University of Calgary

PRISM Repository **https://prism.ucalgary.ca**

The Vault Open Theses and Dissertations

2017

Development of topographical orientation skills in seven to ten year old children

Liu, Irene

Liu, I. (2017). Development of topographical orientation skills in seven to ten year old children (Doctoral thesis, University of Calgary, Calgary, Canada). Retrieved from https://prism.ucalgary.ca. doi:10.11575/PRISM/25692

http://hdl.handle.net/11023/3807

Downloaded from PRISM Repository, University of Calgary

UNIVERSITY OF CALGARY

Development of topographical orientation skills in seven to ten year old children

by

Irene Liu

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF DOCTOR OF PHILOSOPHY

GRADUATE PROGRAM IN CLINICAL PSYCHOLOGY

CALGARY, ALBERTA

MAY, 2017

© Irene Liu 2017

Abstract

In this dissertation, I investigated children's development of topographical orientation skills. Specifically, I examined children's performance on a navigation task in a virtual museum. In Chapter 2, I described the methodology used in this experiment. The computer task comprised of an interactive game that consisted of three sections: a practice motor task, a guided tour around a virtual museum, and a testing phase. After children were introduced to the environment, they were required to navigate from one location of the museum to a goal location as quickly as possible. Game performance was assessed by how much time and travel distance were required to reach a target location. In order to assess different cognitive domains supporting topographical orientation skills, a neuropsychological battery was administered. Finally, both children and parents completed self-rated questionnaires of the children's general spatial behaviours.

In Chapter 3, the main experimental results were described. Game performance was significantly correlated with age and several neuropsychological measures with emphasis on visual spatial processing. Game performance was also correlated with history of gaming experience and technology use. A multiple linear regression analysis revealed that game performance was best explained by performance on spatial working memory and visual-spatial organization tasks, once video game experience was accounted for. Only children's self-reported ratings of their spatial orientation and navigation skills were correlated with one of two measures of game performance, whereas parents' ratings were not. When compared to adult performance on the computer game, even the oldest group of children tested was still not as efficient as adults in solving the task, suggesting that development of topographical orientation skills continue well into adolescence and young adulthood.

Chapter 4 summarized and explored the aforementioned findings in greater detail. Additional statistical analyses and discussion regarding the pilot study, a group of children who participated in a repeat session of the computer game, and a group of younger children tested are described in Appendix B.

Acknowledgements

First and foremost, I would like to thank my supervisor, Dr. Giuseppe Iaria, for the continual guidance, support, and encouragement. Your care and kindness to me during my graduate studies will never be forgotten. Thank you to my supervisory committee members, Dr. Susan Graham and Dr. Frank MacMaster for your insightful comments, feedback, and support over the years. In addition, thank you to my examiners, Dr. Michelle Drefs and Dr. David Uttal for your participation in my defense.

I would like to extend a special thank you to all my current and past NeuroLab colleagues for their contributions to this project and support throughout my academic journey. I am incredibly grateful for all the knowledge I have gained from this bunch of young, bright academics.

To my husband, parents, family, and friends, thank you for your endless support and patience. To my husband, Han, I am very fortunate to have you beside me through every step (forwards and backwards) of this journey.

I am indebted to Alberta Innovates – Health Solutions for providing me with the financial support to make this research pursuit possible. Last but not least, I would like to thank all of the families involved in my research project that devoted their time and made this project possible.

Table of Contents

Abstract……ii

Acknowledgements……iv

Table of Contents……v

List of Tables…… viii

List of Figures……..…..ix

List of Abbreviations……..x

CHAPTER ONE: INTRODUCTION 1

1.1 Historical research approaches to studying development of spatial skills. 1

1.1.1 Eye gaze studies 3

1.1.2 Search behaviour studies 6

1.2 Spatial cognition and navigation in small scale environments 8

1.2.1 Modularity Theory 8

1.2.2 Adaptive Combination Theory 15

1.2.3 Spatial language 16

1.2.4 Maps and models 20

1.3 Spatial cognition and navigation in large scale environments 22

1.3.1 Cognitive maps of large spatial environments 23

1.3.2 Virtual environment studies of spatial navigation 25

1.4 Gender effects of spatial strategies 31

1.5 The current research study 32

CHAPTER TWO: METHODS 35

2.1 Methods 35

2.1.1 Participants 35
2.1.2 Data collection 37
2.1.3 Task Measures - Game 38
2.1.4 Neuropsychology tests 45
2.1.5 Questionnaires 48
2.2 Game performance measures 50
2.2.1 Time Efficiency 50
2.2.2 Distance Efficiency 51
2.3 Statistical analysis 51
CHAPTER THREE: RESULTS 53
3.1 Age and gender groups 53
3.2 Correlation between average time efficiency (ATE) and other measures. 69
3.3 Predictors of ATE with regression analysis 71
3.4 Comparison of ATE between children and adults 73
3.5 Correlation between average time efficiency (ADE) and other measures 75
3.6 Predictors of ADE with regression analysis 76
3.7 Comparison of ADE between children and adults 78
CHAPTER FOUR: DISCUSSION 79
4.1 Summary of main findings 79
4.1.1 Age differences of topographical orientation 79
4.1.2 Neuropsychological performance 80
4.1.3 Video game experience 81
4.1.4 Psychosocial factors 82

4.1.5 Gender differences 86

4.2 Theoretical considerations 87

4.3 Limitations and future directions 89

4.4 General conclusions 90

Bibliography…….…….93

Appendix A1: Parent Adapted Santa Barbara Sense of Direction Scale (SBSOD-P) ……116

Appendix A2: Child Adapted Santa Barbara Sense of Direction Scale (SBSOD-C) …….119

Appendix A3: ADHD Rating Scale……..……...122

Appendix A4: Additional parental questionnaire items…..……..……...126

Appendix B: Supplementary methods and data analysis……...……..……....134

List of Tables

Table 1: Testing phase trial order. 43

Table 2: Characteristics of final sample by age and gender groups. 53

Table 3: Mean ATE scores for each group. 54

Table 4: Mean ADE scores for each group. 55

Table 5: Vocabulary Performance 56

Table 6: Block Design Performance 57

Table 7: Digit Span Performance 58

Table 8: Cancellation Performance 59

Table 9: Children's Color Trail Test – Part 1 Performance 60

Table 10: Children's Color Trail Test – Part 2 Performance 61

Table 11: Spatial Span – Forward Performance 62

Table 12: Spatial Span – Backward Performance 63

Table 13: Hooper Visual Organization Test Performance 64

Table 14: Road Map Test – Time Performance 65

Table 15: Road Map Test – Error Performance 66

Table 16: Santa Barbara Sense of Direction Scale – Parent Report 67

Table 17: Santa Barbara Sense of Direction Scale – Children Report 68

Table 18: ADHD-Rating Scale – Parent Report 69

Table 19: Multiple regression of game experience and cognitive variables on ATE 72

Table 20: Multiple regression of game experience and cognitive variables on ADE 77

List of Figures

Figure 1: Experimental paradigm used in Acredolo's series of eye gaze coding studies. 4

Figure 2: Illustration of a hypothetical experimental space in reorientation studies.. 10

Figure 3: Square enclosure with scalar cues (From Huttenlocher & Lourenco, 2007). 12

Figure 4: Schematic representation of the experimental set up (from Huan *et al*., 2011). 19

Figure 5: Snap-shot and schematic overview of the virtual environment (from Jansen-Osmann & Wiedenbauer, 2004a). 27

Figure 6: Flowchart of participant recruitment and attrition.. 36

Figure 7: Schematic view of the virtual museum environments..... 39

Figure 8: Practice phase that involved following a pathway of dinosaur footprints. 41

Figure 9: An example of a trial during the testing phase.. 44

Figure 10: Comparison of game performance between age groups, as assessed byATE. 74

List of Abbreviations

ADE	Average Distance Efficiency
ADHD-RS	ADHD Rating Scale
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
ATE	Average Time Efficiency
BD	The Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV) – Block Design subtest
CA	The Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV) – Cancellation subtest
CCTT-1	Children's Color Trail Test - Trial 1
CCTT-2	Children's Color Trail Test - Trial 2
DS	The Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV) – Digit Span subtest
HD	Heading direction
HVOT	Hooper Visual Organization Test (HVOT)
RMT	The Standardized Road-Map Test of Direction Sense
SBSOD-C	Santa Barbara Sense of Direction Scale – Children version
SBSOD-P	Santa Barbara Sense of Direction Scale – Parent version
SSB	Wechsler Memory Scale – Third Edition (WMS-III) - Spatial Span subtest – Backward
SSF	Wechsler Memory Scale – Third Edition (WMS-III) - Spatial Span subtest – Forward

VC	The Wechsler Intelligence Scale for Children – Fourth Edition (WISC IV) – Vocabulary subtest
WISC	The Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV)

Chapter One: Introduction

1.1 Historical research approaches to studying development of spatial skills.

In 1948, Edward Tolman introduced the concept of *cognitive maps* (i.e., map-like mental representations of the environment) through a series of animal maze studies on latent learning. The rats in Tolman's studies capitalized on previously unexplored shortcuts in order to quickly reach goal locations and thereby illustrated that they had processed the spatial maze environments beyond simple stimulus-response type of learning. Following Tolman's seminal work, there has been a flurry of research interest aimed at understanding spatial mental representation of the environment in humans. One particularly intriguing question is how humans acquire the ability to form and use cognitive maps, the most complex and efficient strategy of topographical orientation (Wang and Spelke, 2002). Topographical orientation refers to the ability of individuals to situate themselves within a large scale environment, enabling navigation through the environment (Gallistel, 1990; Dudchenko, 2010**;** Wang & Spelke, 2002).

Similar to animal researchers, developmental researchers have long recognized the utility of carefully designed spatial environments to help understand how children mentally represent space in order to guide goal-directed behaviors (Maier, 1936). Past researchers were particularly struck by the finding that human infants demonstrate opposite results from Tolman's rats. While rats are capable of learning spatial relationships, infants are more inclined to use response-based learning (e.g., relying on body turns) and ignore external spatial cues (Bremner, 1978; Acredolo, 1978). Evidently, the ability to form and use cognitive maps is complex and does not emerge until later in childhood. Researchers began to attempt to delineate the underlying developmental processes and spatial-related skills necessary for cognitive map abilities.

Following the scientific revolution of cognitive psychology in the 1950s (Hyman, 2014), the field of developmental psychology was widely influenced by Swiss cognitive theorist, Jean Piaget's (1954) stage theories of cognitive development and developmental researchers interested in topographical orientation were no exception (Acredolo, 1990). Of specific relevance to spatial researchers is Piaget's identification of the *stage IV error,* also referred to as the *A-not-B error*. During the fourth sub-stage of the sensorimotor developmental stage (birth to 2 years), infants with limited concept of object permanence often make a common search error. Infants who repeatedly learn to find a toy in one hiding place then see it hidden in another location make a perseveration error by looking for the toy in the previous spot.

Piaget argued that infants who make the stage IV error code the location of the hidden toy in terms of past accommodations of their own actions of searching for the toy in the first hiding spot. He believed that acquisition of object permanence is a gradual process and related to the ability to create symbolic representations of experiences and environments. Furthermore, Piaget and Inhelder (1948 / 1967) described a gradual transition from *topological* to *projective* to *Euclidean* systems of spatial coding. However, the timeline of the stage IV error and what it truly reflects about the nature and content of infants' representation of objects and space remain controversial to date (Wellman, Cross, Bartsch, & Harris, 1986; Diamond, Cruttenden, & Neiderman, 1994; Smith, Thelen, Titzer, & McLin, 1999).

During the 1970s and early 1980s, spatial researchers adapted the Piagetian stage IV task to investigate how the concept of space evolves through childhood. The general aim was to shed light on the developmental progression from an "egocentric" child who is limited to self-reference perspectives to an individual capable of understanding of spatial relationships relative to external frameworks. Egocentric spatial representation codes objects relative to the self,

whereas allocentric spatial representation refers to coding of object locations relative to another object (Burgess, 2006; Ekstrom, Arnold, & Iaria, 2014; Wang & Spelke, 2002). Based on the stage IV phenomenon, two important lines of spatial development research began to set the groundwork for understanding the egocentric-to-allocentric shift in spatial representation in children: eye gaze studies and search behaviour studies.

Historically, egocentric strategies were also termed "sensorimotor" or "response" learning, whereas non-egocentric strategies were classified as "allocentric", "objective", "cue", or "place" responding. Unfortunately, ambiguous terminology in the literature has lead some to mistaken these terms as interchangeable when in fact they are not. For example, cue learning involves simple associations with landmarks but place learning codes location by distance and direction from distal landmarks (O'Keefe, Nadel, Keightley, & Kill, 1975; Whishaw & Kolb, 1984; Vasilyeva & Lourenco, 2012). The unclear distinction between types of spatial strategies and general lack of agreement in terminology in previous research studies has made it challenging to integrate past research in a cohesive manner. Henceforth, the terms *egocentric* and *non-egocentric* are used to describe types of responses that involve or do not involve the self as the sole spatial reference point, respectively.

1.1.1 Eye gaze studies

A common challenge that child researchers face is to develop methods to assess cognitive processes in young subjects with undeveloped abilities to respond through fine motor behaviors (e.g., pointing) and/or language. In research studies that involve young infants, eye gaze measurement serves as a helpful proxy of spatial information processing. Acredolo (1978) described a series of longitudinal eye gaze studies that examined spatial coding in 6 to 16 months old children. The basic paradigm (Figure 1.1) of these initial studies was that infants learned a

cued event (e.g., an experimenter suddenly appeared after a buzzer sound) that always occurred at one side (i.e., right or left window) of an otherwise featureless square room. Afterwards, the subjects were rotated 180 degrees along a semicircular path. When the buzzer sounded again, the direction of the infants' subsequent eye gaze was presumed to indicate where infants anticipated the event to occur.

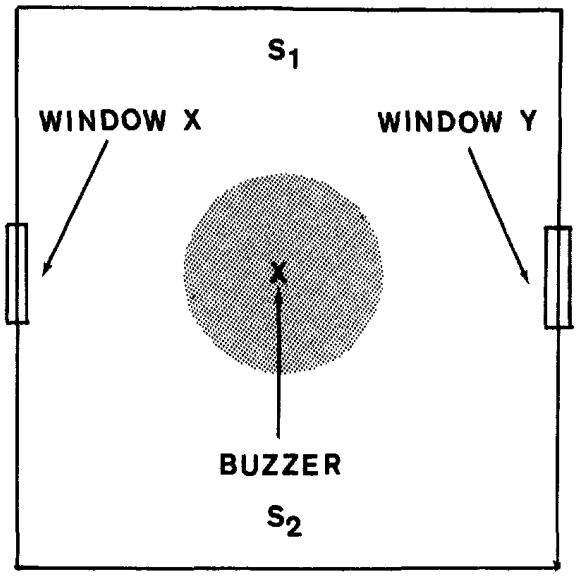

Figure 1. Experimental paradigm used in Acredolo's series of eye gaze coding studies (from Acredolo, 1978).

The results of these initial studies revealed that younger infants tend to rely on egocentric strategies and look at the same side of their bodies as during the initial learning phase. That is, younger children who learn that an experimenter would appear on their right side after a buzzer would gaze towards the right side, despite being moved 180 degrees. As infants mature, there is a reduction in reliance of egocentric responses and greater preference for non-egocentric

strategies that take into account any changes in one's position (Acredolo, 1978; Cornell & Heth, 1979).

It may be possible that infants have greater coding capacity than what is suggested by their high degree of egocentric strategies. As described by Acredolo, Adams, and Goodwyn (1984), incorporation of landmarks helps promote a mix of egocentric and non-egocentric strategies, as well as predominantly non-egocentric type of responses. Adaptations to Acredolo's classic research paradigm have also been useful for demonstrating the facilitative effects of landmarks (Acredolo, 1978; Acredolo & Evans, 1980; Rieser, 1979) and geometric outlines of the spatial environment (Keating, McKenzie, & Day, 1986). Acredolo and Evans (1980) argued that by around nine months old, infants switch to more consistent use of landmarks. Further, 11 months old infants gain the ability to use distal landmark information to indicate irrelevant locations during visual search (Acredolo & Evans, 1980). There appears to be a qualitative transition characterized by a reduction of reliance of egocentric information and an increase of salience of external spatial information, such as important landmarks. As a result of these studies, a theory of spatial development emerged, outlining the order of prominence from an egocentric response based system to the use of single landmarks and, finally, to "map-like" representations (Acredolo, 1990).

While egocentric responses are predominant in infants six months or younger, an egocentric system becomes insufficient at tracking one's location when the infants become independently mobile through crawling or walking (Acredolo, 1990; Keating *et al*., 1986). Acredolo and colleagues (1984) found that 12-month-old infants visually track the target as they move around, taking into account changes in their own position and paying greater attention to relevant environmental information. However, if their view of the target is disrupted, infants tend

to revert to egocentric responses. In contrast, an older group of 18-month-old infants no longer requires continuous visual tracking because they are capable of mentally tracking their positions. As one begins to internally track and predict the consequences of one's own movements, continuous visual tracking is no longer necessary to maintain changes in perspectives.

Following this line of work, some researchers have also proposed that emergence of self-produced locomotion has a facilitative effect on non-egocentric strategies (Bertenthal, Campos, & Barrett, 1984; Bertenthal & Campos, 1990; Thelen & Smith, 1994). Others also have highlighted parallel advancements between motor development (e.g., learning to crawl and walk) and adoption of non-egocentric strategies (Acredolo, 1978; Bremner & Bryant, 1977), with the concurrent emergence of visual tracking playing a particularly key role (Acredolo *et al*., 1984).

1.1.2 Search behaviour studies

A second similar class of early studies attempted to clarify the egocentric-to-allocentric shift by having infants search for a hidden object in one of two possible locations on a table top. In Bremner and Bryant's (1977) initial paradigm, nine month olds learned that a toy could be found in a hiding spot either on the right or left side of the infants' body. The infants were then moved to the opposite side of the table and allowed to search for the toy. Infants frequently searched for the toy in the old hiding position, which suggests egocentric coding of the toy's location. Other researchers (Gratch & Landers, 1971; Evans & Gratch, 1972; Bower & Paterson, 1972; Harris, 1973; Gratch, Appel, Evans, LeCompte, & Wright, 1974) have replicated the finding that infants tend to perseverate with egocentric search strategies, despite changes in movement and location.

Bremner & Bryant (1977) found strong persistence of egocentric responding even when the two hiding positions are differentiated (e.g., the hiding spots are painted in different colours).

However, if the salience of colour cues is especially enhanced, there is a drop in egocentric strategies, indicating that young infants are capable of using very salient external spatial cues to define spatial locations (Bremner & Bryant, 1978; Bremner, 1978).

Although still highly debated, some have hypothesized that the stage IV error involves a memory component. Longer delays between a child seeing an object being hidden and being able to retrieve it is related to poorer search performance (Gratch & Landers, 1971; Harris, 1973). On the other hand, it has been observed that this pattern of errors occurs even when the objects are hidden in plain view, with very little demand on memory processes (Harris, 1974). Nonetheless, the general agreement is that response learning precedes other types of spatial response systems during development, though infants show evidence of preliminary cue learning and a shift towards non-egocentric strategies within the first year of life.

It is important to highlight that infants could correctly respond in these early studies based on more than one type of spatial coding (Newcombe & Huttenlocher, 2000). For example, infants could use cue learning, place learning, dead reckoning, or some combination of these strategies to respond successfully. Dead reckoning, also known as *path integration* or *inertial navigation,* involves continual integration of self-motion information (Mittelstaedt & Mittelstaedt, 1982; Loomis, Klatzky, & Golledge, 2001) and is a type of self-referenced spatial strategy (Newcombe & Huttenlocher, 2000). Dead reckoning may be available in human infants even before 16 months (Newcombe, Huttenlocher, Drummey, & Wilely, 1998). While early studies hint at the existence of a sweeping egocentric-to-allocentric shift, it is also possible that infants choose between different spatial coding systems based on their limited experience with the spatial world. Specifically, they choose what available information to rely on when there are conflicts between coexisting coding systems. Over time, infants experience trial and error within

the environment and use this feedback to help reweigh the relative importance attached to each spatial coding system (Newcombe & Huttenlocher, 2000).

Although earlier research studies that examined the stage IV error have contributed much to our knowledge of early spatial learning, the narrow age groups and issues with methodology limit what conclusions can be drawn from the results. More recent research has examined development of topographical orientation in a variety of small and large scale environments and age groups. As there are no formal distinctions in the literature between large and small-scale environments, this overview classifies small scale environments as those that could be theoretically surveyed from a single location point. Examples of small scale environments include varying sizes of small arenas, rooms, and sandboxes. By comparison, large scale environments require a navigational component to fully explore.

1.2 Spatial cognition and navigation in small scale environments

1.2.1 Modularity Theory

One of the most extensively researched areas in topographical orientation development pertains to reorientation studies. In a seminal study by Hermer and Spelke (1994), it was found that 18 to 24 months old children exclusively rely on geometric properties (the shape of an environment) for reorientation. Following disorientation, young children's search patterns are similar to that of rats employing a geometric module (Cheng, 1986; Margules & Gallistel, 1988; Biegler & Morris, 1993). In the classic paradigm (Hermer & Spelke, 1994), subjects view an object being hidden in a corner of a rectangular shaped room then undergoes a disorientation task by spinning around several revolutions with their eyes closed. Disorientation prevents subjects from maintaining continual tracking of the target location relative to the self. During

reorientation, children often search for the hidden object in either the correct corner or the rotationally equivalent corner (i.e., 180 degrees opposite of the correct one), similar to adult search patterns. Children are capable of forming a representation of the room that preserves the room's metric properties and retain information regarding room geometry despite distraction from disorientation (Hermer & Spelke, 1994; Hermer & Spelke, 1996).

Other studies have also found that geometric information is used to locate target objects when young children are in spaces of different shapes (Hutterlocher & Vasilyeva, 2003; Lourenco & Huttenlocher, 2006; Lourenco, Huttenlocher, & Vasilyeva, 2005), outside of enclosed spaces (Hutttenlocher & Vasilyeva, 2003), and following different types of disorientation – being moved or seeing the space moved (Lourenco & Huttenlocher, 2006). Sensitivity to geometric information likely emerges quite early in infancy, with one study estimating as early as five and a half months old (Lourenco & Huttenlocher, 2008).

Developmental differences between adults and children become quickly apparent when a blue wall is introduced to an otherwise landmark-free environment (Hermer & Spelke, 1994; Hermer & Spelke, 1996; see Figure 2). The coloured wall acts as a *non-geometric* or *featural* cue of the environmental space. Adults are able to reorient and chose the correct corner at a significantly higher rate then its rotational equivalent, indicating that adults are able to benefit from the additional cue. By comparison, children appear sensitive to room geometry but they are less capable of using non-geometric properties of the environment to aid with spatial reorientation. The authors found that increasing the salience of non-geometric spatial cues (e.g., directing children's attention to coloured walls, using toys as additional featural spatial cues, and using distinctly coloured and textured containers to hold the hidden object) fails to help reorientation performance in children (Hermer & Spelke, 1996; Wang, Hermer, & Spelke, 2002).

Hermer and colleagues have interpreted these findings as a result of an innate "geometric module", an encapsulated shape-based reorientation mechanism that children rely on. It has been proposed that the initial modularity in infants is overcome by later spatial language acquisition (Hermer & Spelke, 1996; Hermer-Vazquez, Moffet, & Munkholm, 2001). Mature spatial reorientation processes allow both geometric and non-geometric information to be used (Hermer & Spelke, 1994; Hermer & Spelke, 1996).

