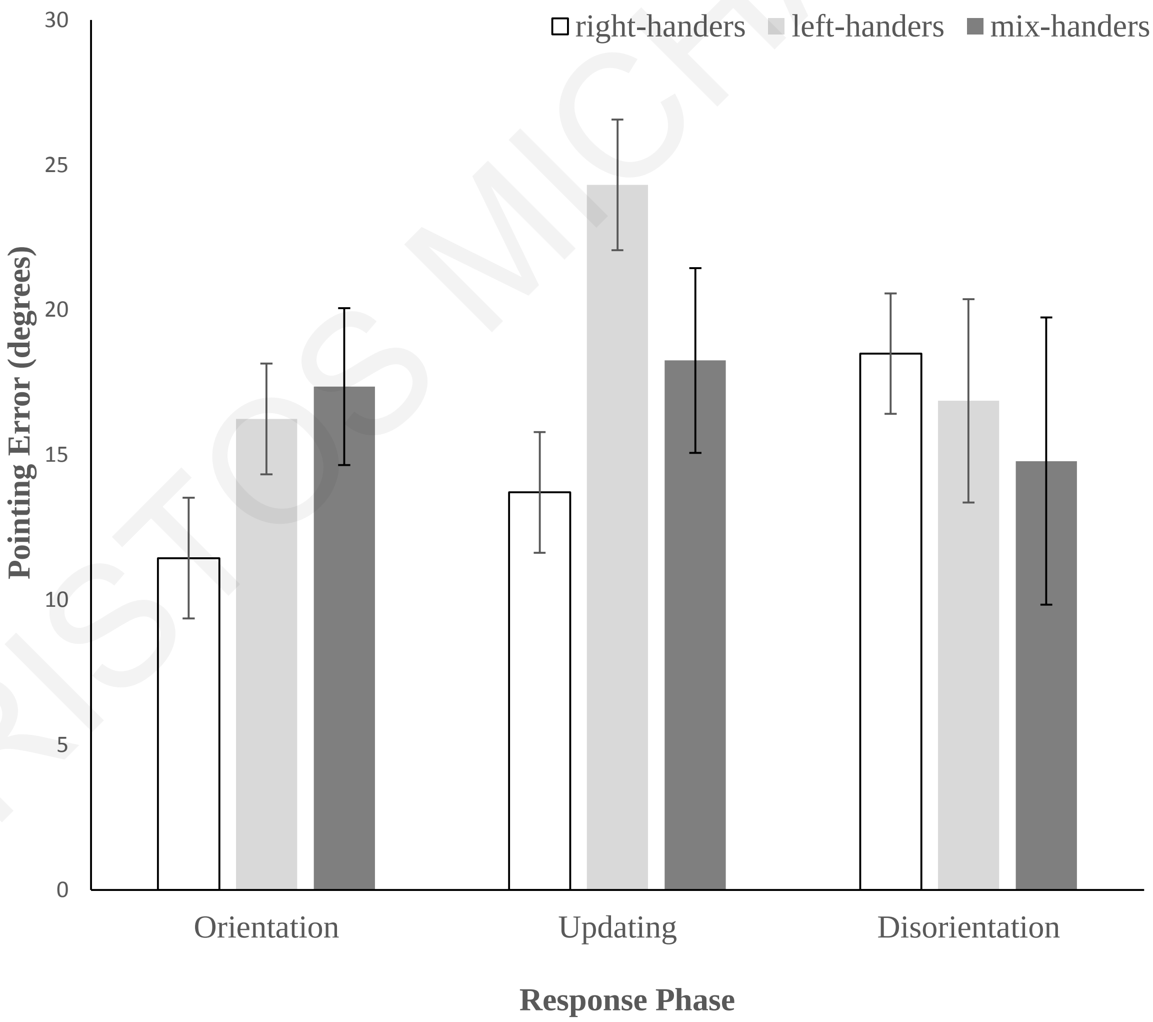


Figure 13. Pointing error in the 3 response phases based on participants' hand preference. Error bars represent standard errors of the mean.

