10-1-2011

Viewpoints and Frames of Reference in Spatial Memory

George S W Chan
McMaster University, gswchan@gmail.com

VIEWPOINTS AND FRAMES OF REFERENCE IN SPATIAL MEMORY

By

GEORGE S. W. CHAN, B.SC (HONOURS)

A Thesis
Submitted to the School of Graduate Studies
In Partial Fulfillment of the Requirement
For the Degree
Doctor of Philosophy

McMaster University

Doctor of Philosophy (2011) McMaster University

(Psychology, Neuroscience, and Behaviour) Hamilton, Ontario

TITLE: VIEWPOINTS AND FRAMES OF REFERENCE IN SPATIAL MEMORY

AUTHOR: George S.W. Chan, B.Sc. (University of Toronto)

SUPERVISOR: Dr. Hong-Jin Sun

NUMBER OF PAGES: 161

Preface

The purpose of the research reported in this dissertation was to explore and understand some of the underlying mechanisms involved in spatial cognition. Specifically, we focused on the contribution and interaction of non-visual and visual information toward the nature of egocentric and allocentric frames of references at various spatial scales (i.e. building size, room sized, and object layouts in peripersonal space). The following three chapters have either been previously published or are under preparation for submission. I am the major contribute to all aspects of the work.

Chapter 2 is a manuscript published in *Memory and Cognition*, 2004, volume 32, pages 51-71 by Sun, H-J., Chan, G.S.W., and Campos, J.L. titled "Active navigation and orientation-free spatial representations". The author of the current thesis is the second author of this published work whose contribution include the development of the original idea and experimental design, data collection and analysis, and manuscript preparation. The thesis supervisor is the first author of this paper, the third author is another graduate student who contributed many insightful comments on the design and interpretation of the data.

Chapter 3 is a manuscript in preparation by Chan, G.S.W., Byrne, P., Becker, S., and Sun, H-J. titled "The importance of multiple viewpoints and different features in understanding our reference frame in spatial memory". The author of the current thesis is the first author whose contribution include the development of the original idea and experimental design, data collection and analysis, and manuscript preparation. The second author is another graduate student whose contribution include the co-development of the original idea and experimental design and data collection. The third author is the supervisor of the second author who provided insightful comments on the interpretation of the data. The last author is the thesis supervisor.

Chapter four is a manuscript in preparation by Chan G.S.W. and Sun, H-J titled “Breaking down our reference frame: The role of different spatial properties and spatial updating in a scene recognition task”. The author of the current thesis is the first author whose contribution include the development of the original idea and experimental design, data collection and analysis, and manuscript preparation. The last author is the thesis supervisor.

Abstract

Previous human behavioral research has provided support for the existence of different frames of reference utilized during spatial processing that can be dependent or independent of the observer. These are known respectively as egocentric and allocentric frames of reference. However, it has been difficult to dissociate these two different processes under realistic conditions. Importantly, how these frames of reference are influenced by the visual and non-visual information is not well understood. Therefore, the studies of this thesis evaluated spatial processing utilizing realistic and ecologically valid stimuli in environments of different scales, while systematically manipulating the visual and non-visual information available during learning. We demonstrated that non-visual information generated by actively walking through an environment leads to more egocentric processing, whereas the same visual motion information presented passively via a video leads to more allocentric processing (Chapter 2). Further, characteristics of the visual scene can also influence how it is processed, dependent on the strength of the verbal identity of the features in the environment (Chapter 3). Specifically, in a small room environment subject's representations of corners-to-corners (corners do not have an obvious verbal component) were not as strongly encoded relative to each other in comparison to objects-to-objects (objects with an obvious verbal identity). Finally, we demonstrated differential influences of non-visual information dependent on whether the features in the visual scene were more allocentrically processed or egocentrically processed (Chapter Four). Specifically, when different features of layouts are made distinguishable by their identity, this lead to more allocentric processing whereas when

different features are made distinguishable by their relative position, this lead to more egocentric processing. Further, non-visual information made available during spatial updating when the observer is changing viewpoints benefitted tasks focused on differentiating changes to objects' identity and less so for differentiating changes in relative object position.

Acknowledgment

I would like thank my supervisor Hong-Jin Sun, to whom I am indebted to in terms of both academic and personal support. Also, I would like to thank my supervisory committee David Shore and Bruce Milliken.

Special thanks need to be made to Patrick Byrne, not just for his helpful insights and academic feedback but also for the wings and beers. And of course, without whom I would not have finished this thesis as smoothly, special thanks to the indelible Jenny Campos.

I would like to dedicate this thesis to my parents. Mr. Peter Chan and Mrs. Lai-Yung Tai Chan. Sir. Mam. For caring no matter what.

Table of Contents **Pages**

Chapter 4
Breaking Down our Reference Frame: The Role of Different Spatial Properties and Spatial Updating in a Scene Recognition Task

List of Figure **Pages**

Chapter 2

Chapter 3

Chapter 4

Chapter One

General Introduction

The study of spatial representations can be traced historically to the work of Tolman (1948). In his study, he proposed that rats may have a representation of their environment that is beyond their immediate visual experience and conditioning. Through a series of experiments, he demonstrated that rats placed in various mazes could demonstrate behaviours consistent with the use of different types of representations of the environment, which he termed as "cognitive maps". In one experiment, rats learned a spatial layout through navigation, after which the experimenter blocked the learned routes. It was observed that some rats were able to utilize a novel route to reach their goal while others were not able to perform the task. Based on the two types of performance, Tolman suggested that rats may have or use two different types of cognitive maps: one which is broader and comprehensive and may provide general knowledge of the vector towards the goal location; and one which is narrow and limited to a learned set of responses (e.g., turn left, go straight past a corner).

1. Neurophysiological Evidence for Spatial Processing

Neurophysiological evidence of a broader cognitive map was first observed in animal studies of rats. Researchers identified cells in the rat's brain that responded when animals were in specific places in the environment (O’Keefe & Dostrovsky, 1971; O’Keefe, 1976). Following this, the concept of place cells was formally introduced and it was proposed that they were located in the hippocampus (O’Keefe & Nadel, 1978). Place cells were observed to fire according to the stable boundary of the environment in which the animal was located. Specifically, their pattern of firing was more connected to distal cues and metric cues (Jeffery & Burgess, 2006; McNaughton et al., 2006; Jeffery, 2007; Moser et al., 2008). Although earlier work demonstrated the hippocampus as being one of the sites for the processing of cognitive maps, it may not be the only area in which spatial information is processed. More recent studies show that other structures may be processing and relaying spatial information to the hippocampus. One such area that was potentially able to do this was the medial entorhinal cortex (MEC), specifically layer II and III (Samsonovich & McNaughton, 1997; Sharp, 1999; Jeffery & Burgess, 2006; McNaughton et al. 2006; Jeffery, 2007). Previously, the MEC was thought to only amplify spatial signals sent to the hippocampus. However, it was later observed that the MEC had firing fields that formed a pattern of triangular arrays, or grid, which behaved very similarly to place cells. These "grid cells" were observed to be anchored to the geometric boundaries and landmarks of an environment (Fyhn et al. 2004; Hafting et al. 2005). Further, unlike place cells, in which firing stops or changes for landmarks that are removed from the environment, grid cells tend to keep firing for landmarks even after their removal and are also not as influenced by change in distal cues (Jeffery, 2007). Although place cells and grid cells are important for spatial memory, it has been argued that the MEC and hippocampus by themselves are still insufficient for processing and translating the encoded representation into actual goal oriented movements (Whitlock et al., 2008).

One possible area that may do this is the parietal cortex which also happens to have strong connections to the motor and pre-motor cortex, ideal for navigation and goal oriented behavior (Cavada & Goldman-Rakic, 1989; Wise, Boussaoud, Johnson, & Caminiti, 1997; Byrne, Becker, & Burgess 2007). Specifically, the posterior parietal cortex (PPC), responsible for multisensory integration, has been demonstrated to be important for spatial representations (Hussain & Nachev, 2007). It has been proposed that the visual system can be broken down into two specific types of visual processes (Goodale & Milner, 1992). Specifically, the ventral stream is responsible for the recognition of objects while the dorsal stream is responsible for processing the location of the objects in space. More recently, the PPC has been suggested to simultaneously develop multiple representations, each one responsible for a specific body-oriented action (Andersen, Essick, & Siegel, 1987; Taira, Mine, Georgopoulos, Murata, & Sakata, 1990; Goodale & Milner, 1992; Milner & Goodale, 1996; Snyder, Grieve, Brotchie, & Andersen, 1998; Andersen & Buneo, 2002). A number of studies suggests that it is possible that the MEC-hippocampal circuit could be connected to the PPC directly via the dorsal part of the lateral band of the MEC, beside the postrhinal cortex (Burwell & Amaral 1998; Kerr, Agster, Furtak, & Burwell, 2007). Or it may be connected indirectly though the postrhinal, retrosplenial, or prefrontal cortices (Whitlock et al., 2008).