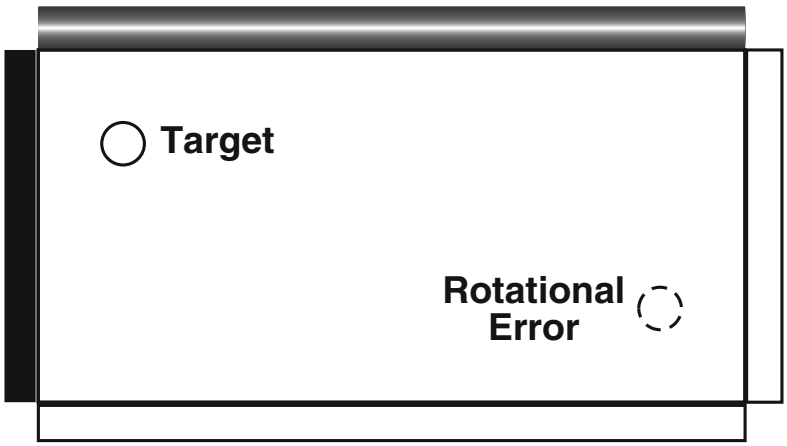

Figure 1. Illustration of a hypothetical experimental space used to investigate the geometric module in reorientation studies. The rectangular layout provides geometric cues of the room, while distinct walls are indicated by different fill patterns in order to provide non-geometric cues (From Cheng, Huttenlocher, & Newcombe, 2013).

There are evolutionary arguments as to why sensitivity to geometric information in the natural environment would be adaptive (Gallistel, 1990). However, not all distinctive geometric properties guide reorientation in children, noting that four year olds are able to use shapes of an array of detached walls for reorientation but not geometric configurations of detached objects or corners (Gouteux & Spelke, 2001; Lew, Foster, & Bremner, 2006) or angles in rhombic shaped

enclosures (Hupbach & Nadel, 2005). The vertical dimension of height information (e.g., slanted ceilings) is also not used as early as other geometric cues (Hu, Zhang, Wu, & Shao, 2015). Some have argued that children adaptively depend on arrangements of walls but not arrangements of objects because walls are stable and unmovable landmarks, unlike other features of the environment that are more likely to change over time (Learmonth, Newcombe, & Huttenlocher, 2001; Newcombe & Ratliff, 2007; Lee & Spelke, 2008). A key factor may be the perceived functional relevance of environmental properties to provide unique, stable, and enduring information to navigators (Lee & Spelke, 2008). However, it has been found that geometric processes are involved only when the experimental enclosures are symmetrical (Lew, Gibbons, Murphy, & Bremner, 2010). This contradicts the functional argument for the viability of the geometric module hypothesis as a mechanism for reorientation in natural environments because there are often ambiguous, asymmetrical geometry in natural environments.

There are arguments against the broad claims of a "pure" encapsulated geometric model that is impenetrable to non-geometric information (Hupbach & Nadel, 2005; Learmonth, Newcombe, & Huttenlocher, 2001; Learmonth, Nadel, & Newcombe, 2002; Leathmonth, Newcombe, Sheridan, & Jones, 2008; Cheng & Newcombe, 2005; Cheng *et al*., 2013; Nardini, Atkinson, & Burgess, 2008). In particular, contradicting studies have revealed that toddlers as young as two are successful at combining geometric features of a room with spatial information from non-geometric landmarks (e.g., discrete objects and coloured walls) when the experimental room is large (Learmonth *et al*., 2001; Learmonth *et al*., 2002). The authors theorized that a larger space with stable landmarks would engage the spatial orientation system differently than a smaller space in which infants can encode the overall shape from a single viewing position. For infants, the size of space is a key determinant of whether featural cues are used (Cheng &

Newcombe, 2005). Another example of when non-geometric features are successfully employed in reorientation tasks is children's ability to use scalar cues (e.g., dots on walls of different sizes; Figure 3) in square enclosures without geometric cues (Huttenlocher & Lourenco, 2007; Lourenco, Addy, & Huttenlocher, 2009). These studies undermine the encapsulated model's claims that geometric cues are the only necessary cues for reorientation.

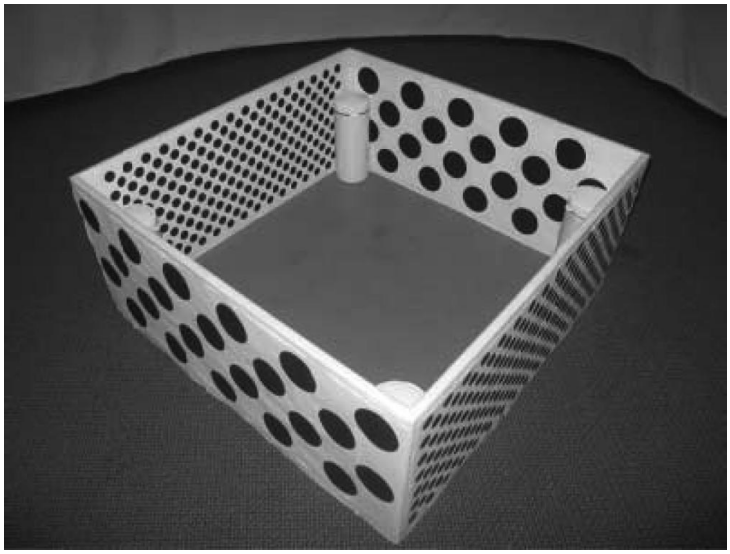

Figure 2. Square enclosure with different size circles as scalar cues (From Huttenlocher & Lourenco, 2007).

Further evidence against the encapsulated geometric module stems from animal studies. The geometric module cannot fully explain why disoriented rats are able to use a non-geometric landmark with very little training to find a hidden escape platform, a contradictory result from their reliance on geometric cues to locate hidden food (Dudchenko, Goodridge, Seiterle, & Taube, 1997; Martin, Harley, Smith, Hoyes, & Hayes, 1997). Also, neurophysiological studies of place and heading direction (HD) cell system suggest that non-geometric cues for a rat's position

and heading are used to help the system "reorient itself" (O'Keefe & Nadel, 1978; Knierim, Kudrimoti, McNaughton, 1995). Rat heading cell activity in accord to non-geometric cues is even noted in the same environments in which rats behaviourally fail to use these cues (Dudchenko *et al*., 1997), though it may be possible that place and HD cells capture richer environmental information than rats typically use during reorientation (Wang *et al*., 1999).

To address these concerns, Lee, Shusterman, and Spelke (2006) proposed two distinct systems of spatial information processing in young children. According to these authors, only geometric information of the surrounding surface layout is used in a true reorientation stage, known as a modular reorientation process. In a separate associative process, non-geometric information is used to associate links between landmarks and locations. This latter stage is not considered reorientation as only one location is learned with a response and this can occur in the absence of directional headings or sense relations (Lee *et al*., 2006).

The modularity model has been recently reconceptualized (Lee & Spelke, 2010a; Lee & Spelke, 2010b). The authors outlined a series of studies revealing children often having problems with using geometric arrays of isolated landmarks (objects). When the objects are flushed against the enclosing walls of a circular arena, however, children are able to successfully interpret the surface geometry of the landmarks for reorientation. Thus, the authors proposed two separate systems supporting one's ability to reorient and find a hidden object after a loss of bearings: a reorientation process based on the geometry of the 3-dimensional surface layout, and the other, a landmark system representing a beacon-guidance process based on the local features. They proposed that a full Euclidian geometry of the environment is constructed by a combination of the innate geometric module and the acquired landmark system. The geometric module is thought to contain information regarding distance and direction, but corner angle and surface

length are captured by the landmark system (Lee, Sovrano, & Spelke, 2012). Lee and Spelke's rebuttal (2011) also classifies scalar cues as geometric cues that would engage in the innate geometric module.

Nonetheless, the modified geometric modularity theory continues to face challenges from critiques. Recent research has found that infants can reorient with cues that are non-geometric and non-scalar in nature. In particular, several studies examining spatial coding in young children found results in contradiction with the two separate process view of the modularity theory. The first one by Newcombe, Ratliff, Shallcross, and Twyman (2010) was conducted in an octagonal room, one that lacks a single axis of symmetry. The addition of a coloured wall to this octagonal environment leads to three geometrically congruent but unmarked corners. The above-chance performance in three- and five-year-olds on a disoriented search task demonstrates that the young children integrate the wall as a cue for the hidden object in a fashion that is beyond simple associative processing. Children are able to incorporate the marked coloured wall to help them differentiate characteristics between different corners of a symmetrical geometric outline.

Another study by Nardini, Atkinson, and Burgess (2008) also showed that disoriented children between the ages of 18 to 24 months are able to orient successfully on the basis of wall colour. In a small square enclosure with distinct walls (two blue and two white walls), children are able to successfully use colours combined with left and right judgments, in relation to landmarks nearby. Therefore, the authors argued that perhaps young children's lack of use for non-geometric cues in earlier studies was due to a poor use of colour brightness. It is suggested that if spatial cues are above a certain salience threshold, young children can use these cues as additional information to guide their reorientation process. Children are also able to use large stable feature cues that form an equilateral triangle, supporting use of features in true

reorientation (Twyman, Newcombe, & Gould, 2013). These results contradicted the findings from earlier work (Lee *et al., 2006)*.

The studies argue against the view that there are separate spatial coding systems that succeed one another during child development. Instead, issues with test paradigms failing to tap into allocentric spatial coding of young children may have led to a premature conclusion that an egocentric sensorimotor individual gains allocentric spatial coding capacities only once he or she is independently locomotive. It may be possible that both systems are available to young children, but the likelihood of relying on one over the other depends on previous experience and salience of spatial cues within the environment. Eventually, mature spatial coding consists of a state of optimal weighing and coordination with response systems (Newcombe & Huttenlocher, 2000).

1.2.2 Adaptive Combination Theory

The adaptive combination theory is an alternative theory proposed by Newcombe and Huttenlocher (2006). As opposed to the modularity theory, both geometric and non-geometric cues can be used for orientation by a combination of cue weights. Multiple factors influence the determination of cue weights, such as perceptual salience, reliability of memory traces, and cue validity given prior experiences. These weights are then combined following Bayesian rules (Newcombe & Huttenlocher, 2006; Newcombe & Ratliff, 2007). A child learns to expect different kinds of spatial information to provide varying degrees of informative utility based on his or her prior history. For example, a child beginning to walk learns to pay more attention to distal landmarks during navigation in large spaces because objects visible from afar tend to be large, immovable, and stable sources of information (Nadel & Hupbach, 2006). As the child

develops, he or she performs continual updates to the assignment of relative weights to geometric and featural cues (Cheng *et al*., 2013).

In support of the adaptive combination theory, when feature cues and geometric cues are pitted to provide contradictory information, learning history is a strong determinant of cue weights assignment. Ratliff and Newcombe (2008) found that adults favor geometric cues in a small room but featural cues in a large room. In addition, adults who are trained in a large room overwhelmingly chose to rely on featural cues in a smaller space, a direct contradiction of the modularity claim. In another study, featural cues have been found to enhance children's representation of a kite-shaped space during a reorientation task, suggesting a potentiation effect of featural information to increase encoding of a geometric layout (Lourenco & Cabrera, 2015). Future research endeavors will need to quantitatively operationalize the adaptive combination theory for more rigorous analysis of whether the model can fully explain cue competitions and age-related changes in the neural correlates supporting navigation (Cheng *et al*., 2013).

1.2.3 Spatial language

Spatial terms are acquired around the second year of life (Newcombe & Huttenlocher, 2000). Comprehension of the terms "in", "on", "under", "up" and "down" are first acquired, followed by terminology indicating proximity (e.g., "beside") then terms indicating frame of reference (e.g., "in front of"). One of the last concepts children acquire relates to "left" and "right", a more complex linguistic coding skill (Newcombe &Huttenlocher, 2000). As an explanation for the discrepant findings in the coding studies, language has been proposed as a key factor that can influence a shift from geometric to landmark based spatial coding systems (Shusterman, Lee, & Spelke, 2011; Hermer-Vazquez *et al*., 2001; Hermer-Vazquez, Spelke, & Katsnelson, 1999; Pyers *et al*., 2010). It has been speculated that the transition to mature

reorientation performance occurs around five to seven years of age and depends on developmental changes in spatial language (Hermer-Vazquez *et al*., 2001). The productive use of language phrases such as "left of X" and "right of X" is related to children's success rates on disorientation search tasks (Hermer-Vazquez *et al*., 2001; Shusterman & Spelke, 2005) and their ability to represent left / right relation in visual memory (Dessalegn & Landau, 2008).

Shusterman and colleagues (2011) tested whether verbal expressions can significantly alter the encoding of spatial environments in four-year-old children performing a disorientation search task in a small rectangular room with a red wall as a distinct landmark. In the control condition, no verbal cues were given as the children watched the experimenter hide the toy. In the second condition, the experimenter provided a cue in the form of a spatial expression ("I'm hiding it at the red wall") in order to see if this cue would aid the relocation of the toy. The third condition consisted of a non-spatial but task relevant expression ("The red wall can help you get the sticker"). And finally, the last condition drew attention to the red wall without the use of any spatial language ("Look at the pretty red wall! I'm hiding it over here!").

A major conclusion from this study was that spatial expressions do help children increase their search performance, while simply drawing attention to the landmark does not. Language, especially linguistic expressions with reference to spatial relationships, serves as a guiding mechanism for children to process the landmarks as reference objects. Language can direct children to think about their spatial environments spontaneously in multiple ways (Shusterman *et al*., 2011). In the same vein, the ability of children to step away from mainly relying on room geometry and start emphasizing landmarks for reorientation is related to their ability to comprehend and produce the words 'left' and 'right' (Hermer-Vazquez *et al*., 1999).

Cross-cultural research also suggests a correlation between spatial memory and dominant language expressions of spatial relations (Haun, Rapold, Janzen, & Levinson, 2011). In a comparison study of Dutch and Namibian elementary children on an array reconstruction task, subjects viewed an array of objects then moved to another perspective (i.e., a different side of a school building) before they reconstructed the array of toys from memory. The Dutch language predominantly uses relative left/right descriptions, while Namibian children are familiarized with absolute cardinal (north, east, south, west) descriptions. Task complexity and whether or not instructions specified a particular cognitive strategy were manipulated in this series of experiments. There were four possible responses based on: egocentric processing (maintained spatial relations relative to own viewpoint), object-centered processing (used spatial relations of the objects to the local landmark of the school building), geocentric processing (maintained cardinal directions), or other strategies that did not use any of the three aforementioned types of spatial processing (Figure 4).

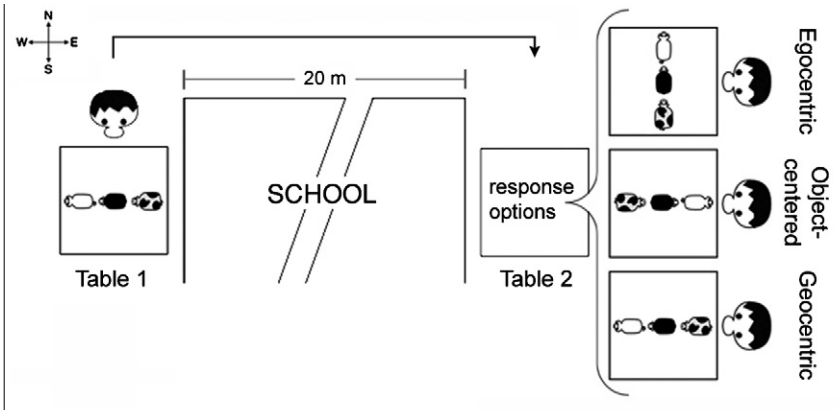

Figure 3. Schematic representation of the experimental set up (from Huan *et al*., 2011). There were three distinguishable frames of references (egocentric, object-centered, and geocentric) as possible response options.

Huan and colleagues (2011) discovered a strong correlation between the dominant linguistic strategy in the native languages and the preferred cognitive spatial strategy. This effect is fully robust by the age of eight. In addition, there appears to be no underlying common frame of reference as the cross-linguistic differences are stable across various levels of task difficulty. If children are instructed to use a non-habitual technique to solve the problem, they face a significant switch-cost to their performances. In summary, language has a powerful influence over both preference and competence for different ways of processing spatial information. The preferential choice for a particular frame of reference in language and cognition is influenced by ecological and cultural factors in given populations (Mishra, Dasen, & Niraula, 2003; Mishra, Singh, & Dasen, 2009).

Language may support spatial development by serving as a medium for combining information from domain specific reasoning systems (Spelke, 2003; Carruthers, 2005). Language may also serve to effectively guide one's attention to relevant landmarks and improve memory of

landmark associations (Shusterman *et al*., 2011). There are age-related developmental differences in acquisition of spatial information from verbal spatial descriptions (Uttal, Fisher, & Taylor, 2006). On the flip side, deprivation of a natural specific language during child development is likely detrimental to the ability to quickly and flexibly integrate geometrical and landmark cues (Hyde, Winkler-Rhoades, Lee, Izard, Shapiro, & Spelke, 2011). Of interest, one study with older school aged children (9 to 10 year olds) revealed that verbal abilities do not correlate with wayfinding performance within a college campus, suggesting that representational abilities during navigation may recruit more visual spatial skills and other cognitive processes later in development (Fenner, Heathcote, & Jerrams-Smith, 2000).

1.2.4 Maps and models

Another type of symbolic processing relates to maps and models of spatial environments. While both maps and models represent the spatial relations among objects, there is a clear contrast in that they differ along several dimensions. A typical map is two-dimensional and uses arbitrary symbolic relations. In contrast, a typical model is three dimensional, symbolizes objects using small-scale replicas with a strong iconic resemblance to the objects they represent, and entails less radical scaling as the areas represented by models are usually smaller than maps (Newcombe & Huttenlocher, 2000).

It appears that children as young as three can recognize the correspondence between iconic representations and real-world counterparts (Dalke, 1998). Further, this age group is able to use simple maps to code location along a single dimension of a larger actual space, an indication of early emergence of distance coding and scaling abilities (Huttenlocher, Newcombe, & Vasilyeva, 1999). Children's representational skills develop gradually and they become better at interpreting arbitrary relationships over time. At around six years old, children are effective at

using arbitrary pairings of symbols of locations in order to represent their locations and locations of target objects (Presson, 1982).

Stea and colleagues (2004) investigated the ability of preschool children to use an aerial view map as an aid for finding a hidden object. As the map in the experiment was not oblique, representations of objects did not match the shapes or angular relations as from the child's perspective. Therefore, it was presumed that successful application of the map to solve the spatial tasks required the abilities to mentally rotate to the vertical, scale the relational information from the map to the real-environment, and convert information from three to two dimensions and vice versa. Children three and five years of age are able to use a two-dimensional planar scale map without prior instructions. The results suggest that these capacities are apparent at young ages.

Uttal and Wellman (1989) found that children as young as four years old benefit from maps in guiding simple navigation. However, children are limited to using maps with low levels of symbolic complexity and maps with low or no demands on alignment and scaling. In addition, the authors showed children routes on maps, which did not require the complex capacity to plan or compare routes. It has been proposed (Uttal, 2000; Davis & Uttal, 2007) that the use of maps facilitates the acquisition of abstract concepts of space and the ability to think systematically about spatial relations that children have not experienced directly.

With regards to the research in capacity to use spatial models, an early study by Deloache (1987) first reported that rapid developmental differences in the use of models to find hidden objects are seen between two and a half years and three years. She found that younger children fail to appreciate the clue of seeing an object hidden under the couch of a representative model of a living room in order to locate the hidden object in the associated larger actual space. Similarly,

younger children struggle to properly indicate the location of the hidden object in a larger space on a smaller model. Although the children's linking of model objects to their larger counterparts is not an all or none phenomenon, there is significant improvement in understanding of spatial models by the age of three.

Huttenlocher, Vasilyeva, Newcombe, and Duffy (2008) examined whether early spatial scaling abilities found in map studies extend to models. In their study, three- and four-year-old toddlers were shown a hidden location of a disc in a model sandbox and then asked to find the corresponding location in a large life-sized sandbox. In order to investigate the differences between searching for object relocation and placement, a second part of the study required children to place the disc in the large sandbox at the location according to the model sandbox. As expected, the older children (four year-olds) significantly outperformed younger children (three and three and a half years old) in the retrieval task, consistent with earlier findings (Huttenlocher, Newcombe, & Vasilyeva, 1999). The age at which children can carry out scaling along a single dimension appears to be around four years. On the placement task, three years old children performed significantly worse than the three and a half and four years old children, suggesting that placements skills emerge approximately half a year earlier than retrieval abilities during development. It should be pointed out that the authors only investigated one-dimensional scaling. As a result, future studies need to assess how children use two- or three-dimensional models.

1.3 Spatial cognition and navigation in large scale environments

Large scale environment studies are generally characterized by using a larger laboratory or real world environment in which the entire environmental space is not perceivable from any single viewpoint. Large scale environments are especially useful for understanding children's use of different strategies and cognitive skills that are critical to spatial orientation during navigation.

For example, in order to understand route knowledge, there must be sufficient space for a child to move and explore his or her surroundings before spatial knowledge of the routes can be assessed. Earlier wayfinding studies have found that children as young as three years can be assessed on their ability to learn an environment through choosing pictures or videos of the correct pathways, placing pictures of the pathway in temporal order, drawing a map of the pathway, or verbally describing a pathway (Cornell & Hay, 1984; Cornell, Heth, & Broda 1989; Cornell, Heth, & Rowat 1992; Cousins, Siegel, & Maxwell, 1983; Darvizeh & Spencer, 1984; Spencer & Darvizeh, 1981).

1.3.1 Cognitive maps of large spatial environments

Siegel and White (1975) argued that spatial representation in children is first landmark oriented. Children first use landmarks to navigate, then construct routes linking landmarks (spatial mini-maps), and finally, integrate routes in an overall framework or spatial representation comprised of a cohesive internal model for navigation (Siegel & White, 1975). The final mental representation allows children to use an observer-independent relational orientation strategy that is allocentric in nature.

While it is difficult to directly assess the quality of a cognitive map, knowledge of environmental landmarks, routes or procedural knowledge, and survey knowledge serve as good indicators. Accumulation of experience with large scale environments contributes to the enrichment of cognitive maps. Cousins *et al*., (1983) showed that children as young as seven are very competent on wayfinding tasks within their own school campus. In this experiment, seven, fourth, and first graders attended the same school and had varying levels of exposure to the certain areas of the campus grounds. In order words, some children had more exposure and familiarity with certain areas than others depending on their grade level. Almost all children in

this study showed sophisticated knowledge of their school environment by navigating novel and direct routes. The results of this study suggest that with minimal exposure, even young children are able to form configuration-like structures of the environment before they are able to completely represent the entire environment.

Studies of children's cognitive mapping abilities have examined how spatial memory for location is impacted by different types of experimental exploration (Feldman & Acredolo; Herman, 1980; Lehnung, Leplow, Ekroll, Herzog, Mehdorn, & Ferstl, 2003). Overall, there is a positive effect of familiarity, experience, and independent locomotion on spatial knowledge (Neidhardt & Popp, 2010; Rissotto & Tonucci, 2002).