In regard with participants' hand-preference and pointing error, the analysis showed that overall, left-handers (M = 19.14, SE = 1.9) had larger pointing error than both the right-handers (M = 14.55, SE = .51) and the mix-handers (M = 16.8, SE = 2.68). The analysis on the orientation phase showed a significant effect of handedness, $F(2, 213) = 5.01$, $p = .007$, $\eta^2 = .05$. Right-handers (M = 11.44, SD = 6.89) had lower error than left handers (M = 16.25, SD = 10.52), $p = .048$. A significant effect of handedness was also found in the updating phase, $F(2, 213) = 11.06$, $p < .001$, $\eta^2 = .09$. Right-handers (M = 13.71, SD = 7.85), had lower pointing error than left-handers (M = 24.32, SD = 13.75), $p < .001$. Nevertheless, the magnitude of these significant effects was small to medium, as indicated by eta squared measures. In the disorientation phase, although mix-handers (M = 14.79, SD = 6.26) had numerically lower error than both the right-handers (M = 18.5, SD = 13.55) and the left-handers (M = 16.87, SD = 7.65), the difference was not significant, $F(2, 213) = .36$, $p = .7$, $\eta^2 = .003$ (Figure 13).

Variable error. The analysis on variable error and handedness revealed only a significant main effect for the different response phases, $F(2, 426) = 8.06$, $p = <.001$, $\eta^2 = .04$. No significant differences were found among right-, left- and mix-handers [$F(2, 213) = .37$, $p = .69$, $\eta^2 = .003$], neither any significant interaction between variable error in the different response phases and handedness, $F(4, 426) = 1.08$, $p = .37$, $\eta^2 = .01$ (for mean and standard deviation of variable error in each response phase based on handedness, see Table 4).

As seen in Figure 14, variable error in the orientation phase (M = 8.48, SD = 5.3) was significantly lower compared to that in the updating (M = 13.99, SD = 8.56) and the disorientation phase (M = 28.44, SD = 29.71), $p < .001$, and $p = .003$ respectively. Although numerically lower, variable error in the updating phase did not differ significantly compared to the one in the disorientation phase, $p = .32$. The analyses for each response phase showed that all pairwise comparisons with right-, left-, and mix-handers were non-significant, all *p's* > .36.