In summary, there is biological evidence for a stable cognitive representation observed in the MEC-hippocampal circuit via place cells and grid cells, while a more transient goal oriented spatial representation is observed in the PPC. These two representations could correspond to the separate spatial representations proposed by Tolman (1948). However, instead of defining them in terms of broad versus narrow (Tolman, 1948), they now are seen as generally reflecting representations that are based on stable allocentric (environment centered) frames of reference in comparison to more transient egocentric (body centered) frames of reference. Importantly, potential connections between the MEC-hippocampal circuit to the PPC suggest that it is possible for an allocentric frame of reference to interact with an egocentric frame of reference.

2. Human Behavioral Studies in Spatial Processing

Early measurement of human spatial performance utilized paper and pencil tests. These tasks were thought to utilize similar cognitive resources to those used during real world spatial behaviour. For example, some studies had subjects watch an experimenter trace a pencil through a 2-D map from a bird's eye view (Money et al., 1965). The subject then had to remember the route which the experimenter drew in addition to making a judgment of which direction the experimenter was going as they traced the route. Other early tasks tested subject's ability to reorient objects or their view of objects. For example, subjects would be presented with a drawing of an object containing three attached straight segments (Shepard & Metzler, 1971; Vandenberg & Kuse, 1978) . Subjects were then required to compare this target object with an array of four other similarly drawn objects. Theses four objects were drawn in different orientations and the subject had to judge which two were the same as the target object. The results revealed that reaction time was positively correlated with the orientation difference between target and test objects, as if participants mentally rotated the representation of the test and target objects to match each other.

While traditional human studies are limited by paper and pencil tasks and verbal reports, more recent studies have focused on making tasks more ecologically valid.

Specifically, participants are immersed in the environment taking a first person perspective. This was first implemented in real world environments (Simons & Wang, 1998; Wang & Simons, 1999) and more recently, with technological advancement, in computer simulated environments (Lehmann, Vidal, & Bulthoff, 2008; Vidal, Lehmann, & Bulthoff, 2009; Annett & Bsichof, 2010).

3. Orientations and Viewpoints Differences Between Learning and Testing

To examine the type of spatial representation formed by humans when they are immersed in an environment, earlier research focused on the difference in observer's orientation between learning and testing (Presson & Hazelrigg, 1984; Presson, Delange, & Hazelrigg, 1989; May, Peruch, & Savoyant, 1995). For example, Presson, Delange, and Hazelrigg (1989) looked at spatially intrinsic conditions leading to different types of spatial representation. In their study, they wished to understand when a spatial representation is orientation specific or orientation free. To examine this issue, they had subjects learn the routes and location of features in an environment. Then they tested them by asking subjects to imagine themselves at a certain location and viewpoint within the environment and then make a directional judgement of the learned features. They determined whether or not the spatial representation subjects used was orientation specific by virtue of whether an alignment effect was observed. The alignment effect is defined as better recall of the environment from the viewpoint subjects first experienced when exposed to the environment, irrespective of the their current physical orientation. Conversely, if an alignment effect was not observed, the spatial representation used was considered to be orientation free. Further experiments led beyond the simple idea of our representation being either orientation specific or free, to the idea that there may be different frames of references utilized during spatial processing such as a body centred system that encodes self-to-features relations in the environment or an environment centred system that encodes feature-to-feature relations of the environment independent of ourselves within it (Sholl, 1987; Easton & Sholl, 1995; Sholl & Nolin 1997; Roskos-Ewoldson, McNamara, & Shelton, 1998). This body centred system is commonly referred to as an egocentric frame of reference whereas an environment centred system is referred to as an allocentric frame of reference.

A more specific extension of the concept "alignment effect" consistent with a body centred system of encoding self-to-features relations is viewpoint dependence, which factors in both the position and direction in which the observer visualize themselves to be in during recall (Diwadakar & McNamara, 1997; Shelton & McNamara, 1997). In their study, Shelton and McNamara (1997) presented subjects with an array of objects located on the floor of a small room from a single static viewpoint and were later given a scene recognition test with pictures from other viewpoints. They demonstrated increasing reaction time and error as the angle of the viewpoint tested differed from the viewpoint learned. In fact, even if subjects were presented with two viewpoints during learning, testing demonstrated two orientation specific representations, each dependent on the learned viewpoint provided by the researcher. This increase in reaction time and error as test angle increased suggested the use of a body centred system in line with the presence of an egocentric frame of reference.

4. Intrinsic Properties of the Environment

In addition to the observer's viewpoint during learning, specific environmental properties can also affect spatial memory (Mou & Mcnamara, 2002; Epstein, Graham, & Downing, 2003; McNamara, 2003; Wang & Brockmole, 2003;). For example, Mou and McNamara (2002) demonstrated that the viewpoint dependence in scene recognition tasks may in fact be modulated by surrounding environmental cues relative to the experimental stimulus. In their experiment, an array of objects was arranged on the floor of a small room in a symmetrical pattern around an intrinsic axis. In one of their conditions, subjects learned the array of objects from a viewpoint inconsistent with the intrinsic axis. Their results showed performance was actually better from an imagined viewpoint that is aligned with the intrinsic axis compared to the initial learned viewpoint. Performance was further improved if the imagined viewpoint was parallel with both the intrinsic axis of the array of objects and the walls of the room, evidence of the use of an allocentric frame of reference.

5. Spatial Updating

Numerous studies have demonstrated that non-visual information can help keep the observer up to date about their surrounding environment even when they are blindfolded (Huttenlocker & Presson, 1973; Huttenlocher & Presso, 1979; Rieser, Guth, D.A., & Hill, E.W., 1986; Rieser, 1989; Rieser, Garing, & Young, 1994). This demonstrates that in some ways our spatial representation is centred around our body and can provide relevant dynamic spatial information to us even without visual information. One key example of a human body centred system of encoding is that of spatial updating. An operational definition and example of spatial updating is best understood from a series of experiments beginning with Simons and Wang (Simons & Wang, 1998; Wang & Simons, 1999). In their study, subjects were presented with an array of objects on a rotatable table. Subjects learned the position of the objects from a single viewpoint and then were given a scene recognition task. Between learning and testing, subjects either remained stationary or moved around the table during retention. In one condition, a viewpoint shift was created by display motion in which subjects remained stationary while the table was rotated. It was observed that performance worsened compared to when neither subject nor table moved. However, in another condition, viewpoint shift was created by observer motion (spatial updating) in which subjects moved during retention while the table remained stationary. It was observed that performance was comparable to when both subjects and table moved to the same degree resulting in no viewpoint change. This result suggested that viewpoint dependence was heavily influenced by the relation of self to features in the environment and not just a matter of cognitive anchoring to specific pre-learned viewpoints.

While spatial updating can be considered to be heavily egocentrically reliant, it has been demonstrated that the benefit of spatial updating can also be affected by environmental cues. In a series of experiments similar to those of Simons and Wang (1999), Burgess et al. (2004) placed subjects in a dark room to test for the effect of spatial updating. The apparatus used included an array of glow-in-the-dark objects that were placed on a table along with glow-in-the-dark cards placed against the walls. Subjects were to remember the position of the array of glow-in-the-dark objects and, similar to Simons and Wang (1999), spatial updating was also manipulated. Their results demonstrated that spatial updating was affected by the manipulation of the environmental cues such that performance was best when both environmental and object array were simultaneously moved. This suggests that allocentric processing was involved during spatial updating.