Finally, homing behaviour is also part of large scale environment studies. For example, children's performance on a homing task was used to evaluate their dependence on visual landmarks and self-generated movement cues (Nardini *et al.,* 2008). In a large dark testing room, participants picked up a series of illuminated objects, then fulfilled the task of returning the first object to its original location. Darkness filters out room features and boundaries, limiting the children to process the initial position with respect to illuminated landmarks or information from the vestibular, proprioceptive and somatosensory systems that evaluate distance and direction travelled. In one condition, returning to the original position depended only on non-visual information (i.e., self motion), while in another, subjects were only able to use landmarks to guide navigation because they were previously disoriented. Finally, the last condition had both visual and self motion cues available for homing.

Not surprisingly, Nardini and colleagues (2008) found that there are age-related improvements in accuracy of both single cued conditions (i.e., self-motion only and landmark only). This suggests that as children develop, they gain better judgments of distances and angles

and of the original position relative to landmarks. However, children do not show the same incremental profits as adults when both types of information are available. In other words, the combined condition of having visual landmarks and no prior disorientation does not result in significantly better performance in children compared to the self-motion only and landmark only conditions. In addition, human adults are able to integrate multiple sources of information and weigh how much reliance should be placed on each type of cues in order to reduce variable error. By contrast, the response pattern of children in a follow-up condition with both types of information in conflict showed that children do not integrate the cues, but alternate between them instead. Children's problems with cue integration by weighted averages in accord with cue reliability suggest that individual spatial representational systems are requirements for the development of a common spatial reference frame between sources of cues (Nardini *et al*., 2008).

1.3.2 Virtual environment studies of spatial navigation

There is a relative dearth of studies conducted in real life large scale spaces compared to the substantial amount of research done in small scale environments. It is much more difficult to design and conduct an experiment in big open spaces for economical and pragmatic reasons. However, the advancement of virtual environments allows investigators to examine topographical orientation in large scale environments without the high costs and disturbing influences from the real world environments. Many of the current research methods used for adults employ highly controlled simulated environments that can tease apart certain spatial skills, and the usefulness of virtual environments extends to children studies as well (Jansen-Osmann, 2007).

Virtual environments allow for active exploration of large scale environments as well as navigational decisions. These distinctive features give researchers opportunities to systematically investigate spatial behaviors, such as wayfinding strategies, route knowledge, and transference of spatial knowledge from virtual to real environments. As a result of this flexibility coupled with improved ease of creating simulated environments, it is increasingly popular to incorporate virtual environments into methodological paradigms.

A series of studies conducted by Jansen-Osmann and Wiedenbauer (2004a) demonstrates the usefulness of simulated environments to understand spatial development. Modeled after an earlier study by Cohen and Schuepfer (1980), children within the age ranges of seven to eight and eleven to twelve explored a virtual maze that contained eighteen different toy animals as landmarks at multiple corridors. These toys were placed adjacent to either a correct or incorrect turn, or at no turn point. As a result, these toys possessed a "direction-correct" function, "direction-incorrect" function, or no function at all, respectively. When children were able to travel through the corridors and reach the goal error-free on four consecutive trials, they were tested on their solution through the maze without any landmarks. At the end of the first learning and testing phase, children re-explored the maze with the landmarks present again. The final testing phase required them to recall the names and positions of the different toy animals they would have encountered as they go through the empty maze (Figure 5).

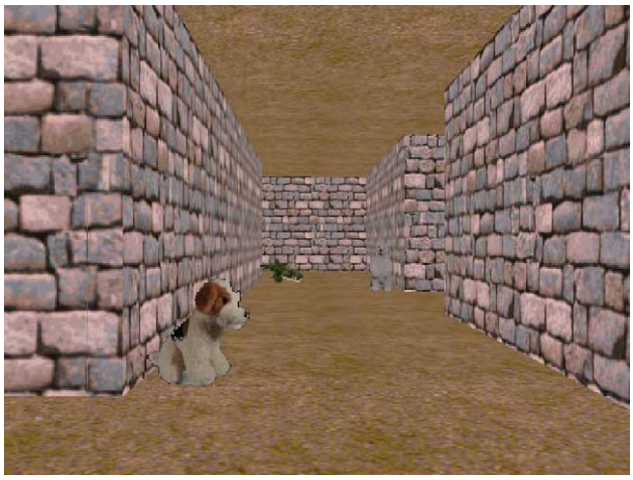

Fig. 1. A snap-shot into the maze.

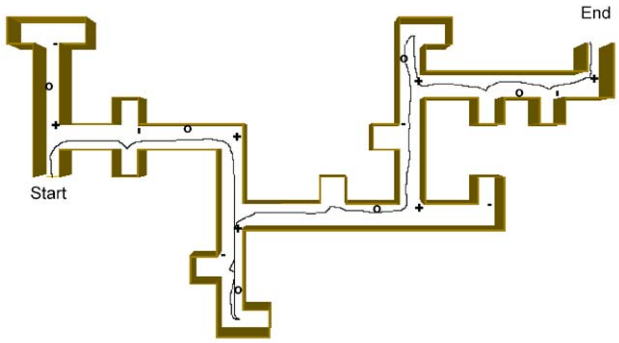

Figure 4. Snap-shot and schematic overview of the virtual environment used to investigate landmark representation and route knowledge (from Jansen-Osmann & Wiedenbauer, 2004a).

The results were that sixth graders had superior wayfinding performance than the younger children in the second grade, even when controlling for video game experience. Second graders have greater reliance on the presence of landmarks, require more trials to reach criterion, and made more errors during the first testing phase. In addition, landmark function is related to recall rates: animals with direction-correct functions are recalled more often than the ones with

incorrect or no functional uses. These findings, like Cohen and Schuepfer's earlier work, suggest that children do attend to landmark objects during route learning and place greater emphasis on the ones that are especially useful. Compared to the original 1980 study that used a series of photographs of the corridors, the opportunity for active exploration of the maze environment likely helps children integrate the spatial information into a more complex spatial configuration (Jansen-Osmann & Wiedenbauer, 2004a).

Virtual environments have also been used to understand how other features of the external environment influence wayfinding performance. In Jansen-Osmann & Wiedenbauer's (2004b) study, participants had to learn a virtual environment with either a coloured ground (on which the main route networks were green, yellow, or red) or a gray ground. The environment was otherwise indistinguishable, as no other visual landmarks were present. During the test trial, second and sixth grade children were asked to identify the shortest way possible to a goal location. Colour is helpful to children finding their way through unfamiliar large environments, similar to the facilitative effect in adults. Children require fewer learning trials to reach the criterion of two consecutive perfect performances when they learn the environment in coloured interior settings. The magnitude of improvement on wayfinding performance in children is comparable to adult participants. While younger children rely heavier external landmark cues, colour help children and adults structure the environment in a similar fashion. Further, colour may be a separate type of navigational aid from landmarks, even though both are used to conceptualize and structure the environmental space (Jansen-Osmann & Wiedenbauer, 2004b).

To assess the acquisition of spatial knowledge of the maze, participants in Jansen-Osmann & Wiedenbauer's (2004b) experiment were also asked to draw a sketch of the environment, as well as indicate the position of the target on an overview diagram of the maze.

An interesting finding was that colour does not seem to influence the acquisition of spatial knowledge once the environment is learned. This finding points to dissociated processes of spatial knowledge and wayfinding performance (Jansen-Osmann & Wiedenbauer, 2004b). It is therefore critical for future research studies to assess both processes and not prematurely conclude that performance in one domain equates to performance in the other.

A recent study (Bullens, Székely, Vedder, & Postma, 2010) attempted to tease apart the developmental timeline of complex navigational strategies. The authors used a virtual environment modeled after the StarMaze task, a pentagonal maze with five radial arms in which children navigated to a target. In the spontaneous condition, children were allowed multiple or single search strategies according to their personal preference. The goal was to assess which age groups (i.e., five, seven, or ten years old children) spontaneously use egocentric and/or allocentric strategies to find the target. Each type of strategy led children down a unique radial arm and both types of responses were rewarded when they reached a target. By contrast, a second condition only rewarded allocentric responses. This latter condition helped assess how allocentric-based skills evolve with development and when these skills become accessible to young children in large environments.

In accordance with earlier theories, all children have a natural preference for egocentric responses and there is a correlation between age and spontaneous use of allocentric strategies. Older children possess heavier reliance on landmarks during searches. However, even five years old are able to employ allocentric strategies to a certain degree. This provides evidence against the earlier Piagetian spatial development theory, which claims that only children nine years or older are able to integrate routes into allocentric representations (Bullens *et al*., 2010).

While the age at which allocentric strategies become available is continually debated, findings from recent and earlier studies point to a general developmental pattern as described by Siegel and White (1975). Recall that in this model, the development of spatial knowledge shifts from landmark-based route knowledge (i.e., learning a sequence of body turns at specific points) to survey knowledge whereby integration of mini-maps of the environment occurs. It is likely that the younger children in Bullens and colleagues' 2010 study only partially encoded the interrelationships among environmental cues, possibly related to the delayed maturation of the hippocampus (Newcombe *et al*., 1998). The consistent finding that older children generally outperform young children suggests that accurate integration of landmarks into a coherent overall representation of the environment occurs when children begin to shift from self-centered to allocentric perspectives.

Another virtual paradigm used to study spatial knowledge is the computerized memory island test (Piper, Acevedo, Craytor, Murray, & Raber, 2010; Piper, Acevedo, Edwards, Curtiss, McGinnis, & Raber, 2011). This is a spatial memory assessment tool modeled after the Morris water maze task. In Piper and colleagues' 2010 study, a virtually simulated island included four quadrants, each with a different target object like a sculpture or a fountain. Children aged seven to ten first completed a training portion by navigating to target locations, which were visibly marked with a flag. The subsequent probe task was to navigate to a hidden target that no longer had a flag indicating its location. It is assumed that efficiency and accuracy of performance are largely determined by the children's ability to make a cognitive map of the virtual island. As trials consisted of different starting orientations, it is unlikely that children are able to solely rely on response strategies to solve the task. Along with the memory island test, children completed a

battery of tests including attention, visual-spatial memory, and executive function measures (Piper *et al*., 2010).

It was found that older children have superior spatial memory, as measured by the percentage of time spent in the target quadrant. However, there are no significant age differences in terms of distance travelled during the visible target phase, suggesting that spatial memory is superior in older children, but this is not a result of acquisition deficits in the younger participants. Instead, the authors speculated that age-related improvement probably reflects age differences in the ability to switch to allocentric coding. There is also a rapid increase in spatial memory abilities at approximately nine to ten years old, correlating with performance on the Conners' Continuous Performance Test and Spatial Span backward subtest (Pipers *et al*., 2010). Therefore, enrichment of spatial memory likely occurs in conjunction with development of attention span and working memory. Both attentional focus and ability to mentally manipulate information are required in allocentric processing of environments.

1.4 Gender effects of spatial strategies

Examination of development of topographical orientation must also consider possible gender differences during development. Gender effects of spatial strategies are often evident and stable across the years in adulthood (Liu, Levy, Barton, & Iaria, 2010). In adults, females are similar to males on performance measures of landmark recognition, heading orientation and left-right orientation, while males are better at path reversal, cognitive map formation and cognitive map use. Other studies have also found a male advantage for cognitive mapping abilities (Iaria, Palermo, Committeri, & Barton, 2009; Sack, Sperling, Prvulovic, & Formisano ,2002). In addition, in the path reversal strategies may be related to the well-known advantage of males in

the processing of distance/metric information during navigation (Ruggiero, Sergi, & Iachini, 2008).

Compared to research examining adults, gender differences are less pronounced in children studies (Kopcha, Otumfuor, & Wang, 2014; Linn & Peterson, 1985; Miller & Halpern, 2014; Voyer, Voyer, & Bryden, 1995). An interesting virtual reality study that examined children's ability to reconstruct a passively explored virtual environment found that boys are not significantly better than girls at spatial reconstruction (Sandamas & Foreman, 2007). It has been speculated that while gender differences are present at young ages, individual differences may be more influential at determining spatial differences than gender (Kopcha *et al*., 2014; Munzer & Stahl, 2011).

1.5 The current research study

To date, there remain questions about when and how children develop the complex spatial ability of forming and using cognitive maps in order to navigate large real-world environments. Cognitive maps are essential to functioning in our everyday spatial world. While previous research has revealed significant knowledge about the developmental processes underpinning topographical orientation, there is a relative dearth of research using systematic approaches to investigate higher order spatial orientation skills. Specifically, as outlined by this chapter, few studies focus on cognitive maps and the developmental cognitive processes supporting cognitive maps. In order to understand how children form and use cognitive maps, a systematic approach must include measures of spatial navigation performance in a large space and underlying cognitive processes and basic spatial strategies supporting cognitive maps. By utilizing a task that assesses the integration of these cognitive processes and spatial strategies, insight into the typical developmental timeline of topographical orientation can be obtained. The

current research study employs a computerized task that assesses the ability to integrate spatial information into a cognitive map and apply this cognitive map to navigate through a virtual environment.

This study attempts to elucidate the developmental process of cognitive maps by assessing children across an age range that is consistent with rapid acquisition of higher order, complex, and abstract thinking skills, as suggested by the extant literature. By examining a large group of children with typical development, one of the goals of this research is to understand the developmental milestone timeline for spatial abilities, in particular, when children begin to form and use cognitive maps effectively. Another goal is to understand the important cognitive processes underlying cognitive maps. To assess how basic cognitive domains impact spatial functioning, a neuropsychological battery is administered to participants. In order to understand how children of different age groups fare compared to adults on the virtual spatial navigation task, children's performance are compared to that of a group of young adults.

Based on previous research findings that support a gradual developmental progression of spatial-related cognition and abilities, I hypothesize that there is an effect of age in performing the virtual spatial navigation task in that older children are better at the spatial task then younger children but they are not as adept as adults. I also hypothesize that there is an effect of gender in that boys outperform girls, similar to the gender differences often revealed in the adult literature.

In order to test my hypothesis, seven to ten year old children were invited to play a computer game designed to assess topographical orientation skills. Performance on this game is dependent on cognitive map abilities as well as other topographical orientation strategies, such as landmark use and route knowledge. Those who are able to form a good mental representation of the virtual environment are afforded short cuts to get to target locations quickly. A

neuropsychological battery assessing different cognitive domains, self- and parent-rated behavioural questionnaires, as well as a questionnaire used to collect information regarding developmental history were also administered.

Chapter Two: Methods

2.1 Methods

2.1.1 Participants

Families were invited through the University of Calgary's Child and Infant Learning and Development (Ch.I.L.D.) Research Group database, a registry of families within the community who voluntarily indicated an interest in participating in research studies. The primary inclusion criterion for this study was children between the ages of 6 to 10 with normal developmental history. Specifically, children with neurological disorders, neurodevelopmental disorders, brain injury, and psychiatric illnesses (according to parental self-report) were excluded. Children and parents who did not have a basic understanding of English were also excluded in order to ensure adequate comprehension of questionnaires and task instructions.

In total, 137 children were tested (63 Males; $M = 8.79$ years, $SD = 1.45$ years), 22 of which were removed from the final sample on which data analyses were performed. Common reasons for excluding participants included incomplete data collection from the computer task or neuropsychology battery, motion sickness, or atypical developmental history identified by parents during the study. An additional nine participants who participated in the pilot study were also removed from the final sample. Please see Appendix B for a description of the pilot study. Finally, a group of 6-year-old participants ($n = 9$) was not included in the main data analysis due to the small sample size; a separate discussion regarding this subgroup is provided in Appendix B. Therefore, a total of 97 children ($M = 8.50$ years, $SD = 1.10$) were included in the final data analyses. Figure 6 depicted a flowchart of participant recruitment. There was no significant difference in terms of socioeconomic status, as estimated by the mother's highest level of

education, between those who completed the study and those that were omitted from analyses ($F_{(4, 125)} = 2.08, p = 0.087$).

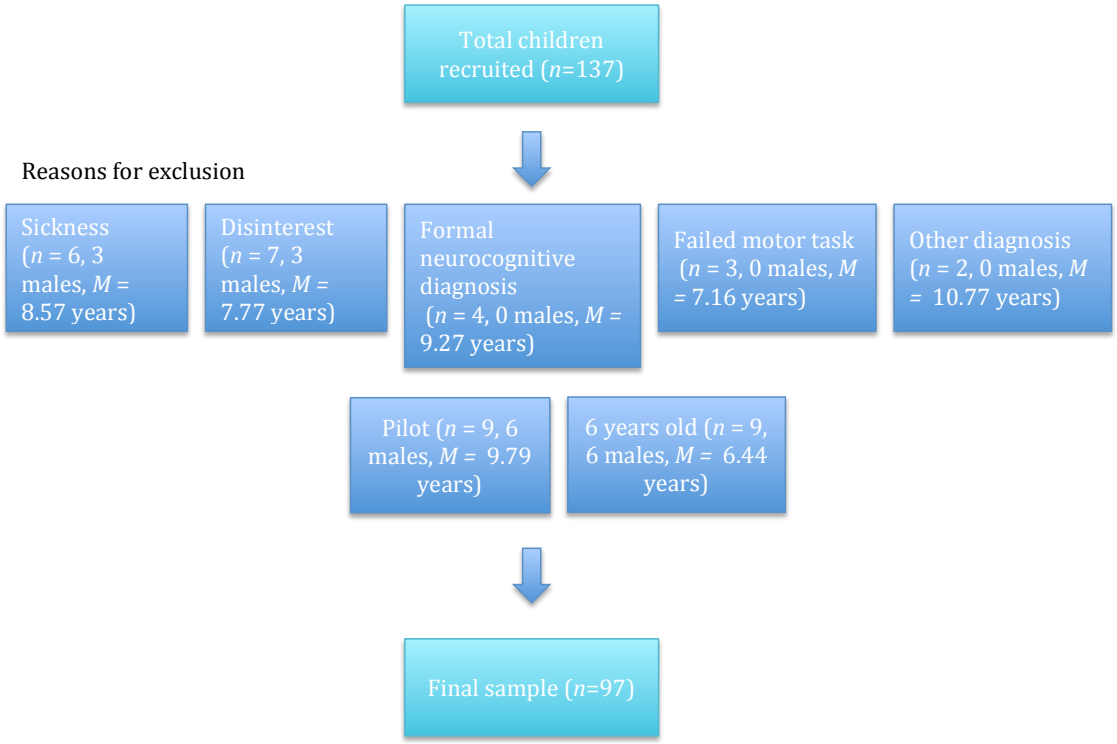

Figure 6. Flowchart of participant recruitment and attrition. For each reason for exclusion from the final sample, the number of participants (*n*), the number of males, and the mean age (M) were provided.

The final sample consisted of children predominantly self-identified as Caucasian and broadly from middle class families (not formally assessed but judged based on parental education and annual household income). English was typically the primary spoken language, with the exception of six children who speak non-English languages at home. Out of 97

participants, 13 parents opted not to provide children's ethnicity, and 17 identified as "Canadian", seven as mixed ethnicity, six as East Indian, one as African, one as Chinese, and the remainder as Caucasian. The experimental protocol received ethics approval from the Conjoint Faculties Research Ethics Board of the University of Calgary (REB14-2176_REN3).

2.1.2 Data Collection

Children were selected from the Ch.I.L.D. database, and parents were invited to participate in the study via telephone or e-mail. Following confirmation of inclusion criteria, families were invited to participate in the experiment, which took place at the NeuroLab (Department of Psychology, University of Calgary). An in-depth explanation of the study and nature of the tasks was provided to families in person. Informed consent was obtained from parents while children were asked for their assent. All parties were allowed opportunities to ask questions prior to beginning the experiment. For younger and/or more reserved children, the experiment allowed extra time to develop rapport and help alleviate anxiety.

Briefly, the general procedure for data collection was the following: children were seated in front of a computer monitor and introduced to the experimental task, which consisted of a game taking place in a virtual museum. An initial practice phase allowed participants to get familiar with the virtual environment and with operating the control pad. Following practice, participants were guided through a separate testing environment and the testing phase began. A brief neuropsychology battery was also administered to children. This battery assessed cognitive functioning of general intelligence, attention, visual perception, visual-constructional abilities, working memory, executive functioning, and map perception skills. Finally, questionnaires were administered to collect information regarding demographic characteristics, developmental history, academic history, extracurricular activities, familial history of orientation skills, screen-

related activities, and parent- and self-ratings of spatial and attentional behaviors. Additional clarification of instruction was provided to children who had difficulty reading, comprehending, or responding to the self-report questionnaires. Detailed explanation of each experimental task is provided below in the 2.1.3 Task Measures section.

Total testing time was approximately 90 minutes, including time for informed consent and building rapport with the families. Following the completion of the tasks, both parents and children were debriefed about the study and given the opportunity to ask further questions. Participants received a $20 gift card and a small toy as a token of appreciation for their contribution to the study.

2.1.3 Task Measures - Game

The game was developed by collaboration between the NeuroLab, Ayogo software experts, and The Human Vision and Eye Movement Laboratory (University of British Columbia). Of note, I did not contribute to the creation of this computer game task. The game consisted of three sections: 1) a practice phase, 2) a guided tour, and 3) a testing phase. Figure 7 shows a bird's-eye view of the virtual museum in which the game took place. The environments included different landmarks, such as painting, statutes, windows, etc. The game was projected on a 24 inch widescreen LED monitor with 1920 x 1080 screen resolution, placed approximately an arm's length away.

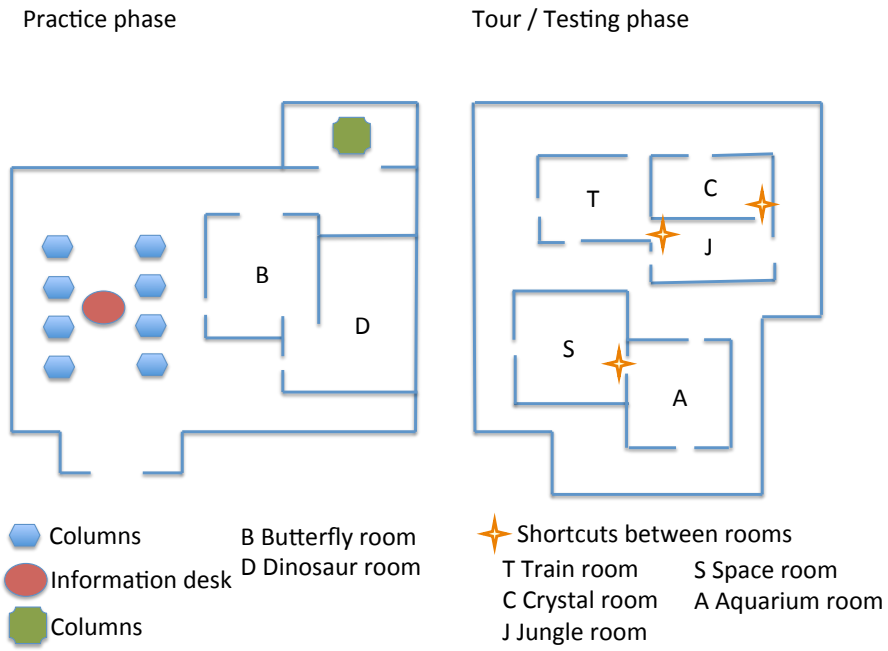

Figure 7. Schematic view of the virtual museum environments. The left environment was used for the practice phase and included one atrium and two themed rooms. The right environment, which consisted of five themed rooms, was used during the tour and testing phase. Both environments included stable landmark structures (e.g., paintings, windows, statues, and etc.) that are not depicted in the figure.