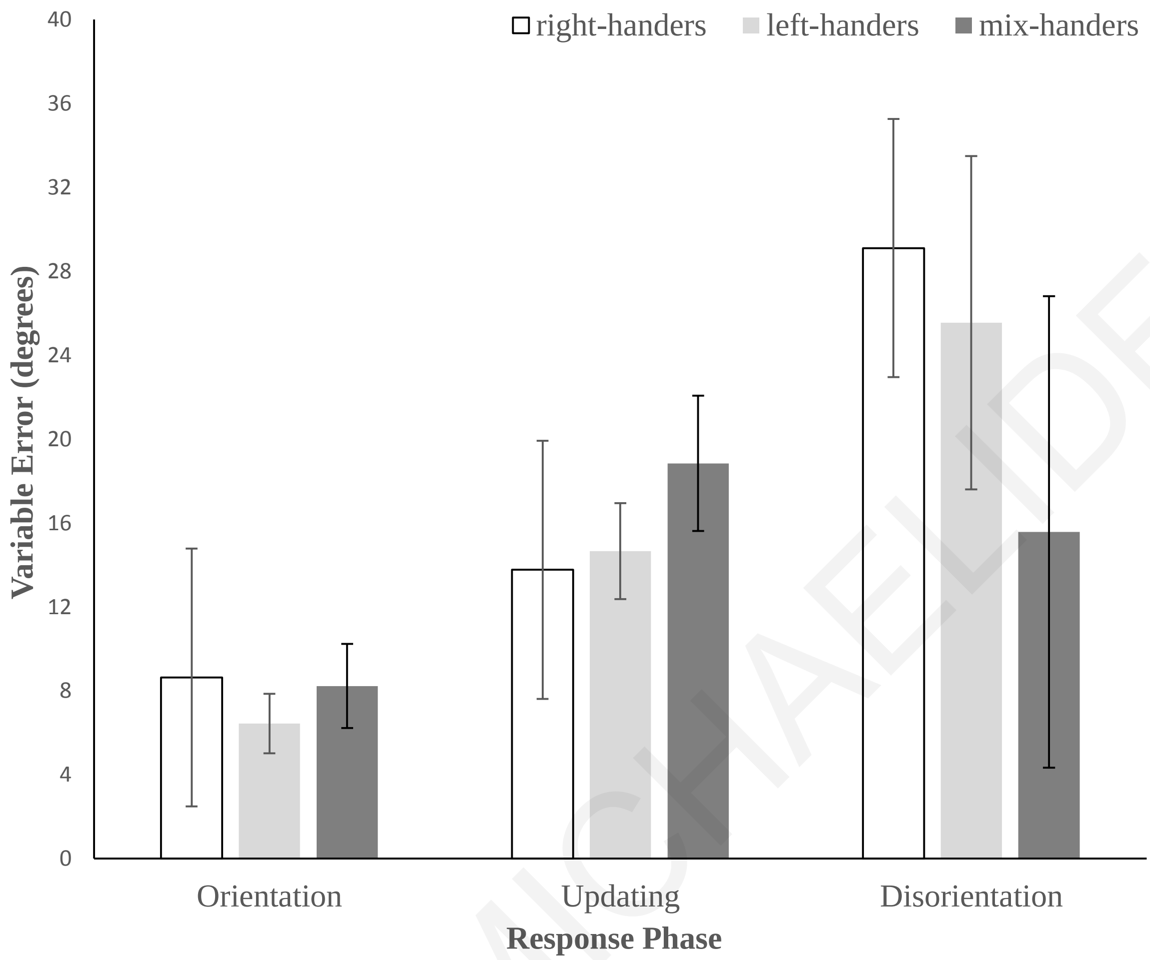


Figure 14. Variable error in the 3 response phases based on participants' hand preference. Error bars represent standard errors of the mean.

Table 4. Mean (SD) variable error in the 3 response phases based on handedness

	Mean (SD) variable error			
Handedness	Orientation phase	Updating phase	Disorientation phase	N
Right-handers	8.64 (5.45)	13.77 (8.51)	29.1 (30.28)	195
Left-handers	6.45 (3.79)	14.66 (6.77)	25.55 (28.15)	14
Mix-handers	8.23 (2.56)	18.84 (12.37)	15.57 (6.46)	7
Total	8.48 (5.3)	13.99 (8.56)	28.44 (29.71)	216

Pointing latency. Although the analysis did not reveal any significant differences among the different groups (right-, left-, mix-handers) in pointing latency [$F(2, 213) = 1.38$, $p = .25$, $\eta^2 = .01$], it showed a significant interaction between latency in the different response phases and handedness, $F(4, 426) = 4.54$, $p = .001$, $\eta^2 = .04$. As seen in Figure 15, in both the orientation and the disorientation phase, mix-handers had lower pointing latency than right-handers, who in turn had lower latency than left-handers. This pattern reversed in the updating phase, with mix-handers having the larger latency of all groups and left-handers having lower latency than right-handers.

The analysis in the orientation phase did not reveal significant differences among different hand preferences, $F(2, 213) = .66$, $p = .52$, $\eta^2 = .006$, although that mix-handers (M = 777.83, SD = 416.87) had numerically lower pointing latency than both the right (M = 1014.82, SD = 574.25) and the left-handers (M = 1089.13, SD = 416.87), $p = .9$, and $p = .78$ respectively. In the updating phase however, the analysis showed a significant difference in the pointing latency and the hand preference, $F(2, 213) = 8.26$, $p < .001$, $\eta^2 = .07$. Left-handers (M = 3213.07, SD = 506.91) had significantly lower pointing latency than both the right-handers (M = 3801.45, SD = 569.37) and the mix-handers (M = 4115.7, SD = 711.28), $p = .001$ and $p = .002$ respectively. Finally, the analysis in the disorientation phase did not reveal any significant differences, $F(2, 213) = 1.84$, $p = .16$, $\eta^2 = .02$, despite the fact that mix-handers (M = 735.12, SD = 264.39) had overall numerically lower pointing latency than both the right- (M = 1300.39, SD = 772.63) and the left-handers (M = 1318.94, SD = 858.42), $p = .17$ and $p = 1$ respectively (Figure 15).