6. Determining the Two Spatial Frame of Reference

Whether humans use either or both type of frame of reference (egocentric versus allocentric) has been the focus of numerous investigations. Some studies have proposed that we mainly utilize an egocentric representation (Wang & Spelke 2000; 2002). In Wang and Spelke (2000), subjects first learned a spatial layout and then were blindfolded and asked to point towards the location of features following either a small rotation (oriented condition) or disorientation. Subject's pointing performance was measured in terms of heading error and the variable error between features (configuration error). They argue that while heading error may increase after disorientation, if an allocentric representation was available, configuration error should be comparable between the oriented and disoriented condition. Whereas, if subjects can only rely on an egocentric representation, the configuration error should increase after disorientation. Their results showed that subject's configuration error was higher in the disoriented condition compared to the oriented condition (but this is limited to objects in the room and not the corners). They therefore concluded that subjects must rely mainly on an egocentric representation for objects.

In a similar study, Hodgson and Waller (2006) demonstrated a similar increase in configuration error after disorientation. However, when subjects pointed to objects in a well learned environment, increase in configuration error was minimal. In addition, they observed that when subjects learned the location of novel objects in a novel environment, a rotation of 135 degrees (without disorienting subjects) was sufficient to increase configuration error relative to those that occur when subjects are disoriented. They therefore argue that an allocentric representation may be generated concurrently with an egocentric representation, and that unless it depicts a well learned environment, it may be much more "coarse" then an intact egocentric representation. In general, subjects may be prompted to rely more on one type of representation over the other. The encoding of the environment may use both types of frame of reference, but certain experimental conditions may better reveal the operation of one type of representation over the other.

7. Thesis Outline

Although there is a surge of interest in the frames of reference used by human observers during spatial learning, there are still unanswered questions regarding the conditions that lead to one or both forms of spatial processing. The current thesis deals with two aspects of learning: how we learn and what we learn.

Our studies manipulated variables in the three phases of a typical spatial memory task: 1) **learning phase -** when subjects are first exposed to the environment; 2) **retention phase** - right after learning, during which subjects may or may not be provided with visual or non-visual information for spatial updating and; 3) **testing phase** - the specific task subjects are required to perform.

7.1 Chapter 2 (Navigation Experiment): Mode of Learning Can Affect Our Frame of Reference

In Chapter 2 (navigation experiment), we tried to identify the type of spatial representation developed dependent on the mode of learning. Subjects were asked to learn a spatial layout of a floor plan of a building and to give a directional judgment of a previously learned landmark. We varied the degree of body involvement during learning by asking subjects to learn the same environment through (1) walking in the actual environment; (2) navigating in a virtual rendition of the same environment using a bicycle simulator; (3) navigating in the virtual rendition of the same environment using a computer mouse; (4) passively watching the same navigation without interaction with the environment; and (5) learning through map reading. In general, we observed that the higher the degree of body involvement, the better the spatial performance overall. However, regardless of the mode of navigation, as long as subjects had active control of their navigation, the representation revealed through their spatial performance was always orientation independent. In contrast, when subjects did not retain active control, even when they received the same rich visual information provided from a first person perspective of the environment, their representation was orientation specific.

7.2 Chapter 3 (Room Experiment): Spatial Properties Learned Can Affect our Frame of References

Chapter 2 focused on the mode of spatial learning (map vs. passive navigation vs. active navigation). Chapter 3 examined whether the type of spatial property (corners vs. objects) will also affect the frame of reference used. Subjects learned the locations of objects or corners in an irregularly shaped room. They were then tested from an aligned and mis-aligned viewpoint before and after disorientation and both absolute and configuration error were calculated. Using a novel analysis combining configuration error and viewpoint variables, we identified the contribution of different combinations of the two frames of reference possibly used for objects and corners. Importantly, we postulated that the nature of the difference between objects and corners lies in the unique identities typically present among different objects.

7.3 Chapter 4 (Table Experiment): Spatial Properties and Spatial Updating

Following Chapter 3, Chapter Four focused on dissociating the different processes for the two spatial properties (position and identity). Moreover, while Chapters 2 and 3 focused on the critical factors during the learning phase that affected the frame of reference generated, the study in Chapter Four also included spatial updating during the retention phase. We adopted a scene recognition paradigm which allowed us to manipulate changes in viewpoint either through movement of the scene or the observer.

In the experiment, subjects first viewed a number of objects (set of 5 or 7 objects) on a rotatable table (during the learning phase) and then were blindfolded. Subjects then either stayed stationary or moved around the table and the table could also stay stationary or rotate by the same magnitude (during the retention phase). Subjects then took off their blindfold and performed a recognition task in which they identified a change made to the array of objects (during the testing phase). The change involved in the recognition task could either be the position of the objects or the identity of the objects. Our results showed a higher cost to performance in the position task than that of the identity task when a viewpoint change occurred as a result of table rotation. Further, performance for the identity task was affected more by manipulation of set size in comparison to the position task. This result suggest that the identity task involved more local processing while the position task involved more global processing.

Through this thesis, we have begun to understand the relation between the observer and the environment in terms of their individual and interactive influence on human spatial processing. Our results provide insights into the importance of visual and non-visual information for the formation of our spatial representation and more specifically the role of allocentric and egocentric frames of references during the encoding of our environment. In addition, our experiments highlight the need to approach scientific questions in spatial processing across different paradigms, spatial range (e.g., environment size), and tasks in order to provide general principles that can account for how the brain integrates multiple sources of spatial information into a coherent whole.

The reference for this chapter along with those of the preface, forewords, and general discussion can be found at the end of this thesis.

Chapter 2

Sun, H-J., Chan, G. S. W., and Campos, J. L. (2004). Active navigation and orientation-free spatial representations. Memory and Cognition. Vol. 32(1). 51-71

Foreword

Previous studies demonstrated that observers can encode an orientation free spatial representation when they learn a large environment by traversing through it (Presson & Hazelrigg, 1984). In comparison, observers who learn an environment by observing it from a single viewpoint encode an orientation specific representation (Roskos-Ewoldsen et al., 1998). Arguments were made that even immersed in a large environment, observers may simply encode multiple orientation specific representations (Shelton & McNamara, 1997; Roskos-Ewoldsen et al., 1998). However, difference in methodology and difficulty in controlling and replicating an experimental condition in which subjects can engage in a large navigable environment made comparison across studies limited. Further, the factors that could potentially lead to the encoding of an orientation free versus an orientation specific representation are not well understood. In this chapter we seek to address this by utilizing a large navigable virtual environment that can provide realistic visual sensation of translation to be yoked to a bicycle. Subjects could therefore navigate through the environment, generating non-visual information similar to the realistic condition of bicycling. This would allow us to systematically test for potential visual and non-visual sources of information that can influence how we encode our environment.

Memory & Cognition
2004, 32 (1), 51-71

Active navigation and orientation-free spatial representations

HONG-JIN SUN, GEORGE S. W. CHAN, and JENNIFER L. CAMPOS
McMaster University, Hamilton, Ontario, Canada

In this study, we examined the orientation dependency of spatial representations following various learning conditions. We assessed the spatial representations of human participants after they had learned a complex spatial layout via map learning, via navigating within a real environment, or via navigating through a virtual simulation of that environment. Performances were compared between conditions involving (1) multiple- versus single-body orientation, (2) active versus passive learning, and (3) high versus low levels of proprioceptive information. Following learning, the participants were required to produce directional judgments to target landmarks. Results showed that the participants developed orientation-specific spatial representations following map learning and passive learning, as indicated by better performance when tested from the initial learning orientation. These results suggest that neither the number of vantage points nor the level of proprioceptive information experienced are determining factors; rather, it is the *active* aspect of direct navigation that leads to the development of orientation-free representations.

Humans can learn and remember information about environmental spatial layouts through direct means (e.g., by navigating through the environment) or indirect means (e.g., by viewing a map or encoding verbal descriptions). Theoretical and empirical work indicates that there may be multiple ways in which to learn spatial information, which results in different spatial representations (Eichenbaum & Cohen, 2001; Golledge, 1999). To understand the nature of these representations, it is important to identify the functional distinctions between the different ways in which humans represent spatial information. One such distinction involves the degree to which one's spatial representation is orientation specific, as identified by whether or not the spatial memory is dependent on the original orientation in which the spatial layout was learned.