Motor Practice Phase

Participants first listened to an audio description from a female narrator who provided an introduction to the game and explained that the goal of the game was to learn the locations of different rooms in order to deliver a letter from one room to another. Children were encouraged to complete the trials as quickly as possible, as points were awarded based on the speed of trial

completion.

In order to ensure adequate use of the controller, children were first asked to complete a motor practice task that required them to move through the virtual museum quickly and precisely by following a predetermined pathway using an analogue joystick of an Xbox controller. Participants were instructed to follow a path of dinosaur footprints (Figure 8) as closely and quickly as possible. The pathway went through parts of a museum, including an atrium, a dinosaur themed room, a butterfly themed room, and corridors. Once participants step over the dinosaur footprints within a predetermined radius, the footprints visually disappeared along with auditory feedback. A counter placed at the top left corner of the screen indicated the number of remaining footsteps, as an additional cue. Although not officially recorded, most participants required two or more attempts of the practice phase. After participants reached criterion (i.e., completing the pathway by clearing all of the footprints within a specific time limit of 90 seconds, as predetermined by a pilot study) and they indicated feeling comfortable with using the controller, the practice phase was completed.

Figure 8. Practice phase that involved following a pathway of dinosaur footprints.

Guided Tour

The tour and testing phases took place in another part of the museum, as depicted by Figure 7. This environment was comprised of five unique themed rooms (crystal, jungle, space, aquarium, and train) and corridors. Each room had multiple exits, and was connected to one or more other themed rooms. Some of the inter-room connections, henceforth referred to as 'shortcuts', were not explicitly revealed during the guided tour. The tour occurred clockwise peripherally around the environment. Participants entered themed rooms in the following order: train, crystal, jungle, aquarium, and space. To ensure equal initial exposure time amongst subjects, the tour was presented as a passive guided tour with a predetermined speed and pathway (i.e., all rooms were revealed in a specific order and for the same amount of time between participants.)

During the tour, participants listened to audio descriptions of interesting facts about each

themed room in order to help direct and maintain attention to the rooms. Participants were encouraged to look around the environments by turning left and right with the controller while guided through the tour. To ensure that participants were exposed to all relevant information at eye level during the tour, they were restricted from looking up and down. During the tour, participants were specifically informed that each room had more than one exit that was marked by a bright red banner. At the end of the tour, participants were guided back to the starting position (i.e., right outside of the train room) and instructed that the testing phase was about to begin.

Testing Phase

The testing phase consisted of 21 trials of varying distances and available shortcuts through connecting rooms. Pairs of the start and target locations were randomized and each start location connected with each available target location exactly once. Each trial consisted of the same order of pairing. In other words, participants completed the trials in the same order as shown in Table 1. In each trial of the testing phase, children were instructed to pick up an envelope that revealed a target location (one of the other four rooms). The instructions were presented in simultaneous audio and written formats, with the written instructions displayed at the top of the monitor for the remainder of the trial. If required, the experimenter provided additional reminders of the target rooms. Participants were asked to travel from their current room to the specified location as quickly as possible (Figure 9). Upon reaching the target location, the trial was considered complete and participants were immediately praised (e.g., hearing an audio clip of "hooray!"). They were also rewarded with points based on the amount of time it took to complete the trial, with shorter completion times earning more points. Reward

points ranged from 10 to 100, with 100 being the best reward for the fastest possible performance.

Table 1 *Testing phase trial order*.

Trial number	**Starting location**	**Target location**
1	Train	Crystal
2	Crystal	Jungle
3	Jungle	Space
4	Space	Aquarium
5	Aquarium	Crystal
6	Crystal	Space
7	Space	Jungle
8	Jungle	Train
9	Train	Aquarium
10	Aquarium	Jungle
11	Jungle	Crystal
12	Crystal	Train
13	Train	Space
14	Space	Crystal
15	Crystal	Aquarium
16	Aquarium	Train
17	Train	Jungle
18	Jungle	Aquarium
19	Aquarium	Space
20	Space	Train
21	Train	Crystal

Figure 9. An example of a trial during the testing phase. In this specific trial, the start location is the jungle room and the target location is the space room. An accumulated total reward points score was displayed in the top right corner of the screen throughout the testing phase. A timer in the top left corner automatically reset at the start each trial.

The first out of 21 trials was not included in the data analysis as some children required additional clarification of instructions during the first trial. Time of completion, distance travelled, and spatial coordinates per 10 milliseconds were recorded. Aside from clarification of instructions and occasional reassurance, the examiner did not provide any additional assistance. A proportion of the participant sample was invited to complete two sessions of the testing phase in order to assess any incremental learning over additional trials. The results of learning across two testing sessions are described in Appendix B. In a group of healthy young adults, test-retest reliability of the computerized was good ($r = 0.785$) (Murias, Kwok, Castillejo, Liu, & Iaria, 2016).

2.1.4 Neuropsychology Tests

A battery of neuropsychological tests was administered to each participant. While standardized scores were available for some of the neuropsychological tests, raw scores were calculated and used in the data analysis instead in order to fully capture the variability of performance. Further, not all of the neuropsychological measures had available age-corrected norms specific for the ages of participants in this research study.

The Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV)(Wechsler, 2003) – Vocabulary subtest (VC)

Participants were asked to verbally express the definition of words that the examiner read aloud and pointed to on a stimulus book. Vocabulary is a general measure of word knowledge, general fund of knowledge, and verbal learning ability. Hereafter is a description of each subtest included in the WISC-IV, and other tests used in the battery. Overall, the internal reliability of the WISC-IV is excellent, with split-half reliabilities ranging from 0.70 and 0.89 and test-retest correlations ranging from 0.72 and 0.92 (Wechsler, 2003). VC has a split-half internal consistency reliability coefficient of 0.89 and a test-retest reliability coefficient of 0.92 (Wechsler, 2003).

WISC-IV Block Design subtest (BD)

During Block Design, children were asked to use identical coloured blocks to build copies of picture designs. This timed subtest assesses skills related to visual perception and organization and visuoconstruction. BD has a split-half reliability coefficient of 0.86 and a test-retest reliability coefficient of 0.82 (Wechsler, 2003).

WISC-IV Digit Span subtest (DS)

Participants were required to repeat series of verbally presented digits in the same order in the first part of the subtest. During the second part, they were asked to repeat series of verbally presented digits in reverse order. Digit span assesses auditory attention, attention span, and working memory. A total score was obtained by summing up performance in forward and backward conditions. DS has a split-half reliability coefficient of 0.87 and a test-retest reliability coefficient of 0.83 (Wechsler, 2003).

WISC-IV Cancellation subtest (CA)

This is a measure of visual selective attention, speed of information processing, and vigilance. Children were told to scan a random array of pictures and mark the target pictures as quickly as possible. In the second part of the subtest, participants repeated the task on a structured array of pictures. A total time was calculated based on performance for both parts. CA has a test-retest reliability coefficient of 0.72 (random array) and 0.76 (structured array; Wechsler, 2003).

Children's Color Trail Test (CCTT) (Llorente, Williams, Satz, & D'Elia, 2003)

In CCTT Part 1 (CCTT-1), children were instructed to connect numbered circles on a sheet of paper in sequential order as quickly as possible. There were two colours of numbered circles. Part 2 (CCTT-2) required participants to quickly connect the circles in sequence while alternating colors. The CCTT is a measure of visual sequencing, processing speed, and mental flexibility. A lower raw time score means better performance. The temporal stability of the CCTT is indicated (Llorente, Voigt, Williams, Frailey, Satz, & Elia, 2009) by test-retest

reliability coefficients between 0.45 to 0.66 for children.

Wechsler Memory Scale – Third Edition (WMS-III) - Spatial Span subtest (Wechsler, 1997)

This test resembles a spatial analogue of the Digit Span subtest. Participants were asked to observe the experimenter touch sequences of blocks then repeat these sequences in the same order (SSF). Afterwards, participants repeated the sequences of blocks in backward order in the second part of the study (SSB). In adults, average split-half reliability for spatial span is $r = 0.79$ and average test-retest reliability is $r = 0.71$ (Lichtenberger, Kaufman, & Lai, 2002).

Hooper Visual Organization Test (HVOT) (Hooper, 1958)

The HVOT is a measure of visual organization skills, mental rotation, and perception. Children were asked to name pictures of objects that had been cut up and rearranged. Participants verbally provided their responses to the examiner. The HVOT has a high internal consistency ($r \geq 0.80$) in adults (Lopez, Lazar, & Oh, 2003; Merten & Beal, 1999) and adequate internal consistency in children ($r = 0.72$; Siedel, 1994). Good test-retest reliability, indicated by a coefficient of concordance of 0.86 after 6 and 12 months, has been reported (Lezak, Howieson, & Loring, 2004). Further, inter-rater reliability is high (>0.95) for two and three raters (Lopez *et al.,* 2003).

The Standardized Road-Map Test of Direction Sense (Money, 1976)

In this task, children were presented with a map-like picture that contained a dotted pathway through building-like figures. Children were asked to follow the pathway and indicate the direction taken (i.e., left or right) at each turn without physically rotating the paper. Children

first completed a short demonstration with the experimenter on an abbreviated pathway. The Standardized Road-Map Test of Direction Sense is a measure of direction sense and mental rotation skills. Performance was recorded in terms of time required to complete the task (RMT-T) and errors made (RMT-E).

2.1.5 Questionnaires

Parental Questionnaire

Parents were invited to complete a questionnaire that collected information about their children's demographic information, developmental history, medical history, academic history, extracurricular activities, average screen time per week (i.e., time spent on activities performed in front of a screen, such as watching television, using a computer, or playing video games), and experience with playing video games (Appendix A4). The parental questionnaire also included a parental rating scale of environmental spatial abilities adapted from the Santa Barbara Sense of Direction Scale (SBSOD-P; Appendix A1) (Hagerty, Richardson, Montello, Lovelace, & Subbiah, 2002). Items were scored on a 1 to 7 scale and were coded and summed such that a higher number indicated better perceived proficient environmental spatial abilities and sense of direction. Hegarty *et al*., (2002) reported a coefficient alpha for the scale as 0.88 and a test-retest correlation of 0.91, which indicated good internal reliability and test-retest reliability. Further, construct validity for the SBSOD is supported by significant correlations to direction (r = 0.43) and distance estimations (r = 0.36) after learning in a real building environment.

Finally, parents were asked to rate the frequency of attention-deficit and hyperactivity behaviors at home over the past six months via the ADHD Rating Scale (ADHD-RS; Appendix A3) – Fourth Edition, Home Version (DuPaul, Power, Anastopoulo, & Reid, 1998). The ADHD-RS has good internal consistency, indicated by Chronbach alphas of 0.92 (total score), 0.86

(inattention), and 0.86 (hyperactivity-impulsivity). Test-retest reliability has also been supported by reported Pearson product-moment correlation coefficients (0.85 for total score, 0.78 for inattention, and 0.86 for hyperactivity-impulsivity) for the parent version.

Children Questionnaire

In conjunction with parental report, participants were asked to describe the frequency and nature of their screen time activities. To gather information regarding participants' judgment of their own spatial abilities, they also completed a version of the Santa Barbara Sense of Direction Scale adapted for children (SBSOD-C, Appendix A2). Some participants, especially younger children, were provided with additional assistance for responding via a Likert scale. The questionnaire was read aloud to all children in order to ensure adequate understanding. A similar coding and scoring method was used as the SBSOD-P.

Coding of self-report videogame measures

Both children and parents were asked to provide the names of videogames most frequently played and whether these games have a navigational component and / or first person perspective. To order to verify the nature of these videogames, I performed Internet searches (e.g., using Google, YouTube, and etc.,) for each game reported. Game experience were classified as 1) navigational versus non-navigational, and 2) first-person perspective versus non first-person perspective. If a child and/or a parent reported any game with a navigational component, then the participant was coded as having navigational game experience. Similarly, participants who currently played one or more games that involved a first-person perspective

were coded as having first-person perspective game experience. Certain games, such as Call of Duty, met criteria for both navigational and first-person perspective classifications.

2.2 Game performance measures

2.2.1 Time Efficiency

As trials contain various distances between the start location and target locations, a transformation of time performance was computed for relative comparison purposes. A similar computation was performed for distance performance scores, as described in the subsequent Distance Efficiency section. In each trial, the time required to complete the task was converted into an efficiency score based on performance compared to the maximum performance (i.e., shortest possible time for each trial). The shortest time possible for each trial was identified by the best performance (i.e., quickest time to complete the trial) amongst all participants included in the present study, as well as a group of university students (n = 103, 51 Males, M = 20.8 years, SD = 2.5 years) who performed the same task for a different study (Murias *et al.,* 2016). To calculate an efficiency score, a participant's trial completion time was divided by the shortest trial time possible. A perfect performance yielded an efficiency score of 1. By contrast, higher efficiency scores indicated poorer performances.

Individual trials with time efficiency scores that exceeded three standard deviations above the mean time efficiency score across participants for that particular trial were treated as outliers and omitted from the final analysis. Using this criterion, a total of 42 time efficiency scores (out of 1940) were omitted. The maximum number of omission within a trial was five and the maximum number of omission from the same participant was three.

For each participant, an average of time efficiency (ATE) was calculated by taking the mean of his / her time efficiency scores across 20 trials.

2.2.2 Distance Efficiency

Similar to time efficiency scores, a distance efficiency score was calculated for performance on each of the 20 trials. The distance efficiency score was calculated by dividing the accumulated distance traveled to complete a trial by the shortest distance possible based performances of the current study sample and the university group (Murias *et al*., 2016). Higher distance efficiency scores indicated poorer performances.

Again, individual trials with distance efficiency scores that exceeded three standard deviations above the mean distance efficiency score across both participant groups for a particular trial were treated as outliers and omitted from the final analysis. A total of 47 distance efficiency scores (out of 1940) were omitted. The maximum number of omission within a trial is five and the maximum number of omission from the same participant is four.

For each participant, an average of distance efficiency (ADE) was calculated by taking the mean of his or her distance efficiency scores across 20 trials.

2.3 Statistical Analysis

Statistical analyses were performed via IBM SPSS Statistics Version 22. Exact age at the day of testing was used in Pearson two-tailed correlation and multiple regression analyses to examine the relationship between game performance and various potential predictors. For correlations between game performance and ordinal data (e.g., socioeconomic status), Spearman's rho was calculated instead Pearson's r. Finally, an analysis of covariance

(ANCOVA) was performed to compare spatial skills between the group of children with best game performance and young adults.

Chapter Three: Results

3.1 Age and Gender Groups

Participants were divided into four age groups (7, 8, 9, and 10 years old groups). Each age group was further divided by gender, with at least ten participants of each gender for each age group (see Table 2)

Table 2 *Characteristics of final sample by age and gender groups. Table 2 describes the number of participants (n), mean age (M), standard deviation (SD), and range in each group.*

Age group	**Males (*n, M, SD, range*)**	**Females (*n, M, SD, range*)**	**Combined (*n, M, SD, range*)**
7	11, 7.11 years, 0.05 years, 7.04 to 7.19 years	13, 7.30 years, 0.34 years, 7.02 to 7.99 years	24, 7.21 years, 0.26 years, 7.02 to 7.99 years
8	13, 8.52 years, 0.24 years, 8.18 to 8.83 years	10, 8.59 years, 0.30 years, 8.02 to 8.92 years	23, 8.55 years, 0.26 years, 8.02 to 8.92 years
9	14, 9.43 years, 0.28 years, 9.03 to 9.94 years	14, 9.57 years, 0.30 years, 9.14 to 9.97 years	28, 9.50 years, 0.29 years, 9.03 to 0.97 years
10	10, 10.67 years, 0.26 years, 10.00 to 10.96 years	12, 10.58 years, 0.32 years, 10.00 to 10.96 years	22, 10.62 years, 0.29 years, 10.00 to 10.96 years

Game performance for each age group, separated by gender, was summarized in Table 3 (ATE scores) and Table 4 (ADE scores).

Table 3 *Mean ATE scores for each group. Number of participants (n), mean ATE score, standard deviation (SD), and range of performance is described.*

Group	***n***	**Mean ATE**	**SD**	**Range**
7 year olds (total)	24	6.26	1.97	3.70 to 12.27
Male	11	5.93	1.39	3.70 to 8.51
Female	13	6.54	2.37	4.02 to 12.27
8 year olds (total)	23	6.51	2.38	3.09 to 12.93
Male	13	5.24	1.03	3.09 to 7.19
Female	10	8.15	2.67	3.79 to 12.93
9 year olds (total)	28	5.60	2.85	3.70 to 18.97
Male	14	6.20	3.90	3.79 to 18.97
Female	14	5.00	0.99	3.70 to 6.76
10 year olds (total)	22	4.33	1.12	2.30 to 6.79
Male	10	3.89	0.85	2.30 to 5.11
Female	12	4.70	1.21	3.08 to 6.79
Young adults (total)	120	3.11	1.23	1.34 to 10.22
Male	55	2.61	1.39	1.34 to 10.22
Female	65	3.53	0.90	1.93 to 6.19

Table 4 *Mean ADE scores for each group*.

Group	***n***	**Mean ADE**	**SD**	**Range**
7 year olds (total)	24	4.38	0.88	2.59 to 7.20
Male	11	4.25	1.16	3.01 to 5.49
Female	13	4.48	1.02	2.59 to 7.20
8 year olds (total)	23	4.39	0.79	2.98 to 5.89
Male	13	4.27	0.65	2.98 to 5.37
Female	10	4.54	0.95	3.09 to 5.89
9 year olds (total)	28	4.09	1.04	2.76 to 7.00
Male	14	4.29	1.27	2.84 to 7.00
Female	14	3.88	0.73	2.76 to 5.10
10 year olds (total)	22	3.62	0.78	1.80 to 4.81
Male	10	3.41	0.85	1.80 to 4.48
Female	12	3.79	0.70	2.63 to 4.80
Young adults (total)	120	3.11	1.37	1.38 to 9.89
Male	55	2.77	2.19	1.38 to 9.89
Female	68	3.26	0.81	2.05 to 5.78

Neuropsychology test performance for each age and gender group is summarized in a similar fashion from Table 5 to Table 15.

Table 5 *Vocabulary Performance*

Age group	**Mean**	**SD**	**Range**
7 (total)	23.39	4.62	16 to 39
Male	23.09	3.27	18 to 30
Female	23.46	5.65	16 to 39
8 (total)	26.57	4.92	18 to 42
Male	27.54	5.19	21 to 42
Female	25.30	4.47	18 to 32
9 (total)	32.21	5.56	20 to 44
Male	30.36	5.97	20 to 44
Female	34.07	4.60	28 to 40
10 (total)	33.91	5.55	23 to 42
Male	32.80	7.19	23 to 42
Female	34.83	3.81	28 to 40

Table 6 *Block Design Performance*

Age group	**Mean**	**SD**	**Range**
7 (total)	20.17	5.23	10 to 28
Male	20.00	5.80	11 to 28
Female	20.31	4.94	10 to 27
8 (total)	24.91	5.57	13 to 37
Male	23.62	8.48	13 to 37
Female	26.60	6.22	15 to 36
9 (total)	30.54	6.06	19 to 40
Male	28.93	6.81	19 to 40
Female	32.14	4.94	23 to 40
10 (total)	32.36	9.92	17 to 48
Male	29.50	9.53	17 to 42
Female	34.75	9.99	23 to 48

Table 7 *Digit Span Performance*

Age group	**Mean**	**SD**	**Range**
7 (total)	12.42	2.17	10 to 17
Male	12.36	2.01	10 to 17
Female	12.46	2.37	10 to 17
8 (total)	14.04	1.75	11 to 17
Male	14.54	1.98	11 to 17
Female	13.40	1.17	12 to 15
9 (total)	15.21	2.18	11 to 20
Male	15.29	2.56	11 to 20
Female	15.14	1.79	11 to 18
10 (total)	15.36	1.94	13 to 21
Male	15.20	2.35	13 to 21
Female	15.50	1.62	13 to 18

Table 8 *Cancellation Performance*

Age group	**Mean**	**SD**	**Range**
7 (total)	55.58	10.07	38 to 72
Male	55.00	8.99	38 to 70
Female	56.08	11.25	38 to 72
8 (total)	64.74	13.22	42 to 84
Male	67.38	14.07	42 to 84
Female	61.30	11.82	47 to 79
9 (total)	66.71	10.55	50 to 87
Male	64.07	10.90	50 to 80
Female	69.36	9.87	54 to 87
10 (total)	76.05	13.17	56 to 98
Male	69.70	12.24	56 to 93
Female	81.33	11.89	60 to 98

Table 9 *Children's Color Trail Test – Part 1 Performance*

Age group	**Mean**	**SD**	**Range**
7 (total)	25.33	9.23	14 to 41
Male	22.00	7.96	14 to 40
Female	28.15	9.58	16 to 41
8 (total)	24.87	6.67	15 to 38
Male	22.69	5.01	15 to 30
Female	27.70	7.72	15 to 38
9 (total)	21.25	6.48	12 to 33
Male	20.36	6.34	12 to 32
Female	22.14	6.74	13 to 33
10 (total)	18.64	4.09	12 to 26
Male	18.30	4.17	13 to 26
Female	18.92	4.19	12 to 26

Table 10 *Children's Color Trail Test – Part 2 Performance*

Age group	**Mean**	**SD**	**Range**
7 (total)	50.71	16.05	27 to 73
Male	50.45	15.90	27 to 73
Female	50.92	16.83	28 to 72
8 (total)	48.61	11.42	29 to 71
Male	48.00	11.85	29 to 70
Female	49.40	11.41	29 to 71
9 (total)	42.79	11.80	26 to 67
Male	40.79	10.38	26 to 59
Female	44.79	13.14	28 to 67
10 (total)	43.27	13.88	21 to 64
Male	44.20	16.54	22 to 64
Female	42.50	11.94	21 to 58

Table 11 *Spatial Span – Forward Performance*

Age group	**Mean**	**SD**	**Range**
7 (total)	7.96	3.14	3 to 14
Male	7.64	3.11	3 to 13
Female	8.23	3.27	3 to 14
8 (total)	9.17	3.53	3 to 14
Male	8.46	3.33	3 to 14
Female	10.10	3.73	3 to 14
9 (total)	7.36	3.17	3 to 14
Male	7.86	3.63	3 to 14
Female	6.86	2.66	3 to 12
10 (total)	8.86	3.67	3 to 14
Male	8.00	4.06	3 to 14
Female	9.17	3.41	3 to 14

Table 12 *Spatial Span – Backward Performance*

Age group	**Mean**	**SD**	**Range**
7 (total)	5.58	2.59	2 to 11
Male	6.82	2.27	4 to 11
Female	4.54	2.44	2 to 10
8 (total)	7.13	3.27	3 to 12
Male	7.85	2.70	3 to 12
Female	6.20	3.82	3 to 12
9 (total)	7.71	3.11	4 to 14
Male	7.43	3.11	4 to 14
Female	8.00	3.21	4 to 12
10 (total)	8.27	3.23	4 to 14
Male	8.90	3.48	4 to 14
Female	7.75	3.05	4 to 12

Table 13 *Hooper Visual Organization Test Performance*

Age group	**Mean**	**SD**	**Range**
7 (total)	19.79	3.82	14 to 27
Male	22.18	3.19	19 to 27
Female	17.77	3.14	14 to 23
8 (total)	23.87	2.38	19 to 27
Male	24.38	2.49	19 to 27
Female	23.20	2.20	20 to 27
9 (total)	23.64	3.05	18 to 28
Male	23.79	3.04	20 to 28
Female	23.50	3.16	18 to 28
10 (total)	26.09	2.76	20 to 30
Male	26.00	2.75	23 to 30
Female	26.17	2.89	20 to 30

Table 14 *Road Map Test – Time Performance*

Age group	**Mean**	**SD**	**Range**
7 (total)	406.54	126.52	200 to 580
Male	387.09	130.28	200 to 544
Female	423.00	126.08	231 to 580
8 (total)	348.39	153.78	94 to 593
Male	304.54	161.18	94 to 587
Female	405.40	127.77	174 to 593
9 (total)	355.96	158.40	104 to 627
Male	308.50	167.38	106 to 607
Female	403.43	138.72	104 to 627
10 (total)	394.18	128.89	180 to 629
Male	392.50	144.53	180 to 615
Female	395.58	120.90	207 to 629

Table 15 *Road Map Test – Error Performance*

Age group	**Mean**	**SD**	**Range**
7 (total)	7.25	4.49	0 to 14
Male	8.18	5.06	0 to 14
Female	6.46	3.99	0 to 11
8 (total)	8.30	4.48	1 to 20
Male	8.92	5.06	1 to 20
Female	7.50	3.69	3 to 14
9 (total)	7.61	3.86	1 to 13
Male	8.79	2.99	1 to 13
Female	6.43	4.36	1 to 13
10 (total)	6.55	4.70	0 to 14
Male	5.40	4.20	1 to 13
Female	7.50	5.05	0 to 14

Finally, Tables 16 – 18 provide the descriptive data for self-report questionnaires.