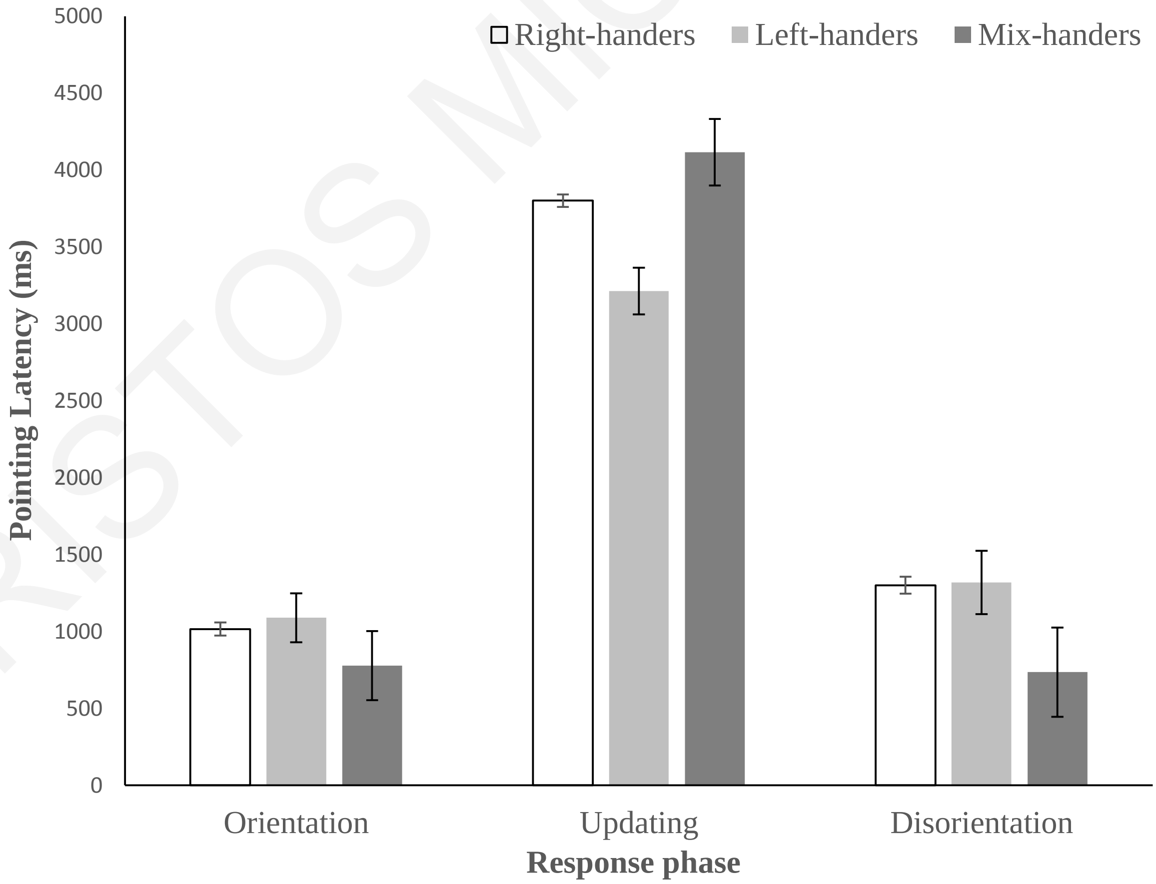


Figure 15. Pointing latency in the 3 response phases based on participant's handedness. Error bars represent standard errors of the mean.