Orientation Specificity as Determined by Mode of Learning

One method by which humans obtain information about their environment is by reading a map, interpreting the spatial information, and utilizing this information to navigate in the real world. Levine, Jankovic, and Palij (1982) required participants to learn the spatial layout of a path by examining a two-dimensional (2-D) map and, subsequently, indicate the direction of a learned target landmark in the real world. They found that the participants were better at indicating the direction of a target landmark when they were in an orientation that was aligned with the orientation in which they learned the 2-D map than from any other orientation. This phenomenon has been demonstrated repeatedly and is commonly referred to as the *alignment effect* (Peruch & Lapin, 1993; Rossano & Warren, 1989; Warren, Rossano, & Wear, 1990). Other studies, however, have demonstrated that under certain circumstances, the alignment effect is not observed (Evans & Pezdek, 1980; Thorndyke & Hayes-Roth, 1982). In these investigations, the performance of participants who were trained with a 2-D map was compared directly with the performance of those who were trained by navigating through an environment. The results demonstrated that those who had learned the environmental layout via a 2-D map demonstrated an alignment effect, whereas those who had navigated through the environment did not. The navigational group performed equally well from an orientation either aligned or misaligned with the initial starting orientation.

A large number of studies have confirmed such a differential performance when a spatial layout is learned via a map, versus when learning occurs via direct navigation (Evans & Pezdek, 1980; May, Peruch, & Savoyant, 1995; Presson, DeLange, & Hazelrigg, 1989; Presson & Hazelrigg, 1984; Presson & Montello, 1994; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Sholl, 1987; Thorndyke & Hayes-Roth, 1982). In general, these studies have shown that when participants learn from a map, their responses are more accurate and/or faster when they are tested from an orientation that is aligned with the orientation in which

This work was supported by grants from the Natural Science and Engineering Research Council of Canada, the Canadian Foundation for Innovation, and Ontario Innovation Trust to H.-J. S. The authors thank Bruce Milliken and Pat Bennett for helpful discussions and comments on an early version of the manuscript and G. Rombough, P. Singh, and D. Zelek for their assistance in collecting data. We also thank three anonymous reviewers for helpful comments on earlier versions of the manuscript. Correspondence concerning this article should be addressed to H.-J. Sun, Department of Psychology, McMaster University, 1280 Main Street West, Hamilton, ON, L8S 4K1 Canada (e-mail: sunhong@mcmaster.ca).

they had learned the environment than when they are tested from an orientation that is misaligned with the orientation in which they had learned the environment. This implies that an *orientation-specific representation* underlies performance. In contrast, after learning through direct navigation, participants appear to form an *orientation-free representation*, so that their performance is not dependent on the orientation in which the spatial array was initially encoded (Presson & Hazelrigg, 1984).

Theories That Account for the Formation of Orientation-Free/Specific Representations

Attempts have been made to explain when or how orientation-free/specific representations are developed. One theory hypothesizes that participants develop an orientation-free representation only when they are provided with a sufficient amount of information (Evans & Pezdek, 1980; Thorndyke & Hayes-Roth, 1982). It is believed that training via a 2-D map exposes the participant to only one presentation of the stimulus from a single vantage point. However, if the participant were to actually navigate through the environment, he or she would be exposed to a succession of presentations of the environment from multiple vantage points over time, providing him or her with a larger quantity of information. Therefore, it is suggested that if the participant has learned the environment from multiple vantage points in the learning phase of the experiment, this would then allow him or her to more quickly and accurately perform such tasks as pointing to a remembered location. This theory will be referred to as the *multiple vantage points theory*.

The second theory, proposed by Presson and Somerville (1985), hypothesized that the differences observed in performance after learning through direct navigation, as compared with learning through a 2-D map, may be due to the fact that participants have directly interacted with the environment in the former. Presson and Somerville classified interactive, *real-world* navigation tasks as *primary* spatial activities. In contrast, a map-reading task may require participants to rely on symbolic representations of the features of the real environment (RE), thus allowing them to experience the environment only indirectly. These tasks were classified as falling under the category of *secondary* spatial activities. This theory will be referred to as the *primary learning theory*.

A Critical Analysis of These Two Theories

Each of the two theories above specifies particular factors that may account for the differences in performance observed following map learning, as compared with direct navigation. However, an in-depth analysis and empirical tests of these two theories are still required.

The multiple vantage points theory distinguishes between different categories of spatial representations on the basis of whether participants experience a single vantage point, as compared with multiple vantage points, with the emphasis resting on the quantitative differences in the information received. When the number of vantage points that one experiences is considered, a number of different sources of information must be taken into account: body orientation, head orientation, and eye orientation. Among the different sources of information, it is most likely that body orientation is the most informative. Although the orientation of the head and eyes provides overall spatial information, it may provide less reliable information regarding orientation within an environment. For instance, participants frequently turn their heads and visually scan an environment when moving forward along a straight path. Consequently, the number of body orientations participants assume during learning could affect whether the resulting spatial representation is orientation free or orientation specific.

The primary learning theory emphasizes that it is the *active* aspect of navigation that leads to the development of orientation-free spatial representations. One way to test this theory is to directly compare spatial performance between conditions in which participants interact with the environment and conditions in which participants passively view the same visual event. If orientation-free representations are found after active learning, but not after passive learning, this would provide critical support for this theory. Moreover, if the active aspect of spatial learning is really the determining factor in the development of an orientation-free representation, it is important to identify the critical factors involved. Two potential factors are (1) the physical motor behavior typically associated with navigation and (2) the degree of active control over one's movement and the resulting information received. Physical motor behavior consists of a sequence of locomotor activities and the associated proprioceptive/efferent and vestibular information. The degree of active control includes such factors as the allocation of attentional resources and the anticipation of the causal relation that exists between motor output and sensory information. We can assess the contributions of each of these two factors by examining conditions in which the presence of natural locomotor behavior is restricted but active control over navigation is retained. This, in turn, would allow us to determine whether an orientation-free representation would still be observed under these circumstances.

Spatial Representations Following Navigation in a Virtual Environment

Until recently, most of the studies in which the alignment effect has been examined have required participants to initially learn an environment by either studying a map or directly navigating in the real world. To explore why orientation-specific/free representations occur, it is imperative to develop other learning paradigms that will allow for the independent manipulation of the critical aspects of spatial processing mentioned above. Virtual reality (VR) technology is an ideal candidate for such a spatial-learning paradigm (Loomis, Blascovich, & Beall, 1999; Wilson, 1997).

Virtual environments (VEs) are designed to simulate our interactions with the real world by providing visual, auditory, and haptic information updated in real time. VR setups are able to track participants' actions and simultaneously update the appropriate visual and nonvisual input in response to their movements. The most commonly used input devices include keyboards, mouses, and joysticks (Richardson, Montello, & Hegarty, 1999; Tlauka & Wilson, 1996). Advanced VR setups are able to incorporate nonvisual information that is normally available in the real world (e.g., leg or body movements during locomotion), allowing users to interact with the VE in a more natural way (Chance, Gaunet, Beall, & Loomis, 1998; Kearns, Warren, Duchon, & Tarr, 2002; Klatzky, Loomis, Beall, Chance, & Golledge, 1998).

When the alignment effect has been examined specifically, the few empirical studies that have been conducted using desktop VR setups have provided mixed results. Richardson et al. (1999) demonstrated a marginal alignment effect for situations in which learning occurred by navigating in a VE and testing occurred by navigating in the real-world equivalent. Another study by Tlauka and Wilson (1996) directly compared the effects of map learning versus navigational learning in a VE. It was reported that the alignment effect was not observed in the VE navigational-learning condition but was observed in the map-learning condition.

The Rationale for the Present Study

The main focus of the present study was to examine the critical factors that lead to the typically observed development of orientation-free representations following real and virtual navigation. Our series of experiments involved having participants learn the spatial layout of a floor of a complex building (in RE, in VE, or through a map). Specifically, the participants learned the locations of a set of landmarks in the environment, after which they were positioned in a location along the learning path that was either aligned or contra-aligned with the orientation in which the path had initially been learned. The participants were then asked to make directional judgments by pointing toward the target landmarks learned along the path. Their spatial performance was assessed through measurements of pointing error and reaction time.

For the VE conditions, the participants navigated through a realistic, immersive, interactive environment containing high-quality visual duplicates of real-world environmental details presented through a head mounted display (HMD). Most importantly, the VR setup included the availability of proprioceptive information by having the participants pedal a stationary bike when navigating. It was expected that the results produced with our high-quality multisensory interface would be comparable to the results produced following real-world navigation.

In Experiment 1, we compared spatial representations obtained through map learning, through navigation in an RE, and through navigation in a VE. As was expected, no alignment effect was observed following either VE navigation or RE navigation but was observed following map learning. However, in this experiment, during navigation, the participants navigated down all the hallways in the environment, and as a result, the overall movement trajectory involved many turns. It remained possible that the orientation-free representations observed in both the VE and the RE conditions may have been a result of the multiple body orientations the participants experienced as they navigated along the path during learning.