Table 16 *Santa Barbara Sense of Direction Scale – Parent Report*

Age group	**Mean**	**SD**	**Range**
7 (total)	4.99	0.79	3.31 to 6.38
Male	4.77	0.83	3.31 to 6.21
Female	5.17	0.74	3.42 to 6.38
8 (total)	4.64	0.78	3.24 to 6.25
Male	4.60	0.91	3.24 to 6.25
Female	4.70	0.61	3.72 to 5.55
9 (total)	4.99	0.93	2.68 to 6.25
Male	5.00	0.97	2.68 to 6.17
Female	4.98	0.93	3.23 to 6.25
10 (total)	5.10	0.64	4.19 to 6.24
Male	5.20	0.56	4.40 to 5.95
Female	5.01	0.72	4.19 to 6.24

Table 17 *Santa Barbara Sense of Direction Scale – Children Report*

Age group	**Mean**	**SD**	**Range**
7 (total)	4.29	0.80	3.25 to 6.70
Male	4.18	0.74	3.25 to 5.60
Female	4.38	0.87	3.26 to 6.70
8 (total)	4.22	0.80	2.47 to 6.25
Male	4.36	0.53	3.47 to 5.15
Female	4.07	1.04	2.47 to 6.25
9 (total)	4.36	0.84	2.60 to 5.85
Male	4.41	0.77	3.25 to 5.58
Female	4.33	0.93	2.60 to 5.85
10 (total)	4.64	0.48	3.82 to 5.75
Male	4.59	0.61	3.82 to 5.75
Female	4.68	0.38	4.06 to 5.15

Table 18 *ADHD-Rating Scale – Parent Report*

Age group	Mean	SD	Range
7 (total)	16.13	9.74	0 to 33
Male	14.91	9.72	0 to 33
Female	17.15	10.03	3 to 30
8 (total)	17.43	10.68	0 to 39
Male	17.92	9.02	6 to 38
Female	16.80	13.01	0 to 39
9 (total)	15.96	11.09	1 to 39
Male	15.57	9.70	1 to 28
Female	16.36	12.70	1 to 39
10 (total)	13.14	11.65	0 to 38
Male	15.30	14.13	0 to 38
Female	11.33	9.38	0 to 28

3.2 Correlation between average time efficiency (ATE) and other measures.

A correlation matrix was created in order to examine the relationship between ATE and other variables. To correct for multiple comparisons, an adjusted *p*-value cut off of 0.02 was applied. Scatterplot analyses were also performed to examine for violations of the assumptions of normality, linearity, and homoscedasticity. ATE and ADE were highly correlated ($r = 0.734$, $p < 0.001$); good performance on time efficiency was correlated with good performance on distance efficiency, and vice versa. Therefore, only analyses using ATE are described in detail although

the same analyses were repeated for ADE. For the sake of completeness, the results of the ADE analyses are reported in Section 3.5 (Correlation between ADE and other measures), Section 3.6 (Predictors with of ADE with regression analysis), and Section 3.7 (Comparison of ADE between children and adults).

As predicted, ATE was significantly correlated with exact age (r = - 0.305, p = 0.002), indicating that better game performance was observed for older children. Game performance was not significantly correlated with social economic status, as estimated by mother's highest level of education completed (ϱ = -0.138, p = 0.186). Mother's highest level of education completed was grouped into 1) less than high school, 2) high school diploma or equivalent and 3) university / college degree or higher.

When examining performance on neuropsychological measures, ATE was significantly correlated with better performance on CCTT-1 (r = 0.246, p = 0.015), DS (r = -0.306, p = 0.002), SSB (r = -0.400, $p < 0.001$), and HVOT (r = -0.321, p = 0.001). In contrast, ATE was not significantly correlated with CCTT-2 (r = 0.054, p = 0.601), BD (r = 0.103, p = 0.317), VC (r = -0.183, p = 0.073), CA (r = -0.157, p = 0.124), SSF (r = 0.002, p = 0.983), RMT-T(r = -0.101, p = 0.324), and RMT-E (r = -0.035, p = 0.734).

With regards to questionnaires related to technology use and videogame experience, ATE was significantly correlated with average screen time (r = -0.256, p = 0.011), playing first-person perspective video games (ϱ = -0.305, p = 0.002), and playing video games that involve navigation (ϱ = -0.454, $p < 0.001$), noting that greater screen time, having experience with first-person perspective video games, and having experience with navigation games were linked to better game performance.

On the other hand, other self-reported variables that were not significantly correlated with ATE included, ADHD-RS ($r = 0.095, p = 0.354$), SBSOD-P ($r = -0.115, p = 0.265$), and SBSOD-C ($r = -0.199, p = .054$).

3.3 Predictors of ATE with regression analysis

A linear multiple regression analysis was used to test if exact age and gender significantly predicted game performance in terms of ATE. The results of the regression analysis indicated that the two predictors explained 11.2% of the variance ($R^2 = 0.112, F_{(2,96)} = 5.927, p = 0.004$). It was found that age significantly predicted ATE ($\beta = -0.310, p = 0.02$) in that older children performed better, whereas gender was not a significant predictor of ATE ($\beta = 0.138, p = 0.158$).

In order to explore the relative contribution of other variables on ATE, a stepwise multiple linear regression analysis generated a model for predicting ATE. To address the possibility of multicollinearity, a correlation matrix of variables found significantly correlated with ATE (exact age, CCTT-1, DS, SSB, HVOT, average screen time, first person game experience, and navigation game experience) was created. First-person game experience and navigation game experience were significantly correlated, $r = 0.791, p < 0.001$), whereas correlations between other predictor variables did not exceed $r = +/- 0.366$. As such, first person game experience was removed as a predictor variable. Measures of tolerance (all exceeded 0.20) and Variance Inflation Factor (all less than 10) did not indicate problems of multicollinearity within the final model. Scatterplot analyses were also performed to examine for violations of the assumptions of normality, linearity, and homoscedasticity.

The following were entered into a stepwise regression as dependent variables: exact age, CCTT-1, DS, SSB, HVOT, average screen time, and navigation game experience, while ATE was the dependent variable. Results from the regression analysis (Table 19) revealed that a

model with navigation experience alone accounted for 19.1% of variance in ATE ($R^2 = 0.191$, $F_{(1,93)} = 22.372$, $p < 0.001$). In the second model, addition of SSB as a predictor variable improved the amount of variance accounted for in ATE scores to 29.1% ($R^2 = 0.291$, $F_{(3,93)} = 19.275$, $p < 0.001$). Finally, the last model with navigation game experience, SSB, and HVOT as predictor variables accounted for a total of 32.7% of the variance in ATE ($R^2 = 0.327$, $F_{(3,93)} = 15.03$, $p < 0.001$). The inclusion of other variables did not significantly account for additional variance in ATE. In summary, after navigation game experience was accounted for, SSB and HVOT were significant predictors of ATE. This suggests that skills related to spatial memory, working memory, visuospatial integration, perceptual organization are necessary for good performance on the computer game task.

Table 19 *Multiple regression of game experience and cognitive variables on average time efficiency scores*

Variable	R^2	R^2 Change	B	SE B	β	p
Model 1	0.191	0.191				
Nav			-2.079	0.439	-0.437	<0.001
Model 2	0.291	0.100				
Nav			-1.762	0.423	-0.370	<0.001
SSB			-0.238	0.065	-0.323	<0.001
Model 3	0.327	0.036				
Nav			-1.648	0.417	-0.346	<0.001
SSB			-0.208	0.066	-0.282	0.002
HVOT			-0.122	0.055	-0.196	0.029

R^2 - the variance accounted for in ATE by predictors altogether in the equation; R^2 - the change in R^2 value when another predictor is added to the equation; B – unstandardized coefficient; *SE B* – standard error of B; β – standardized coefficient; *p – significance level*.

3.4 Comparison of ATE between children and adults

In order to understand how children perform on the computer task in comparison to adults, an analysis of covariance (ANCOVA) was done with navigation experience as the covariate. Participants were divided into five age groups (7 year olds, 8 year olds, 9 year olds, 10 year olds, and young adults) to perform a one-way ANCOVA, with navigation experience controlled for. Levene's test of homogeneity of variance was significant, ($F_{(4, 212)} = 3.467, p = 0.009$) indicating that the assumption of homogeneity of variance was violated. However, the ratio variance for this data set was $2.85^2 / 1.12^2 = 6.48$, which reasonably suggested that the variance is heterogeneous. Nonetheless, a more conservative significance level cut off of p = 0.01 was applied in order to address a "liberal" *F* statistical test (Maxwell & Delaney, 2004).

The analysis revealed a significant effect of age on ATE after controlling for navigation experience ($F_{(4, 207)} = 8.539, p < 0.001$). Bonferoni-corrected post hoc analysis revealed that seven year olds (M = 6.26, SD = 1.97) did not perform significantly worse than eight (M = 6.51, SD = 2.38, $p = 1.00$) and nine year olds (M = 5.60, SD = 2.85, $p = 1.00$) but they performed significantly worse than ten year olds (M = 4.33, SD = 1.12, $p = 0.002$). Eight year olds did not perform significantly worse than nine year olds ($p = 0.513$) but they were significantly slower than ten year olds at solving the task ($p < 0.001$). Finally, the nine year olds performed just as well as ten year olds ($p = 0.158$).

The group of best game performers amongst children (i.e., 10 year olds) was compared to young adults (M = 3.11, SD = 1.23), who presumably have full or close to fully developed

spatial skills. A post hoc comparison found 10 year olds performed significant worse than young adults ($p = 0.005$), after Bonferroni correction for multiple comparisons (Figure 10). To summarize, the oldest group of children who were the fastest at completed the video game task were still not as fast as adults.

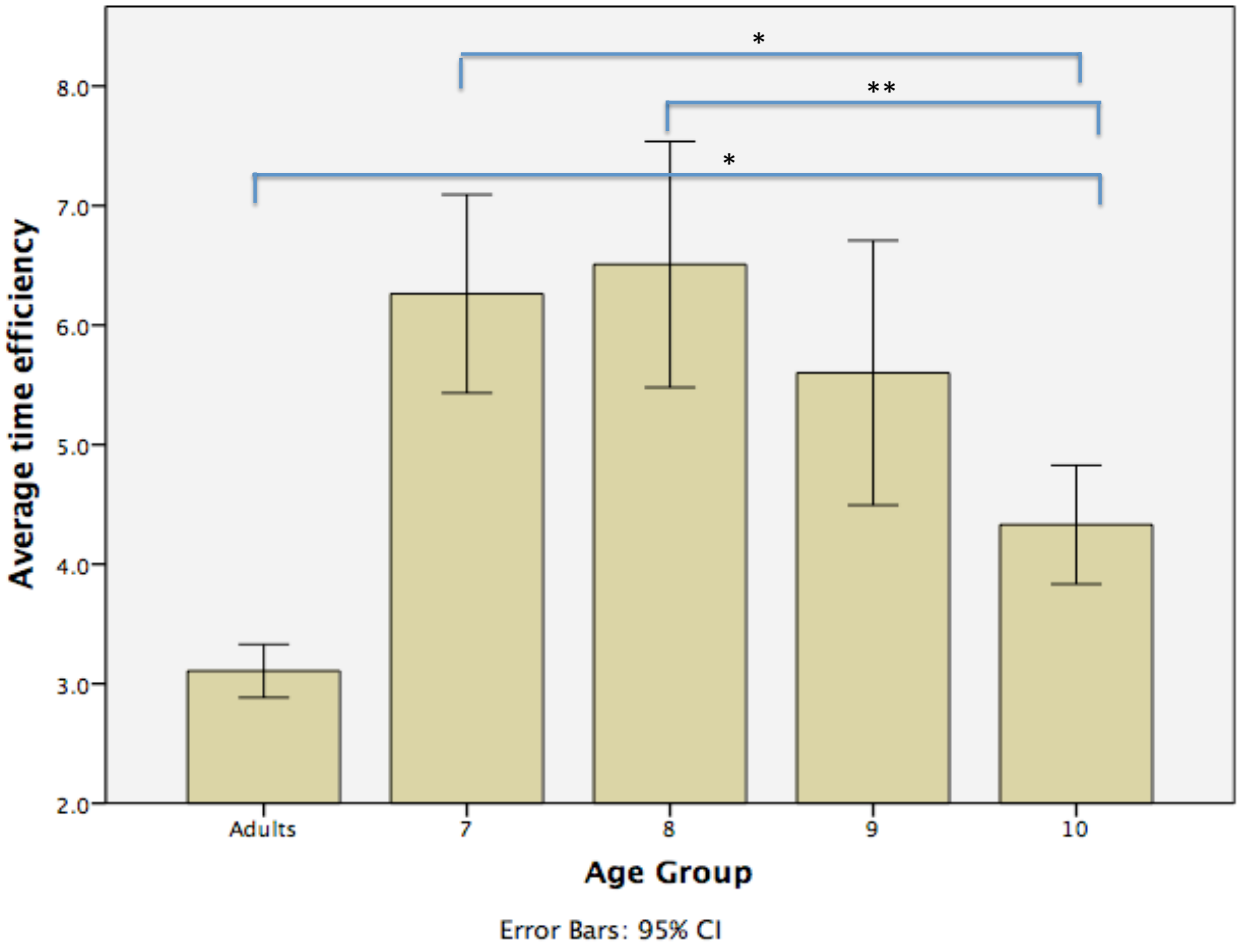

Figure 10. Comparison of game performance between age groups, as assessed by average time efficiency. * indicates Bonferoni-corrected post hoc comparisons significant at p = 0.01; ** indicates significance at p = 0.001.

3.5 Correlation between average time efficiency (ADE) and other measures

ADE was significantly correlated with exact age (r = - 0.304, p = 0.002), which indicated older children tended to travel less distance to reach goal target, compared to younger children. ADE was not significantly correlated with social economic status (ϱ = -0.184, p = 0.075).

Regarding neuropsychological measures, better ADE scores were significantly correlated with better performance on CCTT-1 (r = 0.203 p = 0.046), SSB (r = -0.413 p < 0.001), and HVOT (r = -0.316, p = 0.002). No significant correlations were found between ADE and CCTT-2 (r = 0.097, p = 0.347), BD (r = 0.115, p = 0.263), VC (r = -0.102, p = 0.320), DS (r = -0.098, p = 0.340), CA (r = -0.144, p = 0.159), SSF (r = -0.002, p = 0.986), RMT-T(r = -0.113, p = 0.271), and RMT-E (r = 0.065, p = 0.527).

Significant correlations were found between ADE and average screen time (ϱ = -0.364, p < 0.001), as well as both first-person perspective video games experience (ϱ = -0.224, p = 0.027) and navigational game experience (ϱ = -0.403, p < 0.001). More screen time, having experience with first-person video games, and having experience with navigation games were linked to better ADE scores.

ADE was also significantly correlated with SBSOD-C (r = -0.303, p =0 .003). The inverse correlation suggested that children who rated their own spatial abilities as more proficient tended to perform better on the computer game. However, ADE was not significantly correlated with ADHD-RS (r = 0.083, p = 0.420) and SBSOD-P (r = -0.112, p = 0.279).

With exception of the non-significant correlation found between DS and ADE and the significant correlation between SBSOD-C and ADE, the patterns of significant correlation with other variables remain very similar in terms of directionality and magnitude to ones found from the ATE analysis.

3.6 Predictors of ADE with regression analysis

A linear multiple regression analysis was used to test if exact age and gender significantly predicted game performance in terms of ADE. The results of the regression indicated that the two predictors explained 9.4% of the variance ($R^2 = 0.094$, $F_{(2,96)} = 4.896$, $p = 0.009$). It was found that age significantly predicted ADE ($\beta = -0.232$, $p = 0.002$) in that older children performed better, whereas gender was not a significant predictor of ADE ($\beta = 0.084$, $p = 0.654$).

A stepwise multiple linear regression analysis generated a model for predicting ADE. To address the possibility of multicollinearity, first person game experience was again removed as a predictor variable. Exact age, CCTT-1, SSB, HVOT, average screen time, navigation game experience, and SBSOD-C were entered as independent variables, whereas ADE was imputed as the dependent variable into a stepwise regression analysis. Results from the regression analysis (Table 20) revealed that a model with SSB performance alone accounted for 16.7% of variance in ADE ($R^2 = 0.167$, $F_{(1,93)} = 18.397$, $p < 0.001$). In the second model, addition of navigation experience as a predictor variable improved the amount of variance accounted for to 27.5% ($R^2 = 0.275$, $F_{(2,93)} = 17.297$, $p < 0.001$). In the third model, addition of SBSOD-C ratings as a predictor variable improved the amount of variance accounted for in ADE scores to 32.9% ($R^2 = 0.329$, $F_{(3,93)} = 14.681$, $p < 0.001$). Finally, the last model with average screen time added as a predictor variable accounted for a total of 37.0% of the variance in ADE ($R^2 = 0.370$ $F_{(4,93)} = 13.087$, $p < 0.001$). The inclusion of other variables did not significantly account for additional variance in ADE.

Table 20 *Multiple regression of game experience and cognitive variables on average distance efficiency scores*

Variable	R^2	R^2 Change	B	SE B	β	p
Model 1	0.167	0.167				
SSB			-0.126	0.028	-0.408	<0.001
Model 2	0.275	0.108				
SSB			-0.106	0.028	-0.341	<0.001
Nav			-0.662	0.179	-0.337	<0.001
Model 3	0.329	0.054				
SSB			-0.098	0.027	-0.317	0.001
Nav			-0.626	0.174	-0.318	0.001
SBSOD-C			-0.298	0.112	-0.233	0.009
Model 4	0.370	0.041				
SSB			-0.079	0.028	-0.255	0.006
Nav			-0.484	0.179	-0.246	0.008
SBSOD-C			-0.323	0.109	-0.253	0.004
Ave screen			-0.070	0.029	-0.229	0.017

R^2 - the variance accounted for in ADE by predictors altogether in the equation; R^2 - the change in R^2 value when another predictor is added to the equation; B – unstandardized coefficient; *SE B* – standard error of B; β – standardized coefficient; *p – significance level*.

3.7 Comparison of ADE between children and adults

An ANCOVA was done with navigation experience as the covariate. Participants were again divided into five age groups (7 year olds, 8 year olds, 9 year olds, 10 year olds, and young adults) to perform a one-way ANCOVA, with navigation experience controlled for. Levene's test of homogeneity of variance was not significant, ($F_{(4, 212)} = 1.286, p = 0.278$) indicating that the assumption of homogeneity of variance was not violated.

There is no significant effect of age on ADE after controlling for navigation experience ($F_{(4, 207)} = 0.152, p < 0.962$). There was also no significant interaction effect between age and navigation experience ($F_{(4, 207)} = 0.821, p = 0.514$), meaning that navigation experience did not affect age groups in different ways.

Chapter Four: Discussion

4.1 Summary of main findings

The main goal of the current study is to use systematic approaches in order to comprehensively investigate development of topographical orientation skills. It produced some interesting findings that help understand several general questions: 1) what is the typical developmental pattern of topographical orientation, 2) what cognitive processes drive the advancement of topographical orientation skills, and 3) which psychosocial factors are related to the development of topographical orientation. This was accomplished by having a large group of typically developing children play a computerized spatial task that assessed topographical orientation in a large new space. These children were also administered a set of neuropsychological test and self-report questionnaires.

It is widely accepted that child development involves constant interplay between biology and the environment, in a multi-layered context, in a cumulative fashion, and continues throughout the lifespan (Sameroff, 2010). In order to elucidate the nature of development of topographical orientation, the findings from this study was integrated with important factors that influence topographical orientation.

4.1.1 Age differences of topographical orientation

In general, performance on the spatial task was correlated with age, indicating that better game performance was observed for older children, consistent with my first hypothesis. There is a gradual improvement in game performance with age that likely spans into adolescence and adulthood, as even the oldest group of children in this study still performed significantly worse

than adults. Upon further examination, the results from the stepwise regression analysis indicated that biological age as a number did not predict game performance. Rather, the variability of game performance was significantly accounted for by cognitive factors and game experience, as discussed below. These factors are driving the relationship between age and game performance.

It needs to be discussed that while the results of the correlation analyses were similar between ATE and other variables and ADE and other variables, the relationships were not identical. Specifically, DS was found significantly correlated with ATE but not with ADE, and SBSOD-C was found significantly correlated with ADE but not with ATE. Further, ATE was best predicted by a model with a combination of navigation experience, SSB, and HVOT in the model, whereas ADE was best predicted by SSB, Nav, SBSOD-C, and average screen time as variables in the regression model. This suggested that ATE and ADE, while both were general measures of efficient navigation, assessed spatial navigation performance in slightly different ways. For example, a child who completed a trial with perfect performance would require the least amount of time and least travelled distance to reach the target location. On the other hand, a child who carefully evaluated the possible options to the target location and chose the best route would require more time to think and make a successful decision, which would be indicated by a poor ATE score but a good ADE score. Therefore, ATE and ADE may have tapped into different preferences for cognitive strategies and personality styles.

4.1.2 Neuropsychological performance

Overall the results showed game performance was significantly correlated with exact age and performances on several neuropsychological tests (CCTT-1, DS, SSB, and HVOT). These neuropsychologist tests have heavy emphasis on aspects of speed of information processing, working memory, attention, and visual-spatial processing. This indicated that certain visual

cognitive processes and executive functions are important in supporting the development of topographical orientation skills. Indeed, the results of a stepwise regression analysis revealed that SSB and HVOT were the most significant cognitive factors driving the relationship between age and game performance in terms of ATE. SSB also had a significant impact on game performance as assessed by ADE. Consistent with these findings, Pipers and colleagues (2010) had also found a significant relationship between performance in a virtual spatial task and attention and spatial working memory performances, as assessed by the Conners' Continuous Performance Test and SSB. Based on these results, the mere progression of age does not necessarily support development of topographical orientation. Rather, the maturation of spatial-related cognitive skills, specifically, spatial working memory, visual spatial processing, and visual spatial organization skills are key to supporting the advancement of efficient topographical orientation.