In Experiment 2, the participants were required to maintain the same body orientation when navigating through a single path in the same building. Again, orientation-free representations were observed. The results of Experiment 2 indicated that multiple body orientations are not necessary to develop an orientation-free representation, in contrast to the predictions made by the multiple vantage points theory. An alternative explanation for why the participants developed orientation-free representations in navigation conditions is that the *active* aspect of navigating through an environment affects how participants form spatial representations.

To test this theory, in Experiment 3, we compared conditions in which participants actively navigated through an environment with conditions in which participants passively viewed the equivalent visual scene. Our results demonstrated that orientation-free representations were observed only when the participants actively navigated through the environment.

To understand the critical components in the *active* aspect of the task, in Experiment 4, we tested whether realistic proprioceptive information is critical in forming orientation-free representations. In this experiment, the participants were provided with two levels of proprioceptive information, by having them either pedal a bike (leg movements) or operate a computer mouse (hand/finger movements). An orientation-free representation was observed in both the bicycle and the mouse conditions. This suggests that minimal proprioceptive information is sufficient to produce an orientation-free representation.

EXPERIMENT 1

Typical studies in which the alignment effect has been examined using real-world navigation paradigms have been conducted in environments that are the size of a small room, with the paths marked on the floor (Palij, Levine, & Kahan, 1984; Presson et al., 1989; Presson & Hazelrigg, 1984; Roskos-Ewoldsen et al., 1998; Sholl, 1987; Sholl & Bartels, 2002). Only a few studies have tested spatial learning in a *navigable* large-scale environment beyond room size (Richardson et al., 1999; Rossano, West, Robertson, Wayne, & Chase, 1999; Sholl, 1987; Thorndyke & Hayes-Roth, 1982). In addition to the issue of the absolute size of the environment, spatial processing can be affected by whether the whole environment can be processed from a single view. Siegel (1981) recognized that there may be inherent differences in the processing of spatial layouts that can be viewed from a single glance and those that must be learned in segments, from multiple views, and integrated over time. It is important to further investigate spatial learning in large-scale environments that can be learned only through sequential exploration—for example, exploring a complex building with multiple hallways.

In the present study, we examined the spatial representations of human participants after they had learned the layout of a floor of a complex building (200 × 200 ft). Performance following learning the environment via RE navigation was compared with learning the environment via VE navigation and learning via a map. In all three conditions, the participants were subsequently tested in the RE from a position that was either aligned or contra-aligned with the originally learned orientation. On the basis of a previously established consensus, it was expected that an orientation-free representation would be formed following RE navigation and that an orientation-specific representation would be observed following map learning.

Both the multiple vantage points theory and the primary learning theory would predict that, similar to RE navigation, an orientation-free representation would be formed following VE navigation. That is, because the number of viewpoints experienced would be identical and the degree of *active* navigation would be comparable for each, one would expect that this would result in the development of similar representations.

Method

Participants

Forty-two students from McMaster University (18–25 years of age) were randomly assigned to one of the three learning conditions: the RE condition, the VE condition, and the map condition. The participants had not previously been exposed to the testing environment, and all had normal or corrected-to-normal visual acuity. The participants were compensated with either course credit or money.

Materials

RE condition. For the RE condition, navigation took place in the basement of the Kenneth Taylor Hall (KTH) building (about 200 × 200 ft) on the McMaster University campus. Distinct target landmarks from this environment were used for learning (see Figure 1). The participants estimated the direction of the target landmarks by pointing, and such estimates were measured by a circular floor dial about 2 × 2 ft in size, marked in increments of 1º.

VE condition. For the VE condition, navigation took place in a virtual simulation of the environment used in the RE condition. The VR interface consisted of a stationary mountain bike. The rear tire of the bike was equipped with an infrared sensor that collected information about the rear tire rotation speed. In addition, a potentialmeter was mounted on the handlebars to detect turning movements. Both speed and turning signals were input into the serial port of an SGI Onyx2 with an InfiniteReality2 Engine. The visual environment was rendered by the SGI computer and was presented to the participants via an HMD (V8, Virtual Research; liquid crystal display with a resolution of 640 × 480 pixels per eye and a field of view of 60º diagonal), with each eye receiving the same input. The exact three-dimensional (3-D) layout of the basement of the KTH building was simulated using Open Inventor. Most of the salient landmarks were created by texture-mapping digital photographs of the actual landmarks onto virtual landmarks. Other landmarks in the environment (such as lockers, chairs, doors, bulletin boards, etc.) were created using Showcase drawing software.

Map condition. For the map condition, the participants learned the environment by using an outline of the path of the KTH basement displayed on a 15-in. computer monitor. Locations of the target landmarks were labeled on the map and were accompanied by a picture of the corresponding landmark.

Procedure

All the experimental conditions consisted of two phases: a learning phase and a testing phase (as will be described below). Prior to the experiment, all the participants were instructed on how to use the floor dial to make a directional estimate.

Navigation conditions: RE versus VE. In the learning phase, the participants learned KTH either by being physically led by the experimenter through the RE or by navigating through a simulated version of KTH by pedaling a stationary mountain bike while being verbally directed by the experimenter's commands of "right" and "left." The participants' pedaling speed in the VE was matched to the average walking speed of the participants who learned KTH in the RE. Before the learning phase, the participants who learned the spatial layout of KTH in the VE received practice in another VE (different from the one used in the experiment) to familiarize themselves with navigating in our VE and handling the equipment.

During the learning phase, seven landmarks along the learning path were used (see Figure 1). As each landmark was pointed out and described by the experimenter, the participants were asked to face the landmark and say aloud the name of the landmark, to ensure that there was no ambiguity with respect to the identity of any of the landmarks.

The same set of target landmarks was presented in each of the two paths used, and these target landmarks were learned either from a position of east heading west (Figure 1A) or from a position of west heading east (Figure 1B). Half of the participants in each condition began learning the environment from Landmark 1, which oriented them east prior to learning, and the other half of the participants began at a position between Landmarks 4 and 5, which oriented them west prior to learning.

Prior to the testing phase, the participants were blindfolded and led to two locations along the learning path, which were designated *pointing* locations. The participants traveled a convoluted path prior to arriving at each testing location, to ensure that they would not be able to predict their location in the environment before they removed the blindfold and were tested. These two locations were chosen to ensure that all the participants were tested from both a location that was aligned (same orientation as the initially learned orientation) and a location that was contra-aligned (orientation opposite to the initially learned orientation). They were then instructed to remove the blindfold and were prompted to point to the seven target landmarks learned. None of the target landmarks was visible from the pointing location. The participants stood on the center of the dial facing 0º when making their directional estimates. The angle on the dial corresponding to the participants' pointing direction was recorded.

Map condition. The orientations in which the maps were presented were counterbalanced to control for any biases that may have existed for any particular map configuration. Specifically, half of the participants viewed a map of the KTH basement with the east side at the bottom of the map (map_e), whereas the other half viewed the same map, but with the west side at the bottom of the map (map_w). The orientations of the maps were equivalent to the initial orientation of the navigation conditions, in that map_e would be analogous to traveling from east to west in the navigation condition and map_w would be analogous to traveling from west to east in the navigation condition.

During the learning phase, the participants sat in front of a computer monitor that displayed the map. The participants were required to remember the map and to learn the location of the target landmarks on the map. The experimenter first named each of the target landmarks, and the participants were required to verbally repeat the names back to the experimenter. The order in which the landmarks were learned was the same as that in the corresponding navigation condition. Afterward, the participants were given 3 min to closely examine the map on their own.