4.1.3 Video game experience

A history of video game experience that involves navigation and first person perspective was also significantly related to spatial performance. This finding was not surprising given that adults with more video game experience performed better on the spatial task (Murias *et al.,* 2016). In adults, the effect do not appear to be due to better-developed manual dexterity with game controls, as there was no relationship found between the number of motor practice trials required and later game performance (Murias *et al*., 2016). While manual dexterity was not formally assessed in children of this study, the practice motor trial helped all participants reach a specified level of performance using the controllers before the game began. In a similar vein, another recent study (Ventura, Shute, Wright, & Zhao, 2013) demonstrated that specific types of video game experience with first-person games might have an influence on navigational skills. However, it is difficult to conclude the directionality between level of spatial skills and

preference for playing navigational and / or first person perspective games based on the current study and extant literature.

4.1.4 Psychosocial factors

Game performance was not significantly correlated with socioeconomic status, as estimated by mother's highest level of education completed. This finding was somewhat surprising as socioeconomic status is often associated with health, cognitive, and socioemotional outcomes in children (Bradley & Corwyn, 2002). Socioeconomic status is estimated to predict 5% of variance in academic achievement (White, 1982). Maternal education has been found to be a strong predictor of intellectual attainment (White, 1982; Bradley & Crown, 2002). A review (Hackman & Farah, 2009) examining studies with behavioral, electrophysiological, and neuroimaging methods indicated that socioeconomic status is an important predictor of neurocognitive performance. In particular, language and executive functioning of children seem to be especially impacted by socioeconomic status of the family. Given the demands of executive functioning during topographical orientation, one would suspect that socioeconomic status also impacts topographical orientation performance. However, this relationship was not found in the current study.

From a meta-analysis (White, 1982), an interesting finding was that the relationship between socioeconomic status and cognitive attainment appears to diminish with age when comparing the strength of the relationship between a group of three and seven year old children. It is also likely that numerous other factors impact the relationship between socioeconomic status and cognitive attainment. For example, it is possible that factors such as the children's own characteristics, family characteristics, and external support systems all modulate child cognitive development.

Aligned with this viewpoint, the bioecological systems theory is a contemporary theory of early child development, also known as the ecological systems theory. This model (Bronfenbrenner 1979; Bronfenbrenner, 1986; Bronfenbrenner & Morris, 2006) proposes that multiple environmental factors and systems interact and influence individual development. Development is determined by four ecological systems nested within each other; the microsystem, mesosystem, exosystem, and macrosystem. At the centre of the system is the individual with unique factors affecting development such as sex, age, and health. Family, classmates, school, and other direct influences make up the microsystem. Connection between microsystems also impact individual development in the context of the mesosystem. The exosystem includes contexts within which the individual does not directly interact but has indirect influences on development. Finally, the macrosystem is made up of the broader social context such as laws, culture, and ideologies. Therefore, with the interplay of numerous micro and macros influences on individual development, SES may be directly or indirectly influencing each of the ecological system.

There are several possible explanations for the unexpected non-significant relationship found between SES and topographical orientation skills. First, the sample was recruited from a generally homogenous group of upper middle class Caucasian families. This may result in a non-representative biased sample that does not truly capture the diversity and variability of SES in the general population. Another possible explanation could be the operationalization of SES. Although mother's level of education is commonly used in child development research study, the present study categorizes mother's level of education into only three groups (less than high school, high school diploma or equivalent, and university / college degree or higher). This somewhat crude and artificial categorization of SES may not be sensitive enough to capture the

variability of SES within the same, thereby minimizing the power to detect the relationship between SES and topographical orientation.

Another unexpected finding was the lack of correlation between self-reported and parent reported spatial behaviours with game performance. To date, there is a lack of research examining the relationship between self-rated spatial skills and spatial performance in children. There has been effort (Newcombe, Bandura, & Taylor, 1983) to develop measurements of spatial experience in the pediatric population; however, this scale has only been applied to the study of sex differences in the adolescent population. There is limited evidence for the effect of spatial activity experience on spatial task performance in children (Baenninger & Newcombe, 1989; Newcombe, Bandura, & Taylor, 1983).

Of note, self-ratings of spatial behaviours may be particularly challenging for children who rarely have the opportunity for independent self-exploration of their environments. It is possible that the children tested in the current study rarely observes their own spatial skills because they are usually accompanied and /or led around their environments by adults. In addition, lack of supervision is considered a type of substantiated child neglect, and there are legal implications for leaving a minor unsupervised in Canada. Therefore, it is likely that children from developed Western societies have limited opportunities for independent self-explorations and opportunities to get lost and find their way again.

Issues with the self-reported rating items may have also influenced the observed results. While the Santa Barbara Sense of Direction Scale (Hegarty *et al*., 2002) has been validated in a sample of adults to examine its utility to measure of spatial knowledge and spatial skills, the current study is the first to adapt the SBSOD to children and parents. It is generally found that children from the ages of eight years old and up are reliable in their self-reports on well-being

questionnaires (Rebok, Riley, Forrest, Starfield, Green, Robertson, & Tambor, 2001; Juniper, Guyatt, Feeny, Griffith, & Ferrie, 1997; Marsh, 1986). Further, it has been found that both a younger group (6 to 12 years old) and an older group (13 to 18 years old) of children prefer Likert scales over visual analogue scales and numeric visual analogue scales, suggesting that Likert scales are appropriate for children (van Laerhoven, van der Zaag-Loonen, & Derkx, 2004). However, Marsh (1986) found that younger children and children with poorer reading skills are less able to respond to negative items on questionnaires, which may bias the interpretation of responses when a Likert scale is applied. The younger age group of children in this experiment may be less reliable at estimating their own spatial behaviour with a self-report questionnaire; hence, only SBSOD-C was significantly related to ADE.

Given the age of the sample, parents may also be unreliable observers of their children's spatial behaviour. The majority of school aged children spend a significant portion of time in school and away from home. It is therefore reasonable to assume that parents have less opportunities to observe their children in unfamiliar spatial environments when considering the age range tested. Further, some of the SBSOD items tapped into internalized thoughts (e.g., "I like to know where I am and where I'm going"), which are often difficult for parents to infer if children rarely explicitly express these thoughts. The poor reliability of parent ratings are not unique to spatial behaviour, as comparisons between parent and teacher ratings reveal that teacher ratings have better sensitivity and specificity at identifying attentional-deficit related problems (Tripp, Schaughency, & Clark, 2006). It may be beneficial for future studies to incorporate teacher ratings of spatial behaviour with self and parent reports in order to obtain better questionnaire reliability and validity.

4.1.5 Gender differences

Gender differences in spatial skills across the lifespan have been replicated by many studies (e.g., Coluccia & Louse, 2004; Halpern, 2007; Kimura, 1999; Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005; Voyer, Voyer, & Bryden, 1995). Some have suggested that gender differences in spatial tasks emerge in the beginning of school, around kindergarten or first grade. Levine and colleagues (2005) revealed that preschool boys are superior at spatial transformation and solving mazes than peer-group girls. This difference that could be observed as early as age four years of age. Some have speculated that gender differences may emerge even earlier in life but are inaccessible to reliable experimental testing until preschool (Jansen-Osmann & Wiedenbauer, 2004a).

In contrast to earlier studies, the current study did not reveal any gender differences in spatial game performance in seven- to ten-year-old children. Meta-analytic studies suggest that spatial ability is not a unitary construct, and that the magnitude of gender differences deeply depend on task demands (Coluccia & Louse, 2004; Kimura, 1999; Linn & Petersen, 1985; Voyer *et al*., 1995). Indeed, there is some evidence supporting that gender differences are less pronounced in children (Kopcha, Otumfuor, & Wang, 2014; Linn & Peterson, 1985; Miller & Halpern, 2014; Voyer, Voyer, & Bryden, 1995). It has been speculated that while gender differences are present at young ages, individual differences may be more influential at determining spatial differences than gender (Kopcha *et al*., 2014; Munzer & Stahl, 2011). Therefore, it is possible that the gender effects in the young age group of this study are not prominent enough to be detected until later life.

4.2 Theoretical considerations

The novelty and main contribution of this experiment was that the findings allow us to understand the gradual progression of topographical orientation strategies, namely the ability to build and use cognitive maps in a new environment. The superior spatial performance of older children is supported by development of several cognitive domains, specifically working spatial memory and visual spatial organization skills.

I have illustrated multiple studies that examined aspects of spatial orientation in children, but mystery remains about the underlying neural correlates supporting their acquisition and successful implementations of these skills. It is important to consider the neuromechanisms of spatial orientation skills because multiple cognitive processes are necessary for successful goal-directed navigation. This complex and important function relies on several processes that contribute to spatial cognition, such as memory, attention, perception, mental imagery and decision-making (Berthoz & Viaud-Delmon, 1999; Brunsdon, Nickels, & Colheart, 2007; Burgess, Trinkler, King, Kennedy, & Cipolotti, 2006; Corbetta, Kincade, & Shulman, 2002; Davis & Coltheart, 1999; Farah, 1989; Lepsien & Nobre, 2006; Riddoch & Humphreys, 1989). It is important to consider aspects of structural and functional brain development that can explain the timeline of topographical orientation. In adults, there is a reliable network of multiple neural correlates underlying topographical orientation, specifically allocentric representation (Arnold *et al.,* 2014). Significant advances in pediatric neuroimaging and developmental biology have revealed some clues into the maturational processes in brain structure during the first several decades of life.

One of the most studied anatomical regions in the area of spatial processing is the hippocampus, which lies within the cortex of the temporal lobe. The discovery of place cells in

this region has led to a burst of research interest in understanding its role in spatial knowledge (O'Keefe & Nadel, 1978). Proper hippocampal functioning is critical for formation and usage of cognitive maps (Tolman, 1948; Iaria, *et al.,* 2009; Kumaran & Maguire, 2005). As previous literature have found, there is a marked improvement in non-egocentric strategies around the second year of life, a possible correspondence with changes in hippocampal functioning (Sluzenski, Newcombe & Satlow, 2004). While the hippocampus completes its growth mainly during the first few years of life (Lupien, McEwen, Gunnar, & Heim, 2009), connections with other important developing brain regions continue to change and strengthen to support complex spatial functioning.

Of relevance to this study, cognitive processes linked to higher order cognitive functioning, including working memory, response inhibition, attention allocation, and abstract representation, have been linked to the prolonged development and organization of the prefrontal cortex during childhood (Goldman-Rakick, 1987; Diamond, 1988, Fuster, 1989; Casey, Giedd & Thomas, 2000). Based on post-mortem and pediatric neuroimaging studies, the prefrontal cortex appears to be one of the last brain regions to fully mature (Gogtay *et al*., 2004). The current study's spatial task demands higher order cognitive processing, consistent with functional magnetic resonance imaging studies that have demonstrated higher activation of the cortex in the superior frontal and intraparietal cortex in order children than the younger children (Klingberg, Forssberg, & Westerberg, 2002). Working memory capacity is also significantly correlated with brain activity in the same frontal and parietal regions known to be involved in the control of attention and spatial working memory.

Overall, the findings from this current study that showed continual improvements in topographical orientation skills with age align with structural and functional neuroimaging

findings of ongoing brain development throughout childhood and adolescence. What is important to consider is that while children as old as ten are still not as efficient with topographical orientation as mature adults, they already possess evidence of emerging complex strategy use of cognitive maps when learning new large scale environments. Similar to research studies supporting the adaptive combination theory, spatial topographical orientation skills in children likely comprise of different strategies available for use. With further maturation of brain processes and increase familiarity with the spatial world, children can learn to choose the best strategies to use in different situations in order to adapt to their environments.

4.3 Limitations and future directions

In order to solve the video game task, participants were free to decide which cues are important to their goal and select a strategy to accomplish that goal. While these decisions are reflective of real-world situations when one explores through an environment, it is uncertain which spatial processes children were engaging in when solving the computer task. It is possible some children were able to form mental representations of the environment in order to situate themselves within the virtual museum and navigate to the goal location. It is also possible that some children purely relied on memorizing turns, wandering around to look for landmarks, or employing no strategy at all (i.e., moved around the environment with no particular strategy and located the goal by chance). Future directions include development of tools to differentiate which spatial strategies children use during free and active navigation around a new environment and whether these strategies change with increase familiarity and knowledge of the environment.

Another limitation to the study is the lack of ecological validity. Although collateral self-reports of spatial behavioural were obtained, the results revealed that both children and parents

could be unreliable observers for different reasons. Biases occur if children do not possess the adequate language skills to fully understand the questionnaire items and if parents lack the opportunities to observe their children's skills and inner thoughts. Therefore, it is vital that future research examining topographical orientation skills with virtual paradigms also pay attention to whether spatial performance on tasks translates to real-life spatial skills.

It also needs to be highlighted that the present study is the first attempt to apply the computer game to a younger population of children. Although, previous work has demonstrated good test-retest reliability in a large sample of young adults (Murias *et al., 2016*), reliability of the computer game when used to test children remains largely unknown without further testing. It may be possible that there are unidentified reliability concerns with using the computer game to test spatial skills in 7 to 10 year-old children. Potential issues with reliability of this task, if present, would ultimately limit the interpretation of the findings.

Finally, other limitations of this study are inherent to its study design. Given the cross-sectional design, it is difficult to draw causal conclusions. We cannot exclude cohort effects to account for age differences found in this study. Longitudinal designs will need to determine the developmental progression of topographical orientation skills over time.

4.4 General Conclusion

Overall, the present study significantly contributes to the flourishing body of research in development of topographical orientation in several ways. First, results obtained from the large sample of typically developing children provide a clearer picture of developmental timelines of complex orientation strategies. Specifically, children between the ages of seven to ten show progressive development of spatial navigation skills in new environments, as assessed by

performance on a virtual reality spatial task. By age 10, children are able to solve the spatial task quite well, with the oldest group of children showing the best performance. However, 10 year-olds do not reach the same level of proficiency as young adults, providing evidence for continual growth of topographical orientation skills during late childhood. In fact, the significant difference in performance between young adults and 10 year-olds reveals that topographical orientation skills continue to advance from childhood to at least early adulthood. It is therefore reasonable to assume that children require more time and practice than adults in order gain mastery of new spatial environments

Another important finding of the present study is that it identifies several basic cognitive processes that are responsible for promoting the maturation of topographical orientation skills during aging. In particular, spatial working memory, visual spatial processing, and visual spatial organization skills are critical underlying cognitive components supporting spatial orientation and navigation. Indeed, brain development and the associated increasing capacity to process spatial information is crucial for successfully acquiring and applying complex topographical orientation strategies in large novel environments.

Implications of the present study include helping educators, parents, and clinicians understand typical development of topographical orientation in school-aged children and providing normative data for performance on a complex spatial task. By gaining knowledge of what constitutes “normal” development, it is then possible to identify children at-risk for delayed topographical orientation development. As lifelong topographical orientation deficits may significantly deteriorate quality of life and pose numerous barriers for daily functioning, it is necessary that future researcher and clinicians develop effective rehabilitative programs for those in need. The findings from the present research study also help direct future efforts to examine

specific visual cognitive processes as potential rehabilitative targets in order to help improve spatial functioning for patients.

Bibliography

Acredolo, L. P. (1978). Development of spatial orientation in infancy. *Developmental Psychology, 14*, 224-234. doi: 10.1037/0012-1649.14.3.224.

Acredolo, L. P. (1990). Behavioral approaches to spatial orientation in infancy. *Annals of the New York Academy of Sciences, 608(1)*, 596-612. doi:10.1111/j.1749-6632.1990.tb48911.x.

Acredolo, L. P., Adams, A., & Goodwyn, S. W. (1984). The role of self-produced movement and visual tracking in infant spatial orientation. *Journal of Experimental Child Psychology, 38*(2), 312-327. doi: 10.1016/0022-0965(84)90128-0.

Acredolo, L. P. & Evans, D. (1980). Developmental changes in the effects of landmarks on infant spatial behavior. *Developmental Psychology, 16*(4), 312-318. doi: 10.1037/0012-1649.16.4.312.

Baenninger, M., & Newcombe, N. S. (1989). The role of experience in spatial test performance: A meta-analysis. *Sex Roles, 20*(5), 327-245.

Bertenthal, B. I. & Campos, J. J. (1990). A systems approach to the organizing effects of self-produced locomotion during infancy. In C. Rovee-Collier and L. P. Lipsitt (Eds.), *Advances in Infancy Research, Vol. 6* (pp.1-60). Norwood, NJ: Ablex Publishing.

Bertenthal, B. I., Campos, J. J., & Barrett, K. (1984). Self-produced locomotion: An organizer of emotional cognitive, and social development in infancy. In R. Emde & R. Harmon (Eds.), *Continuities and discontinuities in development* (175-210). New York: Plenum Press.

Berthoz, A. & Viaud-Delmon, I. (1999). Multisensory integration in spatial orientation. *Opinions in Neurobiology, 9*, 708–712. doi: 10.1016/S0959-4388(99)00041-0.

Biegler, R. & Morris, R. G. M. (1993). Landmark stability is a prerequisite for spatial but not discrimination learning. *Nature, 361*, 631-633. doi: 10.1038/361631a0.

Bower, T. G. & Paterson, J. G. (1972). Stages in the development of the object concept. *Cognition, 1*(1), 47-55. doi: 10.1016/0010-0277(72)90044-3.

Bradley, R. H., & Corwyn, R. F. (2002). Socioeconomic status and child development. *Annual Review of Psychology, 53*(1), 371-399. doi: 10.1146/annurev.psych.53.100901.135233.

Bremner, J. G. & Bryant, P. E. (1977). Place versus response as the basis of spatial errors made by young infants. *Journal of Experimental Child Psychology, 23*(1), 162-171. doi: 10.1016/0022-0965(77)90082-0.

Bremner, J. G. (1978). Egocentric versus allocentric spatial coding in nine-month-old infants: Factors influencing the choice of code. *Developmental Psychology, 14*(4), 346-355. doi: 10.1037/0012-1649.14.4.346.

Brofenbrenner, U. (1979). *The ecology of human development*. Cambridge, MA: Harvard University Press.

Brofenbrenner, U. (1986). Ecology of the family as a context for human development: Research perspectives. *Developmental Psychology, 22,* 723-742. 10.1037/0012-1649.22.6.723.

Brofenbrenner, U. & Morris, P. A. (2006). The bioecological model of human development. In R. M. Lerner & W. Damon (Eds.), *Handbook of child psychology: Vol. 1, Theoretical models of human development* (6th ed., pp. 793-828). Hoboken, NJ: John Wilely.

Brunsdon, R., Nickels, L., & Coltheart, M. (2007). Topographical disorientation: Towards an integrated framework for assessment. *Neuropsychological Rehabilitation, 17*, 34–52. doi: 10.1080/09602010500505021.

Bullens, J., Székely, E., Vedder, A., & Postma, A. (2010). The effect of experience on children's ability to show response and place learning. *British Journal of Developmental Psychology, 28*(4), 909-920. doi: 10.1 348/02615 1010X487285

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

Burgess, N., Trinkler, I., King, J., Kennedy, A., & Cipolotti, L. (2006). Impaired allocentric spatial memory underlying topographical disorientation. *Reviews in the Neurosciences. 17*, 239–251.

Carruthers, P. (2005). Distinctly human thinking: Modular precursors and components. In P. Carruthers, S. Laurence, & S. Stich (Eds.). *The innate mind: Structure and contents* (pp. 69 – 88). Oxford: Oxford University Press.

Casey, B. J., Giedd, J. N., & Thomas, K. M. (2000). Structural and functional brain development and its relation to cognitive development. *Biological Psychology, 54*(1), 241-257. doi: 10.1016/S0301-0511(00)00058-2.

Cheng, K. (1986). A purely geometric module in the rat's spatial representation. *Cognition, 23*(2), 149-178. doi: 10.1016/0010-0277(86)90041-7.

Cheng, K., Huttenlocher, J., & Newcombe, N. S. (2013). 25 years of research on the use of geometry in spatial reorientation: A current theoretical perspective. *Psychonomic Bulletin & Review, 20*(6), 1033-1054. doi:10.3758/s13423-013-0416-1.

Cheng, K. & Newcombe, N. S. (2005). Is there a geometric module for spatial orientation? Squaring theory and evidence. *Psychonomic Bulletin & Review, 12*(1), 1-23. doi: 10.3758/BF03196346.

Cohen, R. & Schuepfer, T. (1980). The Representation of landmarks and routes. *Child Development, 51*(4), 1065-1071. doi:10.2307/1129545.

Coluccia, E., & Louse, G. (2004). Gender differences in spatial orientation: A review. *Journal of Environmental Psychology, 24*(3), 329-340. doi: 10.1016/j.jenvp.2004.08.006.

Corbetta, M., Kincade, J. M., & Shulman, G. L. (2002). Neural systems for visual orienting and their relationships to spatial working memory. *Journal of Cognitive Neuroscience, 14*, 508–523. doi: 10.1162/089892902317362029.

Cornell, E. H., Heth, C. D., & Broda, L. S. (1989). Children's wayfinding: Response to instructions to use environmental landmarks. *Developmental Psychology, 25*(5), 755-764. doi:10.1037/0012-1649.25.5.755.

Cornell, E. H., Heth, C. D., & Rowat, W. L. (1992). Wayfinding by children and adults: Response to instructions to use look-back and retrace strategies. *Developmental Psychology, 28*(2), 328-336. doi:10.1037/0012-1649.28.2.328.

Cornell, E. H. & Hay, D. H. (1984). Children's acquisition of a route via different media. *Environment and Behavior, 16*(5), 627-641. doi: 10.1177/0013916584165005.

Cornell, E. H. & Heth, C. D. (1979). Response versus place learning by human infants. *Journal of Experimental Psychology, Human Learning and Memory, 5(*2), 188-196. doi:10.1037/0278-7393.5.2.188.

Cousins, J. H., Siegel, A. W., & Maxwell, S. E. (1983). Way finding and cognitive mapping in large-scale environments: A test of a developmental model. *Journal of Experimental Child Psychology, 35*(1), 1-20. doi: 10.1016/0022-0965(83)90066-8.

Dalke, D. E. (1998). Charting the development of representational skills: When do children know that maps can lead and mislead? *Cognitive Development, 13*(1), 53-72. doi:10.1016/S0885-2014(98)90020-X.

Darvizeh, Z., & Spencer, C. (1984). How do young children learn novel routes? The importance of landmarks in the child's retracing of routes through the large-scale environment. *Environmental Education and Information, 3*(2), 97-105.

Davies, C. & Uttal, D. H. (2007). Map use and the development of spatial cognition. In J. Plumert & J. Spencer (Eds.), *The emerging spatial mind* (pp. 219–247). Oxford: Oxford University.

Davis, S. J. C. & Coltheart, M. (1999). Rehabilitation of topographical disorientation: An experimental single case study. *Neuropsychological Rehabilitation*. *9*, 1–30. doi: 10.1080/713755586.

DeLoache, J. S. (1989). Young children's understanding of the correspondence between a scale model and a larger space. *Cognitive Development, 4*(2), 121-139. doi: 10.1016/0885-2014(89)90012-9.