During the testing phase, the participants were blindfolded and taken to the two designated pointing locations in the RE. The participants were then presented with a map similar to the one used in

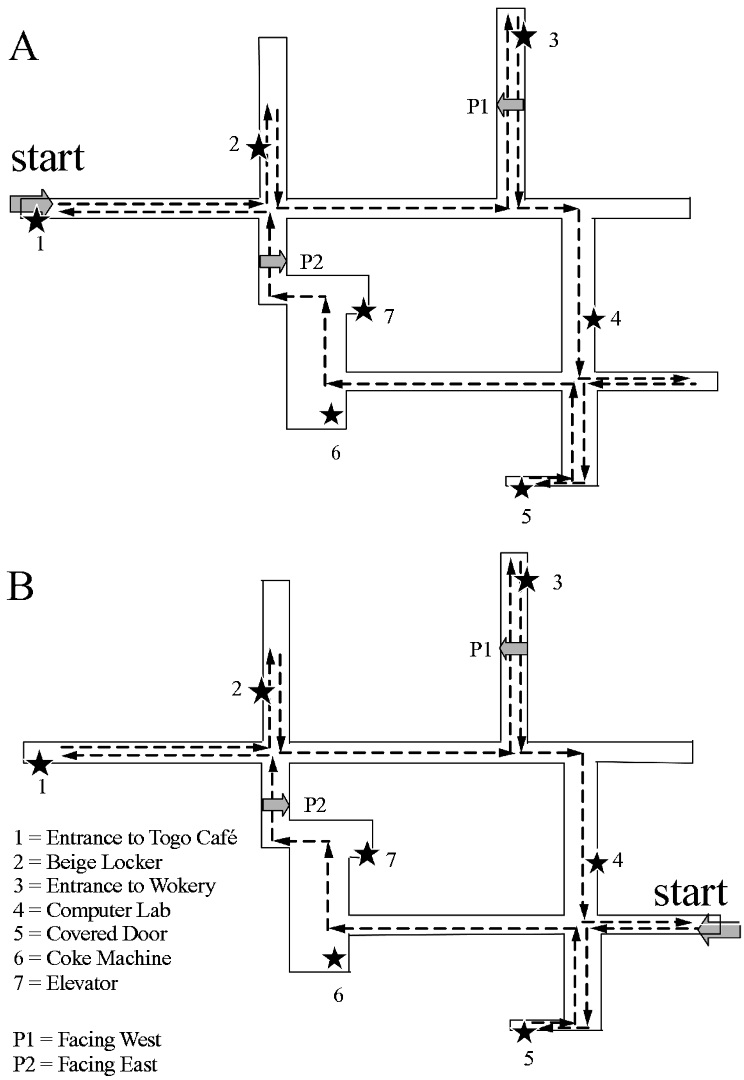


Figure 1. (A) Experiment 1: Learning Path One, starting orientation facing east. The dashed arrow indicates the trajectory and travel direction of the learning path. Each star represents the location of one of the four target landmarks. The two positions and orientations from which the participants were tested are represented by the small block arrows (P1 and P2). (B) Experiment 1: Learning Path Two, starting orientation facing west.

the learning phase in order to orient them within the learned environment. No target landmarks were presented on this map, but a small arrow was drawn as an indicator of the participants' current position and facing direction. The participants were then prompted to point to the seven learned target landmarks in the same way as in the navigation conditions (using the dial).

Results

For all three conditions (RE, VE, and map), there was no significant difference between starting locations [i.e., whether the participants started from the east heading west or started from the west heading east or whether they learned map_e or map_w; $F(1,36) = 0.874, p > .1$], and therefore, the data were collapsed across starting locations.

The raw score distribution of absolute pointing errors for the RE, VE, and map conditions are shown in Figures 2A, 2B, and 2C, respectively. Absolute pointing errors were defined as the absolute difference between the participants' pointing responses and the correct pointing responses. The distributions of all conditions were unimodal, with the majority of errors falling within the range of 0º–30º. There were some differences in performance between aligned and contra-aligned orientations, and such differences were most apparent in the map condition, as compared with the other two conditions.

The distribution of errors observed in the map condition when the participants were tested from a contra-aligned orientation (Figure 2C) was more dispersed, as compared

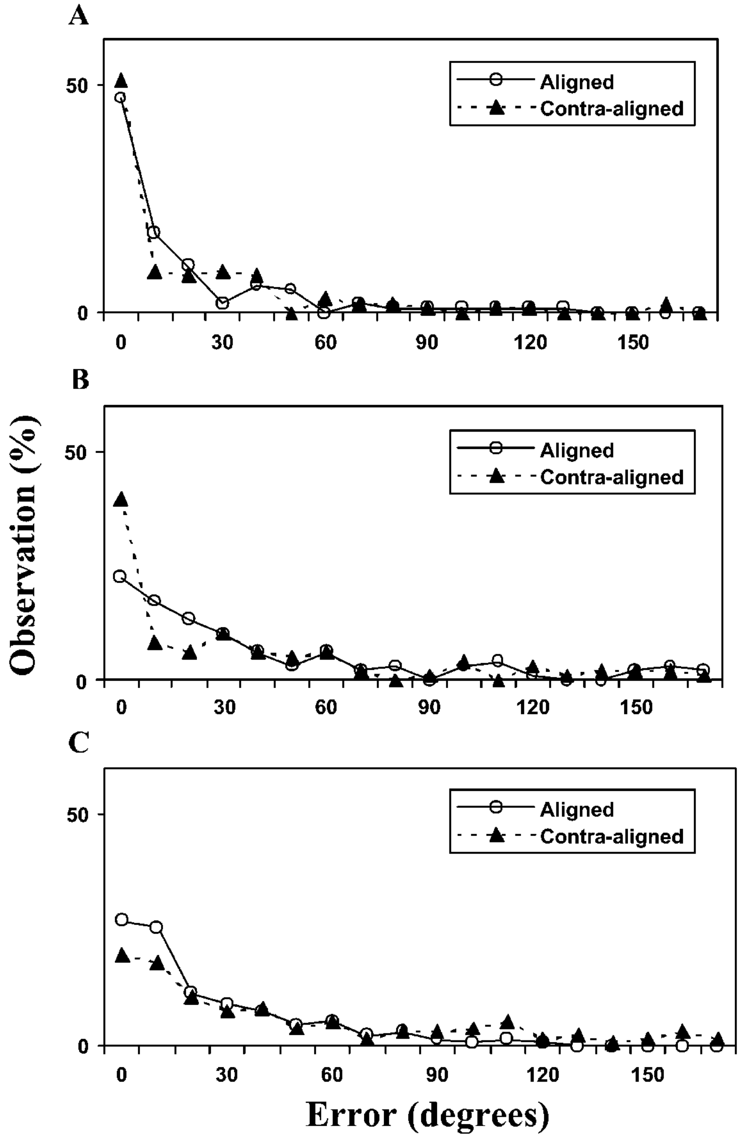


Figure 2. Experiment 1: pointing error distributions for (A) the real environment condition, (B) the virtual environment condition, and (C) the map condition.

with when they were tested from an aligned orientation. The observed distribution is best described as being multimodal, with scattered clusters of large errors. Although some errors were close to 180º, the majority of the errors were distributed variably between 0º and 180º. There was no apparent peak in response error centering around 180º.

Absolute pointing errors were subject to a log transformation to normalize the distribution before statistical analysis. A 3 × 2 between-subjects analysis of variance (ANOVA; three learning conditions [RE learning, VE learning, and map learning] and two testing orientations [aligned and contra-aligned]) was conducted on the mean log pointing error. Figure 3 illustrates the mean log pointing error for each learning condition and each testing orientation, collapsed across participants in each learning condition and in each testing orientation.

A main effect of learning condition was observed [$F(2,44) = 8.95$, $MS_e = 0.10$, $p < .01$; $M_{RE} = 1.04$, $M_{VE} = 1.32$, $M_{MAP} = 1.36$]. A main effect of orientation was not observed [$F(1,44) = 0.37$, $MS_e = 0.03$, $p > .05$; $M_{aligned} = 1.23$, $M_{contra\text{-}aligned} = 1.25$]. However, an interaction effect between learning condition and orientation was observed [$F(2,44) = 7.22$, $MS_e = 0.03$, $p < .05$]. A Tukey post hoc test of comparison was conducted between aligned orientation and contra-aligned orientation for each condition. A significant difference was observed only in the map condition ($p < .001$), but not in either the RE or the VE condition. A Tukey test of comparison was also conducted for learning con-

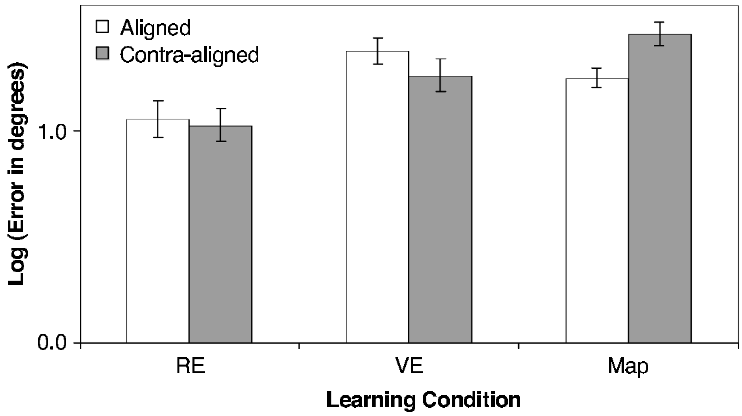


Figure 3. Experiment 1: mean log pointing errors for the real environment (RE), the virtual environment (VE), and the map conditions. Error bars indicate standard errors.

dition, indicating that the errors observed in the RE condition were significantly smaller than the errors observed in the VE or the map condition. There was no significant difference observed between the VE and the map conditions.