Dessalegn, B. & Landau, B. (2008). More than meets the eye: The role of language in binding and maintaining feature conjunctions. *Psychological Science, 19*(2), 189-195. doi: 10.1111/j.1467-9280.2008.02066.x.

Diamond, A., (1988). The abilities and neural mechanisms underlying AnotB performance. *Child Development, 59*, 523–527.

Diamond, A., Cruttenden, L., & Neiderman, D. (1994). AB with multiple wells: I. Why are multiple wells sometimes easier than two wells? II. Memory or memory+ inhibition? *Developmental Psychology, 30*(2), 192-205. doi: 10.1037/0012-1649.30.2.192.

Dudchenko, P. (2010). *Why people get lost: The psychology and neuroscience of spatial cognition*. Great Britain: Oxford University Press.

Dudchenko, P. A., Goodridge, J. P., Seiterle, D. A., & Taube, J. S. (1997). Effects of repeated disorientation on the acquisition of spatial tasks in rats: Dissociation between the appetitive radial arm maze and aversive water maze. *Journal of Experimental Psychology: Animal Behavior Processes, 23*(2), 194-210. doi: 10.1037/0097-7403.23.2.194.

DuPaul, G. J., Power, T. J., Anastopoulos, A. D., & Reid, R. (1998). *ADHD Rating Scale-IV: Checklists, norms, and clinical interpretation*. New York: Guilford.

Ekstrom, A. D., Arnold, A. E. G. F., & Iaria, G. (2014). A critical review of the allocentric spatial representation and its neural underpinnings: Toward a network-based perspective. *Frontiers in Human Neuroscience, 8*, 1-15, doi: 10.3389/fnhum.2014.00803.

Evans, W. & Gratch, G. (1972). The stage IV error in Piaget's theory of object concept development: Difficulties in object conceptualization or spatial localization? *Child Development, 43*(2), 682-688. doi:10.2307/1127567.

Farah, M. J. (1989). The Neuropsychology of Mental Imagery. In F. Boller & J. Grafman (Eds.), *The Handbook of Neuropsychology: Disorders of Visual Behavior* (pp. 395-413). Amsterdam, Elsevier.

Feldman, A. & Acredolo, L. (1979). The effect of active versus passive exploration on memory for spatial location in children. *Child Development, 50*, 698–704. doi: 10.2307/1128935.

Fenner, J., Heathcote, D., & Jerrams-Smith, J. (2000). The development of wayfinding competency: Asymmetrical effects of visuo-spatial and verbal ability. *Journal of Environmental Psychology, 20*(2), 165-175. 10.1006/jevp.1999.016.

Fuster, J. M. (1989). *The Prefrontal Cortex: Anatomy, Physiology and Neuropsychology of the Frontal Lobe*. Raven Press, New York.

Gallistel, C. R. (1990). *The organization of learning*. Cambridge: Bradford Books/MIT Press.

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., Nugent, T. F., Herman, D. H., Clasen, L. S., Toga, A. W., Rapoport, J. D., & Thompson, P. M. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. Proceedings of the National Academy of Sciences of the United States of America, 101(21), 8174–8179. doi: 10.1073/pnas.0402680101

Goldman-Rakic, P. S. (1987). Circuitry of primate prefrontal cortex and regulation of behavior by representational memory. In: V.B. Mountcastle, F. Plum and S.R. Geiger (Eds.), *Handbook of physiology. The Nervous System: Higher Functions of the Brain. Sect. 1, Vol V, Pt. 1*. (pp 373–417.) Bethesda: American Physiological Society.

Gouteux, S. & Spelke, E. S. (2001). Children's use of geometry and landmarks to reorient in an open space. *Cognition, 81*(2), 119-148. doi: 10.1016/S0010-0277(01)00128-7.

Gouteux, S., Vauclair, J., & Thinus-Blanc, C. (2001). Reorientation in a small-scale environment by 3-, 4-, and 5-year-old children. Cognitive Development, 16(3), 853-869.

Gratch, G., Appel, K., Evans, W., LeCompte, G., & Wright, N. (1974). Piaget's stage IV object concept error: Evidence of forgetting or object conception*? Child Development, 45*(1), 71-77. doi:10.2307/1127751.

Gratch, G. & Landers, W. F. (1971). Stage IV of Piaget's theory of infant's object concepts: A longitudinal study. *Child Development, 42*, 359-372. doi: 10.2307/1127472.

Hackman, D. A. & Farah, M. J. (2009). Socioeconomic status and the developing brain. *Trends in Cognitive Sciences, 13*(2), 65-73. doi: 10.1016/j.tics.2008.11.003.

Halpern, D. F., Benbow, C. P., Geary, D. C., Gur, R. C., Hyde, J. S., & Gernsbacher, M. A. (2007). The Science of Sex Differences in Science and Mathematics. *Psychological Science in the Public Interest : A Journal of the American Psychological Society, 8*(1), 1–51. http://doi.org/10.1111/j.1529-1006.2007.00032.x.

Haun, D. B., Rapold, C. J., Janzen, G., & Levinson, S. C. (2011). Plasticity of human spatial cognition: Spatial language and cognition covary across cultures. *Cognition, 119*(1), 70-80. doi: 10.1016/j.cognition.2010.12.009.

Harris, P. L. (1973). Perseverative errors in search by young infants. *Child Development, 44*(1), 28-33. doi: 10.2307/1127675.

Harris, P. L. (1974). Perseverative search at a visibly empty place by young infants. *Journal of Experimental Child Psychology, 18*(3), 535-542. doi: 10.1016/0022-0965(74)90131-3.

Hegarty, M., Richardson, A. E., Montello, D. R., Lovelace, K., & Subbiah, I. (2002). Development of a self-report measure of environmental spatial ability. *Intelligence, 30*(5), 425-447. doi:10.1016/S0160-2896(02)00116-2.

Herman, J. F. (1980). Children's cognitive maps of large-scale spaces: Effects of exploration, direction, and repeated experience. *Journal of Experimental Child Psychology, 29*, 126–143. doi: 10.1016/0022-0965(80)90096-X.

Hermer, L. & Spelke, E. S. (1994). A geometric process for spatial reorientation in young children. *Nature, 370*, 57-59. doi: 10.1038/370057a0.

Hermer, L. & Spelke, E. S. (1996). Modularity and development: The case of spatial reorientation. *Cognition, 61*(3), 195-232.

Hermer-Vazquez, L., Moffet, A., & Munkholm, P. (2001). Language, space, and the development of cognitive flexibility in humans: The case of two spatial memory tasks. *Cognition, 79*(3), 263-299. doi: 10.1016/S0010-0277(00)00120-7.

Hermer-Vazquez, L., Spelke, E. S., & Katsnelson, A. S. (1999). Sources of flexibility in human cognition: Dual-task studies of space and language. *Cognitive psychology, 39*(1), 3-36. doi: 10.1006/cogp.1998.0713.

Hooper, H. E. (1958). *The Hooper Visual Organization Test: Manual*. Beverly Hills, Calif.: Western Psychological Services.

Hu, Q., Zhang, J., Wu, D., & Shao, Y. (2015). Is height a core geometric cue for navigation? Young children's use of height in reorientation. *Journal of Experimental Child Psychology, 130*, 123-131. doi:10.1016/j.jecp.2014.10.003.

Hupbach, A. & Nadel, L. (2005). Reorientation in a rhombic environment: No evidence for an encapsulated geometric module. *Cognitive Development, 20*(2), 279-302. doi: 10.1016/j.cogdev.2005.04.003.

Huttenlocher, J. (2008). Coding location: the view from toddler studies. *American Psychologist, 63*(8), 641. doi: 10.1037/0003-066X.63.8.641.

Huttenlocher, J. & Lourenco, S. F. (2007). Coding location in enclosed spaces: Is geometry the principle? Developmental Science, 10(6), 741–746. doi:10.1111/j.1467-7687.2007.00609.x.

Huttenlocher, J., Newcombe, N., & Vasilyeva, M. (1999). Spatial scaling in young children. *Psychological Science, 10*(5), 393-398. doi: http://dx.doi.org/10.1006/cogp.1994.1014.

Huttenlocher, J. & Vasilyeva, M. (2003). How toddlers represent enclosed spaces. *Cognitive Science, 27*(5), 749-766. doi:10.1207/s15516709cog2705_3.

Huttenlocher, J., Vasilyeva, M., Newcombe, N., & Duffy, S. (2008). Developing symbolic capacity one step at a time. Cognition, 106(1), 1-12. doi: 10.1006/cogp.1994.1014.

Hyde, D. C., Winkler-Rhoades, N., Lee, S., Izard, V., Shapiro, K. A., & Spelke, E. S. (2011). Spatial and numerical abilities without a complete natural language. *Neuropsychologia, 49*(5), 924-936. doi:10.1016/j.neuropsychologia.2010.12.017.

Hyman, I. (2014). The rallying cry for the cognitive revolution. In U. Neisser (Ed.), *Cognitive Psychology* (xv - xvii). New York: Psychology Press.

Iaria, G., Palermo, L., Committeri, G., & Barton, J. J. S. (2009). Age differences in the formation and use of cognitive maps. *Behavioural Brain Research, 196*(2), 187-191. doi: 10.1016/j.bbr.2008.08.040.

Jansen-Osmann, P. (2007). Use of virtual environments to investigate development of spatial behavior and spatial knowledge of school-age children. *Psychological Reports, 100*(2), 675-690. doi:10.2466/PR0.100.2.675-690.

Jansen-Osmann, P. & Wiedenbauer, G. (2004a). The representation of landmarks and routes in children and adults: A study in a virtual environment. *Journal of Environmental Psychology, 24*(3), 347-357. doi: 10.1016/j.jenvp.2004.08.003

Jansen-Osmann, P., & Wiedenbauer, G. (2004b). The influence of turns on distance cognition new experimental approaches to clarify the route-angularity effect. *Environment and Behavior, 36*(6), 790-813. doi: 10.1177/0013916503262537.

Juniper, E. F., Guyatt, G. H., Feeny, D. H., Griffith, L. E., & Ferrie, P.J. (1997) Minimum skills required by children to complete health-related quality of life instruments for asthma: comparison of measurement properties. *The European Respiratory Journal, 10*, 2285-2295.

Keating, M., McKenzie, B., & Day, R. (1986). Spatial localization in infancy: Position constancy in a square and circular room with and without a landmark. *Child Development, 57*(1), 115-124. doi:10.2307/1130643.

Kimura, D. (1999). *Sex and cognition*. Cambridge, MA: MIT Press.

Klingberg, T., Forssberg, H., & Westerberg, H. (2002). Increased brain activity in frontal and parietal cortex underlies the development of visuospatial working memory capacity during childhood. *Journal of Cognitive Neuroscience, 14*(1), 1-10. doi: 10.1162/089892902317205276.

Kopcha, T. J., Otumfuor, B. A., & Wang, L. (2014). Effects of spatial ability, gender differences, and pictorial training on children using 2-D and 3-D environments to recall landmark locations from memory. *Journal of Research on Technology in Education, 47*(1), 1-20. doi:10.1080/15391523.2015.967536

Kumaran, D., & Maguire, E. A. (2005). The human hippocampus: cognitive maps or relational memory?. Journal of Neuroscience, 25(31), 7254-7259. doi: 10.1523/JNEUROSCI.1103-05.2005Lakusta, L., & Landau, B. (2005). Starting at the end: The importance of goals in spatial language. Cognition, 96(1), 1-33.

Learmonth, A. E., Nadel, L., & Newcombe, N. S. (2002). Children's use of landmarks: Implications for modularity theory. *Psychological Science, 13*(4), 337-341.

Learmonth, A. E., Newcombe, N. S., & Huttenlocher, J. (2001). Toddlers' use of metric information and landmarks to reorient. *Journal of Experimental Child Psychology, 80*(3), 225-244. doi: 10.1006/jecp.2001.2635.

Learmonth, A. E., Newcombe, N. S., Sheridan, N. & Jones, M. (2008). Why size counts: Children's spatial reorientation in large and small enclosures. *Developmental Science, 11*, 414–426. doi:10.1111/j.1467-7687.2008.00686.x.

Lee, S. A., Shusterman, A., & Spelke, E. S. (2006). Reorientation and landmark-guided search by young children: Evidence for two systems. *Psychological Science, 17*(7), 577-582. doi: 10.1111/j.1467-9280.2006.01747.x.

Lee, S. A., Sovrano, V. A., & Spelke, E. S. (2012). Navigation as a source of geometric knowledge: Young children's use of length, angle, distance, and direction in a reorientation task. *Cognition, 123*(1), 144-161. doi:10.1016/j.cognition.2011.12.015.

Lee, S. A. & Spelke, E. S. (2008). Children's use of geometry for reorientation. *Developmental Science, 11*(5), 743-749. doi: 10.1111/j.1467-7687.2008.00724.x.

Lee, S. A., & Spelke, E. S. (2010a). A modular geometric mechanism for reorientation in children. *Cognitive Psychology, 61*(2), 152-176. doi: 10.1016/j.cogpsych.2010.04.002.

Lee, S. A., & Spelke, E. S. (2010b). Two systems of spatial representation underlying navigation. *Experimental Brain Research, 206*(2), 179-188. doi:10.1007/s00221-010-2349-5.

Lee, S. A. & Spelke, E. S. (2011). Young children reorient by computing layout geometry, not by matching images of the environment. *Psychonomic Bulletin & Review, 18*(1), 192-198. doi: 10.3758/s13423-010-0035-z.

Lehnung, M., Leplow, B., Ekroll, V., Herzog, A., Mehdorn, M., & Ferstl, R. (2003). The role of locomotion in the acquisition and transfer of spatial knowledge in children. *Scandinavian Journal of Psychology, 44*(2), 79-86. doi: 10.1111/1467-9450.00324.

Lepsien, J. & Nobre, A. C. (2006). Cognitive control of attention in the human brain: insights from orienting attention to mental representations. *Brain Research. 1105*, 20–31. doi: 10.1016/j.brainres.2006.03.033.

Levine, S. C., Vasilyeva, M., Lourenco, S. F., Newcombe, N. S., & Huttenlocher, J. (2005). Socioeconomic status modifies the sex difference in spatial skill. *Psycho Sci, 16*(11), 841-5. doi: 10.1111/j.1467-9280.2005.01623.x.

Lew, A. R., Foster, K. A., & Bremner, J. G. (2006). Disorientation inhibits landmark use in 12-18-month-old infants. *Infant Behavior and Development, 29*(3), 334-341. doi: 10.1016/j.infbeh.2006.01.001.

Lew, A. R., Gibbons, B., Murphy, C., & Bremner, G. J. (2010). Use of geometry for spatial reorientation in children applies only to symmetric spaces. *Developmental Science, 13*(3), 490-498. doi:10.1111/j.1467-7687.2009.00904.x.

Lezak, M. D., Howieson, D. B., & Loring, D. W. (2004). *Neuropsychological assessment* (4th ed.). New York: Oxford University Press.

Liben, L. S., Myers, L. J., Christensen, A. E., & Bower, C. A. (2013). Environmental‐Scale Map Use in Middle Childhood: Links to Spatial Skills, Strategies, and Gender. *Child development, 84*(6), 2047-2063. doi:10.1111/cdev.12090.

Lichtenberger, E. O., Kaufman, A. S., & Lai, Z. C. (2001). *Essentials of WMS-III Assessment*. New York: John Wiley & Sons, Inc.

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

Liu, I., Levy, R. M., Barton, J. J. S., & Iaria, G. (2011) Age and gender differences in various topographical orientation strategies. *Brain Research, 1410*(2), doi: 10.1016/j.brainres.2011.07.005.

Llorente, A. M., Voigt, R. G., Williams, J., & Frailey, J. K. (2009). Children's color trails test 1 & 2: Test-retest reliability and factorial validity, *Clinical Neuropsychologist, 23*(4), 645-660). doi:10.1080/13854040802427795.

Llorente, A. M., Williams, J., Satz, P., & D'Elia, L. F. (2003). *Children's Color Trails Test professional manual*. Lutz, FL: Psychological Assessment Resources.

Loomis, J. M., Klatzky, R. L., & Golledge, R. G. (2001). Navigating without vision: Basic and applied research. *Optometry and Vision Science, 78*(5), 282–289. doi: 10.1097/00006324-200105000-00011.

Lopez, M. N., Lazar, M. D., & Oh, S. (2003). Psychometric properties of the Hooper Visual Organization Test. *Assessment, 10,* 66-70. doi: 10.1177/1073191102250183.

Lourenco, S. F., Addy, D., & Huttenlocher, J. (2009). Location representation in enclosed spaces: What types of information afford young children an advantage? *Journal of Experimental Child Psychology, 104*(3), 313-325. doi: 10.1016/j.jecp.2009.05.007.

Lourenco, S. F., & Cabrera, J. (2015). The potentiation of geometry by features in human children: Evidence against modularity in the domain of navigation. *Journal of Experimental Child Psychology, 140*, 184-196. doi:10.1016/j.jecp.2015.07.007.

Lourenco, S. F. & Huttenlocher, J. (2006). How do young children determine location? Evidence from disorientation tasks. *Cognition, 100*(3), 511-529. doi: 10.1016/j.cognition.2005.07.004.

Lourenco, S. F. & Huttenlocher, J. (2007). Using geometry to specify location: Implications for spatial coding in children and nonhuman animals. *Psychological Research, 71*(3), 252-264. doi: 10.1007/s00426-006-0081-3.

Lourenco, S. F. & Huttenlocher, J. (2008). The representation of geometry cues in infancy. *Infancy, 13,* 103-127. doi: 10.1080/15250000701795572.

Lourenco, S. F., Huttenlocher, J., & Vasilyeva, M. (2005). Toddlers' representation of space. The role of viewer perspective. *Psychological Science, 16*(4), 255-259. doi: 10.1111/j.0956-7976.2005.01524.x.

Lupien, S. J., McEwen, B. S., Gunnar, M. R., & Heim, C. (2009). Effects of stress throughout the lifespan on the brain, behaviour and cognition. *Nature Reviews Neuroscience, 10*(6), 434 – 445.

Maier, N. R. (1936). Reasoning in children. *Journal of Comparative Psychology, 21*(3), 357-366. doi: 10.1037/h0063259.

Margules, J. & Gallistel, C. R. (1988). Heading in the rat: Determination by environmental shape. *Animal Learning & Behavior, 16*(4), 404-410.

Martin, G. M., Martin, G. M., Harley, C. W., Smith, A. R., & Hoyles, E. S. (1997). Spatial disorientation blocks reliable goal location on a plus maze but does not prevent goal location in the morris maze. *Journal of Experimental Psychology: Animal Behavior Processes, 23*(2), 183-193. doi:10.1037/0097-7403.23.2.183.

Marsh H. W. (1986) Negative item bias in rating scales for preadolescent children: a cognitive-developmental phenomenon. *Developmental Psychology, 22*, 37–49.

Maxwell, S. E., & Delaney, H. D. (2003). Designing Experiments and Analyzing Data: A Model Comparison Perspective (2). Florence, US: Routledge.

Merten, T. & Beal, C. (1999). An analysis of the Hooper Visual Organization Test with neurological patients. *The Clinical Neuropsychologist, 13,* 521-529. doi: 10.1076/1385-4046(199911)13:04;1-Y;FT521.

Miller, D. I. & Halpern, D. F. (2014). The new science of cognitive sex differences. *Trends in Cognitive Sciences, 18*(1), 37-45. doi:10.1016/j.tics.2013.10.011.

Mittelstaedt, H. & Mittelstaedt, M. L. (1982). *Homing by path integration*. New York: Springer.

Mishra, R. C., Dasen, P. R., & Niraula, S. (2003). Ecology, language, and performance on spatial cognitive tasks. *International Journal of Psychology, 38*(6), 366-383. doi: 10.1080/00207590344000187.

Mishra, R. C., Singh, S., & Dasen, P. R. (2009). Geocentric dead reckoning in Sanskrit-and Hindi-medium school children. *Culture & Psychology, 15*(3), 386-408. doi: 10.1177/1354067X09343330.

Money, J., Alexander, D., & Walker, H. T. (1965). *A standardized road-map test of direction sense: Manual*. Johns Hopkins Press.

Münzer, S. & Stahl, C. (2011). Learning routes from visualizations for indoor wayfinding: Presentation modes and individual differences. *Spatial Cognition & Computation, 11*(4), 281–312. doi: 10.1080/13875868.2011.571326.

Murias, K., Kwok, K., Castillejo, A., Liu, I., & Iaria, G. (2016). The effects of video game use on performance in a virtual navigation task. Computers in Human Behavior, 58, 398-406. doi:10.1016/j.chb.2016.01.020.

Nadel, L. & Hupbach, A. (2006). Cross-species comparisons in development: The case of the spatial "module." In Johnson M. H. & Munakata Y. (Eds.), *Attention and performance*

XXI: Processes of change in brain and cognitive development (pp. 499–511). Oxford, England: Oxford University Press.

Nardini, M., Atkinson, J., & Burgess, N. (2008). Children reorient using the left/right sense of coloured landmarks at 18–24 months. *Cognition, 106*(1), 519-527. doi: 10.1016/j.cognition.2007.02.007.

Neidhardt, E. & Popp, M. (2010). Spatial tests, familiarity with the surroundings, and spatial activity experience. *Journal of Individual Differences, 31*(2), 59-63. doi: 10.1027/1614-0001/a000010.

Newcombe, N. S., Bandura, M. M., & Taylor, D. G. (1983). Sex differences in spatial ability and spatial activities. *Sex Roles, 9*(3), 377-387.

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

Newcombe, N. S, 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., & Ratliff, K. R. (2007). Explaining the development of spatial reorientation: Modularity-plus-language versus the emergence of adaptive combination. In J. Plumert & J. Spencer (Eds.), *The emerging spatial mind* (pp. 53–76). Oxford: Oxford University Press

Newcombe, N. S., Ratliff, K. R., Shallcross, W. L., & Twyman, A. D. (2010). Young children's use of features to reorient is more than just associative: Further evidence against a modular view of spatial processing. *Developmental Science, 13*(1), 213-220. doi: 10.1111/j.1467-7687.2009.00877.x.

O'Keefe, J. & Nadel, L. (1978). The hippocampus as a cognitive map. Oxford, Clarendon.

O'Keefe, J., Nadel, L., Keightley, S., & Kill, D. (1975). Fornix lesions selectively abolish place learning in the rat. *Experimental Neurology, 48*(1), 152-166. doi:10.1016/0014-4886(75)90230-7.

Pappas, D. (2006). ADHD Rating Scale-IV: Checklist, norms, and clinical interpretation. *Journal of Psychoeducational Assessment, 24,* 172-178. doi: 10.1177/0734282905285792.

Piaget, J. (1954). *The construction of reality in the child*. New York: Basic Books.

Piaget, J. & Inhelder, B. (1948 / 1967). *The child's conception of geometry*. London: Routledge and Kegan Paul.

Piper, B. J., Acevedo, S. F., Craytor, M. J., Murray, P. W., & Raber, J. (2010). The use and validation of the spatial navigation memory island test in primary school children. *Behavioural Brain Research, 210*(2), 257-262, doi:10.1016/j.bbr.2010.02.040.

Piper, B. J., Acevedo, S. F., Edwards, K. R., Curtiss, A. B., McGinnis, G. J., & Raber, J. (2011). Age, sex, and handedness differentially contribute to neurospatial function on the Memory Island and Novel-Image Novel-Location tests. *Physiology & Behavior, 103*(5), 513-522. doi: 10.1016/j.physbeh.2011.03.024.

Presson, C. C. (1982). Strategies in spatial reasoning. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 8*(30) 242-251. doi:10.1037/0278-7393.8.3.243

Pyers, J., Shusterman, A., Senghas, A., Spelke, E., Emmorey, K., & Purves, D. (2010). Evidence from an emerging sign language reveals that language supports spatial cognition. *Proceedings of the National Academy of Sciences of the United States of America, 107*(27), 12116-12120.

Ratliff, K. R. & Newcombe, N. S. (2008). Reorienting when cues conflict: Evidence for an adaptive-combination view. *Psychological Science, 19*(12), 1301 – 1307. doi: 10.1111/j.1467-9280.2008.02239.x.

Rebok, G., Rilely, A., Forrest, C., Starfield, B., Green, B., Robertson, J., & Tambor, E. (2001). Elementary school-age children's reports of their health: A cognitive interviewing study. *Quality of Life Research, 10*, 59-70. doi: 10.1023/A:1016693417166.

Riddoch, M., Humphreys, G., 1989. Finding the way around topographical impairments. In: J.W. Brown (Ed.), *Neuropsychology of visual perception* (pp. 79-103). Hillsdale, Lawrence Erlbaum Associates.

Rieser, J. J. (1979). Spatial orientation of six-month-old infants. *Child Development, 50,* 1078-1087. doi:10.2307/1129334.

Rissotto, A., & Tonucci, F. (2002). Freedom of movement and environmental knowledge in elementary school children. Journal of environmental Psychology, 22(1), 65-77. doi: 10.1006/jevp.2002.0243.

Ruggiero, G., Sergi, I., & Iachini, T. (2008). Gender differences in remembering and inferring spatial distances. *Memory, 16*(8). 821-835. doi: 10.1080/09658210802307695.

Sandamas, G. & Foreman, N. (2007). Spatial reconstruction following virtual exploration in children aged 5–9 years: Effects of age, gender and activity–passivity. *Journal of Environmental Psychology, 27*(2), 126-134. doi:10.1016/j.jenvp.2007.03.001

Sack, A. T., Sperling, J. M., Prvulovic, D. & Formisano, E. (2002). Tracking the mind's image in the brain II: Transcranial magnetic stimulation reveals parietal asymmetry in visuospatial imagery. *Neuron, 35*(1), 195-204. doi:10.1016/S0896-6273(02)00745-6.

Sameroff, A. J. (2010). A unified theory of development: A dialectic integration of nature and nurture. *Child Development, 81*, 6-22.

Sandberg, E. H., Huttenlocher, J., & Newcombe, N. (1996). The development of hierarchical representation of twodimensional space. *Child Development, 67*, 721–739. doi: 10.2307/1131858.

Shusterman, A., Lee, S. A., & Spelke, E. S. (2011). *Cognitive effects of language on human navigation*. *Cognition, 120*(2), 186-201. doi:10.1016/j.cognition.2011.04.004.

Shusterman, A. & Spelke, E. S. (2005). Language and the development of spatial reasoning. In P. Carruthers, S. Laurence, & S. Stich (Eds.), *The innate mind: Structure and contents* (pp. 89-106). New York, NY: Oxford University Press.

Seidel, W. T. (1994). Applicability of the Hooper Visual Organization Test to pediatric populations: Preliminary findings. *Clinical Neuropsychologist, 40,* 1459-1463. doi: 10.1080/13854049408401543.

Siegel, A. W., & White, S. H. (1975). The development of spatial representations of large-scale environments. Advances in Child Development and Behavior, 10, 9-55.

Sluzenski, J., Newcombe, N. S., & Satlow, E. (2004). Knowing where things are in the second year of life: Implications for hippocampal development. *Journal Of Cognitive Neuroscience, 16*(8), 1443-1451. doi:10.1162/0898929042304804.

Smith, L. B., Thelen, E., Titzer, R., & McLin, D. (1999). Knowing in the context of acting: The task dynamics of the A-not-B error. *Psychological Review, 106*(2), 235-260. doi:10.1037/0033-295X.106.2.235

Spelke, E. S. (2003). What makes us smart? Core knowledge and natural language. In D. Gentner & S. Goldin-Meadow (Eds.). *Language in mind: Advances in the study of language and thought*. Cambridge, MA: MIT Press

Spelke, E. S., Lee, S. A., & Izard, V. (2010). Beyond core knowledge: Natural geometry. *Cognitive Science, 34,* 863 – 884. doi: 10.1111/j.1551-6709.2010.01110.x

Spencer, C. & Darvizeh, Z. (1981). Young children's descriptions of their local environment: A comparison of information elicited by recall recognition and performance techniques of investigation. *Environmental Education and Information*, *1*(4), 275-84.

Stea, D., Kerkman, D. D., Piñon, M. F., Middlebrook, N. N., & Rice, J. L. (2004). Preschoolers use maps to find a hidden object outdoors. *Journal of Environmental Psychology, 24*(3), 341-345. doi: 10.1016/j.jenvp.2004.05.003.

Thelen, E. & Smith, L. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge: MIT Press.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological review, 55*(4), 189. doi:10.1037/h0061626.

Tripp, G. Schaughency, E. A., & Clark, B. (2006). Parent and teacher rating scales in the evaluation of Attention-deficit Hyperactivity Disorder: Contribution to diagnosis and differential diagnosis in clinically referred children. *Journal of Developmental and Behavioural Pediatrics, 27*(3), 209-218.

Twyman, A. D., Newcombe, N. S. and Gould, T. J. (2013), Malleability in the development of spatial reorientation. *Developmental Psychobiology*, *55,* 243–255. doi:10.1002/dev.21017.

Uttal, D. H. (2000). Maps and spatial thinking: A two-way street. *Developmental Science, 3*(3), 282-286.

Uttal, D. H., Fisher, J. A., & Taylor, H. A. (2006). Words and maps: Developmental changes in mental models of spatial information acquired from descriptions and depictions. *Developmental Science, 9*(2), 221-235. doi: 10.1111/j.1467-7687.2006.00481.x.

van Laerhoven, H., van der Zaag-Loonen, H. and Derkx, B. (2004), A comparison of Likert scale and visual analogue scales as response options in children's questionnaires. *Acta Paediatrica, 93*, 830–835. doi:10.1111/j.1651-2227.2004.tb03026.x.

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

Ventura, M., Shute, V., Wright, T., & Zhao, W. (2013). An investigation of the validity of the virtual spatial navigation assessment. *Frontiers in Psychology, 4*, 852. doi:10.3389/fpsyg.2013.00852.

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.

Wang, R. F., Hermer, L., & Spelke, E. S. (1999). Mechanisms of reorientation and object localization by children: A comparison with rats. *Behavioral Neuroscience, 113*(3), 475-485. doi: 10.1037/0735-7044.113.3.475.

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.

Wechlser, D. (1987). *WMS-III administration and scoring manual*. San Antonio, Texas: The Psychological Corporation.

Wechsler, D. (2003). *WISC-IV technical and interpretive manual*. San Antonio, Texas: The Psychological Corporation.

Wellman, H., Cross, D., Bartsch, K., & Harris, P. (1986). Infant search and object permanence: A meta-analysis of the A-not-B error. *Monographs of the Society for Research in Child Development, 51*(3), 1-67. doi:10.2307/1166103.

Whishaw, I. Q. & Kolb, B. (1984). Decortication abolishes place but not cue learning in rats. *Behavioural Brain Research, 11*(2), 123-134. doi: 10.1016/0166-4328(84)90135-9.

White, K. R. (1982). The relation between socioeconomic status and academic achievement. *Psychological Bulletin, 91*(3), 461-481. doi:10.1037/0033-2909.91.3.461.

Appendix A1

Parent Adapted Santa Barbara Sense of Direction Scale (SBSOD-P)

After reading each statement carefully, circle the number that indicates how well each statement applies to your child. If you are unsure or have not observed these behaviors in your child, circle unsure.

1. My child is very good at giving spatial directions

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

2. My child has poor memory for where he/she left things

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

3. My child is very good at judging distances

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

4. My child's "sense of direction" is very good

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

5. My child tends to think of environment in terms of cardinal directions (N, E, S, W)

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

6. My child gets lost very easily in a new city

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

7. My child enjoys reading maps

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

8. My child has trouble understanding spatial directions

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

9. My child is very good at reading maps

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

10. My child doesn't remember routes very well while travelling in a car

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

11. My child doesn't enjoy giving directions

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

12. It is not important to my child to know where he or she is

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

13. My child can usually remember a new route after he or she has travelled it only once

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

14. My child doesn't have a very good "mental map" of his or her environment

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

15. My child is good at recognizing familiar places

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

16. My child is good at discriminating between left and right

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

17. My child gets lost easily in familiar environments that he or she visits at least once a month

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

18. When my child gets lost, it is difficult for him or her to find the way back

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

19. My child likes to explore new environments

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

20. My child frequently visits new or unfamiliar environments (e.g., a park that he or she has never been to before)

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

Appendix A2

Child Adapted Santa Barbara Sense of Direction Scale (SBSOD-C)

1. I am very good at giving directions to help people find places or things

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

2. I forget where I leave things

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

3. I am good at guessing how far away things are

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

4. I can imagine directions

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

5. I like to use north, west, east, south when I find places

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

6. I get lost easily

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

7. I like to read maps

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

8. It is hard for me to follow directions to new places

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

9. I am good at reading maps

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

10. I don't usually remember how to get to places

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

11. I don't like giving people directions

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

12. I like to know where I am and where I'm going

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

13. I can remember how to get somewhere after going there once

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

14. I can imagine where things are in my environment

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

15. I am good at knowing when I've been to a place before

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

16. I can tell the difference between left and right

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

17. I get lost in my own neighborhood

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

18. When I am lost, I cannot find my way back

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

19. I like visiting new places

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

20. I visit new places often

Strongly agree 1 2 3 4 5 6 7 Strongly disagree Unsure

Appendix A3

ADHD Rating Scale

Circle the number that *best describes* your child's home behavior over the past 6 months

1. Fails to give close attention to details or makes careless mistakes in schoolwork

Never or rarely	Sometimes	Often	Very often
0	1	2	3

2. Fidgets with hands or feet or squirms in seat

Never or rarely	Sometimes	Often	Very often
0	1	2	3

3. Has difficulty sustaining attention in tasks or play activities

Never or rarely	Sometimes	Often	Very often
0	1	2	3

4. Leaves seat in classroom or in other situations in which remaining seated is expected

Never or rarely	Sometimes	Often	Very often
0	1	2	3

5. Does not seem to listen when spoken to directly

Never or rarely	Sometimes	Often	Very often
0	1	2	3

6. Runs about or climbs excessively in situations in which it is inappropriate

Never or rarely	Sometimes	Often	Very often
0	1	2	3

7. Does not follow through on instructions and fails to finish work

Never or rarely	Sometimes	Often	Very often
0	1	2	3

8. Has difficulty playing or engaging in leisure activities quietly

Never or rarely	Sometimes	Often	Very often
0	1	2	3

9. Has difficulty organizing tasks and activities

Never or rarely	Sometimes	Often	Very often
0	1	2	3

10. Is “on the go” or acts as if “driven by a motor”

Never or rarely	Sometimes	Often	Very often
0	1	2	3

11. Avoids tasks (e.g., schoolwork, homework) that require sustained mental effort

Never or rarely	Sometimes	Often	Very often

0	1	2	3

12. Talks excessively

Never or rarely	Sometimes	Often	Very often
0	1	2	3

13. Loses things necessary for tasks or activities

Never or rarely	Sometimes	Often	Very often
0	1	2	3

14. Blurts out answers before questions have been completed

Never or rarely	Sometimes	Often	Very often
0	1	2	3

15. Is easily distracted

Never or rarely	Sometimes	Often	Very often
0	1	2	3

16. Has difficulty awaiting turn

Never or rarely	Sometimes	Often	Very often
0	1	2	3

17. Is forgetful in daily activities

Never or rarely	Sometimes	Often	Very often
0	1	2	3

18. Interrupts or intrudes on others

Never or rarely	Sometimes	Often	Very often
0	1	2	3

Appendix A4

Additional Parental Questionnaire Items

Child's demographic information

Date of birth _____ Age_____

Gender [ ] female [ ] male

Current school grade_____

In order to help us describe our study sample, please provide the following information:

Ethnicity_____

Mother's highest completed grade_____

Mother's usual type of work _____

Father's highest completed grade_____

Father's usual type of work_____

Average annual household income _____

Primary language _____

Please list all languages spoken at home_____

Developmental history

Please check the box if your child has any of the following:

[ ] neurological disorder (including colorblindness)

[ ] seizure

[ ] stroke

[ ] cognitive disorder or impairment

[ ] brain damage, malformation or tumor

[ ] ADHD

[ ] learning disorder or dyslexia

[ ] developmental disorder

[ ] communication disorder

[ ] motor skills disorder

[ ] psychological or psychiatric disorder

[ ] other medical illnesses or disabilities

If you checked off one of the above, please specify_____

Do you have or has anybody expressed any concerns about your child's development or cognitive abilities? [ ] no [ ] yes

If yes, please specify_____

Do you have or has anybody expressed any concerns about your child's mood or behaviors? [ ] no [ ] yes

If yes, please specify_____

Does your child have any medical conditions you are concerned with, such as frequent headaches, infections, and etc.? [ ] no [ ] yes

If yes, please specify_____

If your child is on any medication, please list the drug name, dosage and reason for the medication(s) _____

Were there any complications that occurred during pregnancy or your child's birth?

[ ] no [ ] yes

If yes, please specify_____

Does your child have any biologically related brothers, sisters or parents with neurological conditions (e.g. epilepsy, multiple sclerosis, early stroke) or cognitive impairment (e.g. developmental delay, autism, dyslexia)? [ ] no [ ] yes

If yes, please specify_____

Extracurricular and Academic

List the sports your child likes to take part in the most. For example, swimming, baseball, skating, skateboarding, bike riding, soccer, etc.

	How often does your child spend time in each?		
	Often (>3x/wk)	Sometimes (1-2 x/wk)	Rarely (> 1x/month)
a) _____	[ ]	[ ]	[ ]
b) _____	[ ]	[ ]	[ ]
c) _____	[ ]	[ ]	[ ]
d) _____	[ ]	[ ]	[ ]

List your child's favorite hobbies, activities, and games, other than sports. For example, dolls, books, piano, crafts, cars, singing, etc. Do **not** list any computer games or TV.

How often does your child spend time in each?

	Often (>3x/wk)	Sometimes (1-2 x/wk)	Rarely (> 1x/month)
a) _____	[ ]	[ ]	[ ]
b) _____	[ ]	[ ]	[ ]
c) _____	[ ]	[ ]	[ ]
d) _____	[ ]	[ ]	[ ]

List any organizations, clubs, teams, or groups your child belongs to

How often does your child spend time in each?

	Often (>3x/wk)	Sometimes (1-2 x/wk)	Rarely (> 1x/month)
a) _____	[ ]	[ ]	[ ]
b) _____	[ ]	[ ]	[ ]
c) _____	[ ]	[ ]	[ ]
d) _____	[ ]	[ ]	[ ]

How many close friends does your child have? (Do not include siblings)

None [ ] 1 [ ] 2 or 3 [ ] 4 or more [ ]

Approximately how many times a week does your child do things with any friends outside of regular school hours? (Do not include siblings)

None [ ] 1 [ ] 2 or 3 [ ] 4 or more [ ]

Approximately how many hours a week does your child spend

a) watching TV_____

b) playing video games on TV_____ Name/Type of game_____

c) playing video games on computer_____ Name/Type of game _____

d) playing games on cell-phones_____ Name/Type of game_____

e) playing games on personal devices _____ Name/Type of game_____

f) using the computer for non-game related activities_____

Does your child play any video games that are in a first-person perspective (i.e., from the viewpoint of the game character) [ ] no [ ] yes

If yes, please specify the title of the game, if known. _____

Indicate your child's academic performance in the following areas. In answering, please consider these descriptions

Failing = not meeting grade-level expectations

Below average **=** having more difficulty than same-grade peers

Average = performing at grade-level expectations

Above average = exceeding grade-level expectations

	Failing	Below Average	Average	Above Average
a) Reading, English, or Language Arts	[ ]	[ ]	[ ]	[ ]
b) Social Studies	[ ]	[ ]	[ ]	[ ]
c) Mathematics	[ ]	[ ]	[ ]	[ ]
d) Science	[ ]	[ ]	[ ]	[ ]
Others _____	[ ]	[ ]	[ ]	[ ]
Others _____	[ ]	[ ]	[ ]	[ ]

Please list all languages your child is taught at school_____

Does your child receive any special education or remedial services or attend special classes or special schools? [ ] no [ ] yes

If yes, please specify_____

Has your child repeated any grades? [ ] no [ ] yes

If yes, please specify grade repeated and reason_____

Has your child had any academic problems in school or has his or her teachers raised any concerns? [ ] no [ ] yes

If yes, please specify the nature of the problem and when this problem began_____

Have these issues been resolved? [ ] no [ ] yes

How frequent does your child visit new environments (e.g., average times per month)? _____

List some examples of new environments you child has visited in the past month. _____

If your child has brothers or sisters, have you observed any differences in spatial orientation and navigation skills between them and your child _____

Do you have or has anybody expressed any concerns about your child's spatial orientation? [ ] no [ ] yes

If yes, please specify_____

Do you have any other observations about your child's spatial and navigational behaviors_____

Over the last five years, have your child lived primarily in an urban or rural setting? _____

Over the last five years, what country have your child lived in for the majority of the time? _____

Does your child have any biological relatives with problems in orientation or navigation? For example getting repeatedly lost in familiar environments? Please report who and give examples of issues? [ ] no [ ] yes

If yes, please specify_____

We are inviting family members with spatial orientation problems to participate in a related study conducted by NeuroLab at the University of Calgary. May we ask you to give them our contact?

[ ] no [ ] yes

Your child might be eligible for future neuroimaging or behavioral research conducted by NeuroLab. Would you like to be contacted for further information?

[ ] no [ ] yes

If yes, what is the best method and time to contact you? _____

Appendix B

Supplementary Methods and Data Analysis

In this section, related additional methods, data analysis, and discussion are discussed. First, I describe the pilot study that preceded the final data collection and analysis. Second, I describe a subgroup of the final participants who were invited to extend the spatial game assessment by repeating the testing phase. Finally, data from a subgroup of 6 year olds is provided.

Pilot study

A subset of the sample ($N = 9$**,** 6 males, mean age = 9.90, $SD = 1.11$) participated in the pilot testing of the computer game and questionnaire measures. The main goal of the pilot testing was to ensure that school-age children are able to comprehend the test instructions and complete the task within a reasonable amount of time, without excessive fatigue or frustration. Pilot testing also revealed a general user preference and familiarity with the analogue joystick on an Xbox controller over other available options, which included arrow keys on a keyboard, arrow keys on the Xbox controller, and a joystick controller. Finally, the criterion of completing the practice trial within 90 seconds was established based on the general performance of the pilot test subjects during the motor practice phase.

Additional trials of the computer game.

A small subset of children was invited to repeat the computer game after they finished all 21 trials (session 1). In these cases, the testing phase was immediately repeated after the completion of the session 1. The second testing session followed the identical order as outlined

in Table 1. Unlike the session 1, a practice phase and a guided tour did not precede session 2. Session 2 included the identical 21 trials within the same environment. The goal of administering session 2 was to understand whether children can learn to perform as well as young adults with additional time and practice.

It should be noted that the majority of children declined to repeat the computer game due to a variety of reasons, including fatigue and loss of interest. Also due to limited testing time, children who were atypically slow during the first session of the game were not invited to participate in order to ensure that the remainder of testing was completed.

Data from the young adult sample was collected by my colleagues at the University of Calgary and described in Murias *et al*., 2016. A paired sample t-test found that young adults who repeated the spatial computer game show additional gains in performance; the average time efficiency of young adults who played the game during the first time ($M = 2.97$, $SD = 1.03$) decreased during the repeated session ($M = 2.69$, $SD = 1.55$), a statistically significant decrease of 0.288 (95% CI, 0.06 to 0.51), $t_{(109)} = 2.51$, $p < 0.014$).

Similar to adults, 32 children repeated the computer game and showed a pattern of gradual improvement in performance across trials. A paired sample T-test found that (Mean age = 8.92) average time efficiency in the first session ($M = 4.86$, $SD = 1.62$) decreased when compared to the second session ($M = 3.87$, $SD = 0.97$), with the overall decrease in time efficiency (0.98) statistically significant (95% CI, 0.63 to 1.33), $t_{(31)} = 5.75$, $p < 0.001$).

In order to see whether children or young adult show more benefits from additional practice in the game, performances between groups on the repeated game performance in terms of average time efficiency were compared. Results from an analysis of variance (ANOVA) revealed that session 2 game performance significantly different between young adults and

children, $F_{(1,140)} = 16.70$, $p < 0.001$, in that adults were faster ($M = 2.69$, $SD = 1.54$) at solving the second session trials than children ($M = 3.87$, $SD = 0.97$). However, when looking at the oldest group of children, the ten year olds, their performance on the second session did not differ from adults (mean difference = 0.89, $SD = 0.42$, $p = 0.342$).

Together, this limited data analysis revealed that both children and adults are capable of additional game performance improvement when given more opportunities to learn the environment over 40 trials instead of 20 trials. It is important to note that the results obtained in Chapter 3 are most relevant to the initial phase of learning a spatial environment. It is foreseeable that with increased familiarity to this virtual spatial environment, children are capable of forming more detailed and accurate cognitive maps, as reflected by better game performance. Future research studies will need to allow children more time to familiarize with an environment in order to truly capture the latter stages of learning that occur.

These results also suggest that children as young as seven to ten are potentially able to form and use cognitive maps as well as young adults given the additional opportunities to familiarize with the environment. It may be possible that once fully formed, the quality and nature of cognitive maps, as well as their abilities to apply these maps to aid in spatial behaviours, are equivalent to that of young adults. Regardless of whether or not children may possess these capabilities, the findings from this study revealed that they are slower than adults in their learning process and require additional time and trials in order to reach comparable performance with adults.

Six year old participants

A subgroup of six year olds ($N = 9$, Males = 3, Mean age = 6.44, $SD = 0.29$) were also invited to participate in order to test whether a younger group of children are able to complete

the spatial computer task. However, data collection of the computer task and the neuropsychological battery was limited due to a number of factors, including poor comprehension of task instructions, fatigue, lack of interest, and lack of available normative data for some of the neuropsychological tests. Therefore due to limited data collection and small sample size, the group of six year old children was not included in the main analyses. Instead, their data is presented in this appendix.

An independent sample t-test between six year olds and seven year olds found that the assumption of equal variances was violated and therefore variances were not equal across both groups. Correcting for non equal variances, game performance between six year olds ($M = 5.17$, $SD = 1.47$) and seven year olds ($M = 6.26$, $SD = 1.96$) did not differ significantly, $t_{(19.22)} = -1.719$, $p = 0.102$.

These results suggested that it is possible six year olds have similar topographical orientation skills as seven year olds. However, the practical issues encountered during testing of the six year old would indicate that six year olds may face additional barriers to successful completion of the computer task. While these negative factors were not formally assessed in this study, they could include a variety of cognitive and psychological barriers such as poorer attention to the task, less cognitive and physical stamina for testing, reduced self-motivation, and less self-regulation. Future studies examining age differences in spatial performance of young groups of children will need to consider these factors when interpreting the results.