Discussion

The results of Experiment 1 suggest that orientation-free representations were developed following navigational learning in both the RE condition and the VE condition. These findings contrast sharply with the strong alignment effect observed in the map-learning condition. Not only do the orientation-free representations developed during RE navigational learning remain *consistent* with what is commonly shown in the literature (e.g., Sholl, 1987; Thorndyke & Hayes-Roth, 1982), but also our results indicate that this same form of orientation-free representation is developed through learning in a VE.

The findings observed for the VE condition differ from past results reported by Richardson et al. (1999), who found a marginal alignment effect ($p < .1$) for situations in which learning occurred by navigating in a VE and testing occurred by navigating in the real world equivalent. A number of explanations could account for the differences observed in the two studies. In Richardson et al.'s study, the participants were required to estimate route distance and straight-line distance, as well as target direction. In contrast, in our study, the participants were required only to estimate direction. The differences in task requirements could have resulted in the participants' employing different strategies for retrieving spatial information.

A further explanation for the differing results may relate to the qualitative differences that exist between the VR simulations used in the present study and the desktop system used in Richardson et al. (1999). The visual simulation presented in the present experiment included high-quality visual graphics, including digital images of real landmarks textured-mapped onto 3-D shapes. Rich environmental textures were also included in order to enable the participants to use optic flow information to continuously monitor distance traveled and direction of movement experienced. The visual environment was experienced via an HMD, thus increasing the level of presence the participants experienced. The HMD also allowed for a larger viewing angle than would a typical computer monitor.

In the navigation conditions in Experiment 1, the amount of error observed following learning in the VE was higher, as compared with the error observed following learning in the RE. However, because testing was always conducted in the RE, it is possible that these results reflected a difficulty in transferring the spatial knowledge obtained from a VE to an RE.

With regard to the map condition, when participants were tested from a contra-aligned orientation, it is conceivable that some participants may have had difficulty placing themselves in a position opposite to their initial learning orientation, thus resulting in pointing responses aimed in a direction exactly opposite to that for the target objects (producing errors of around 180º). It could be, in fact, that such observations reveal deficits in accessing the correct representation, rather than deficits in developing an accurate representation. The fact that the pointing error distribution did not peak around 180º (see Figure 2C) indicates that, for the most part, when tested from a contra-aligned orientation, a representation bias is observed, rather than a bias in accessibility.

EXPERIMENT 2

Evans and Pezdek (1980) have suggested that successive presentations of multiple vantage points during navigation through an RE is important for the formation of an orientation-free representation. One issue that remains to be clarified is whether it is necessary for participants to experience multiple body orientations in order to form orientation-free representations.

In Experiment 1, the learning paths consisted of multiple straight paths connected by 90º turns. As a result, the participants' heading orientation at any moment was not necessarily consistent with their initial orientation. Furthermore, the participants may have encountered particular locations multiple times from different directions. For these reasons, navigation involving multiple turns may result in the encoding of either *one* orientation-free representation or *multiple* orientation-specific representations. In other words, it is possible that the design of Experiment 1 masked the presence of an alignment effect by facilitating the encoding of multiple orientation-specific representations as a result of the multiple body orientations the participants assumed during the learning phase. To control for this, it is important to examine whether navigation through paths that do not involve turning the body still leads to orientation-free representations.

Presson, DeLange, and Hazelrigg (1987) examined this problem by testing the effect of being presented with a spatial layout from a single orientation during blindfolded walking in a small environment (less than 10 × 10 ft). They found that after participants had learned an environment while maintaining a single body and head orientation, orientation-specific representations were observed. In contrast, the participants formed orientation-free representations after experiencing multiple orientations while learning the path. Therefore, experiencing multiple orientations by turning while walking appeared to be necessary for blindfolded participants to form orientation-free representations during navigation.

In Experiment 2, we tested whether an orientation-free representation would still be observed should participants maintain a uniform body orientation along the entire path during sighted navigation. To examine this issue, we implemented a navigation task that required the participants to travel in a single heading direction. Such a learning paradigm was expected to be much more sensitive to an alignment effect. To avoid the increased demand required to transfer knowledge between learning and testing modes, as may have been the case in Experiment 1, in Experiment 2 both training and testing were conducted in the same mode. Consequently, each of the participants both learned and was tested in the VE and also learned and was tested in the RE.

Method

Materials

The equipment used was the same as that used in the VE and RE conditions of Experiment 1. The paths used in this experiment made up a portion of the entire environment used in Experiment 1.

Participants

Twenty-four undergraduate students from McMaster University participated in this study and were compensated with either course credit or money. All had normal or corrected-to-normal visual acuity.

Procedure

All the participants completed two conditions: (1) learning and testing in the RE and (2) learning and testing in the VE. Four possible paths in KTH were used: Two horizontal (east–west) paths (H1 and H2) and two vertical (north–south) paths (V1 and V2; see Figure 4). These four paths were included as a portion of the learning path used in Experiment 1. The lengths of the paths were roughly matched, so that each of the horizontal paths covered a distance of 156 ft and each of the vertical paths covered a distance of 135 ft. The horizontal paths were perfectly straight, whereas the two vertical paths included a small, brief, horizontal deviation, which resulted in a 90° left turn followed by a 90° right turn. All the participants learned and were tested in the RE, using one of the horizontal paths (e.g., H1) and one of the vertical paths (e.g., V1). All the participants also learned and were tested in the VE, using the remaining horizontal (e.g., H2) and vertical (e.g., V2) paths. For half of the participants, V1/H1 were tested in the RE, whereas V2/H2 were tested in the VE, and vice versa for the remaining participants. Furthermore, the order of the environments, the order of the testing locations (path chosen), and the order of the target landmarks were pseudorandomized.

Prior to learning, the participants were given practice and feedback on the pointing task in both the RE and the VE conditions and were trained to effectively navigate in the VE. A single starting position was used, and an invariable direction of travel for each path was maintained. For H1 the starting position was at the west end, for H2 it was at the east end, for V1 it was at the south end, and for V2 it was at the north end. For each learning path, the testing landmarks were located on paths that intersected the training path perpendicularly (see Figure 4 for landmark locations and identities).

Each learning trial required the participants to travel along a particular path once from beginning to end. The participants were required to maintain a constant body orientation (facing movement direction) throughout the travel, although they had to turn their heads to view various landmarks in the environment. As the participants were led along the path, the experimenter stopped at specific locations along the path to point out the target landmarks. In addition to the target landmarks, there were also distinct *prompting landmarks* (pictures posted by the experimenter prior to the experiment) placed at the corners of each of the intersections and at the end of each learning path. These prompting landmarks were brought to the attention of the participants by the experimenter during the learning phase. The purpose of providing these prompting landmarks was to assist the participants in recognizing their location along a path once they were brought back to that location some time later during testing.

The testing phase occurred immediately after the completion of the learning phase. There were two testing positions that the participants were brought to on each path: an aligned position and a contra-aligned position (Figure 4).

In the RE, between each testing trial, the participants were led blindfolded along a path *outside* of the testing area that consisted of many disorienting turns, before being brought back to each testing location (disorientation phase). This was to ensure that the participants were unable to update either their location along a path (via nonvisual cues) or their orientation in the environment *before* taking off the blindfold and beginning the test trial (Sholl & Bartels, 2002; Sholl & Nolin, 1997). In the VE condition, the participants were "teleported" to the pointing locations. In order to mimic the amount of proprioceptive information experienced during the disorientation phase in the RE condition, in the VE condition, the participants pedaled backward with no visual input for an equivalent duration. Once the participants reached the pointing locations and regained visual input, they were prompted to familiarize themselves with their position in the environment. The participants were then prompted by the experimenter to point to each of the target landmarks. The method used to measure the participants' pointing estimations in the RE was the same as that used in Experiment 1 (floor dial). In the VE condition, the participants pointed to the landmarks by turning the bike's handlebars in the desired direction until they believed the landmark's location to be centered in their visual field. In the testing phase for the VE condition, the participants were provided with a crosshair in the middle of the display, to assist in centering/locating their desired response. In addition to pointing direction, the participants' reaction time was also recorded.

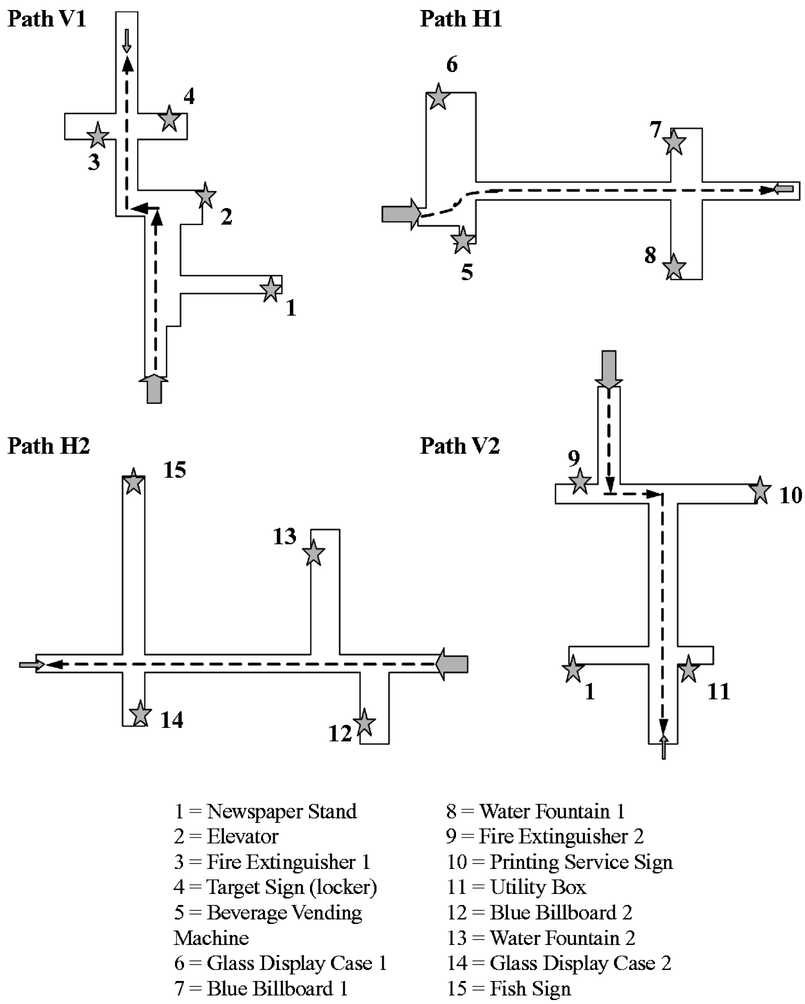


Figure 4. Experiment 2: The four vertical (V1 and V2) and horizontal (H1 and H2) learning paths, marked with all the corresponding target landmarks (indicated by stars). The orientations from which the participants were tested are indicated by block arrows, with the aligned orientation represented by wider arrows.

Results

There was no significant difference between the performance of the participants who completed the RE condition first, as compared with those who completed the VE condition first [order effect: $F(1,22) = 0.001, p > .1$], and therefore, the data were collapsed across learning order to simplify the results.

The raw score distribution of absolute pointing errors for the RE and VE conditions are shown in Figures 5A and 5B, respectively. Similarly, the raw score distribution of reaction times for the RE and VE conditions are shown in Figures 5C and 5D, respectively. All the distributions were unimodal. With regard to both errors and reaction times, in both the RE and the VE conditions, the distributions for aligned and contra-aligned orientations appear to be quite similar. This served to verify that there is minimal difference across the entire range of errors and reaction times across all the participants.

Both pointing errors and reaction times were subject to a log transformation to normalize the distribution before statistical analysis. A 2×2 repeated measures ANOVA (2 learning conditions [RE and VE] $\times$ 2 testing orientations [aligned and contra-aligned]) was conducted on the mean log pointing error and the mean log reaction time. Figures 6A and 6B illustrate mean log pointing error and mean log reaction time collapsed across participants in each learning condition and in each testing orientation.

Pointing Errors

With regard to pointing error, a main effect of learning condition (VE vs. RE) was not observed [$F(1,23) = 2.96$, $MS_e = 0.07$, $p = .10$; $M_{RE} = 1.16$, $M_{VE} = 1.07$]. A main effect of orientation was not observed [$F(1,23) = 0.44$, $MS_e = 0.05$, $p > .05$; $M_{aligned} = 1.10$, $M_{contra\text{-}aligned} = 1.13$]. In addition, an interaction effect between the learning condition and orientation was not observed [$F(1,23) = 1.94$,

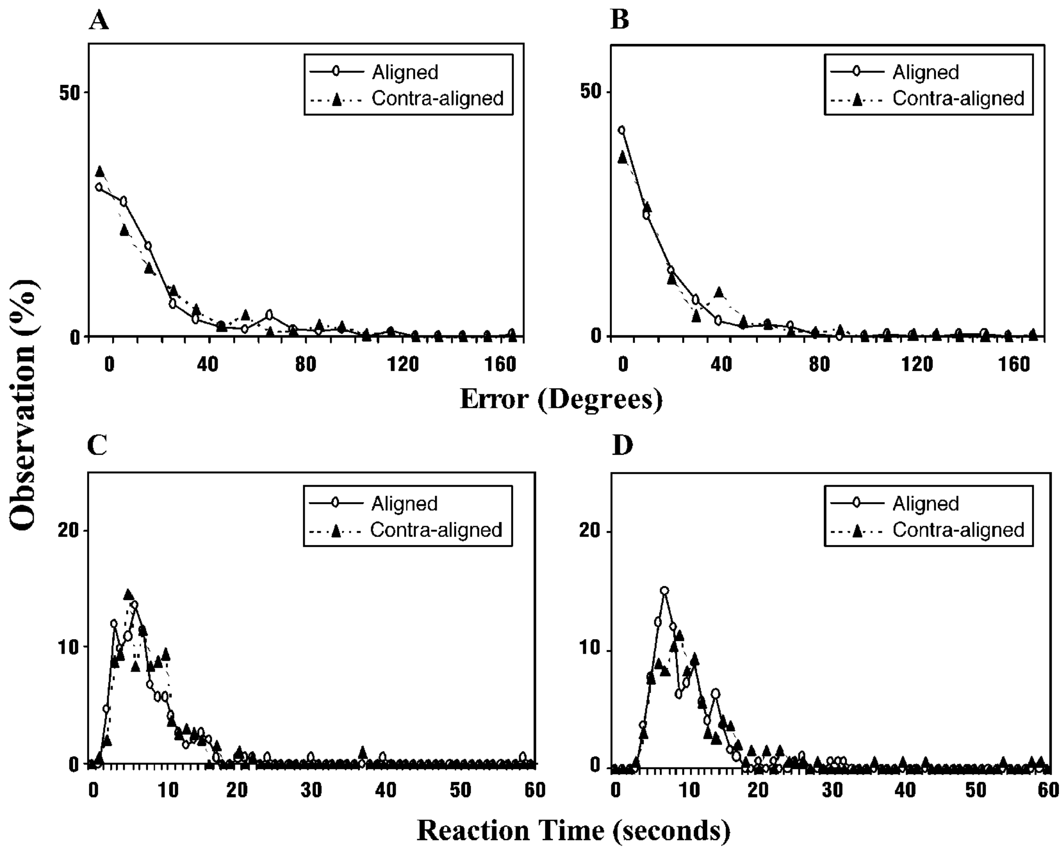


Figure 5. Experiment 2: pointing error distributions for (A) the real environment (RE) condition and (B) the virtual environment (VE) condition and reaction time distributions for (C) the RE condition and (D) the VE condition.

$MS_e = 0.03, p > .05$]. Therefore, no alignment effect was observed in either the RE or the VE condition.

Reaction Time

With regard to reaction time, a main effect of learning condition was observed [$F(1,23) = 21.11, MS_e = 0.02, p < .01; M_{RE} = 0.82, M_{VE} = 0.94$]. The participants required significantly longer time to respond in the VE condition than in the RE condition. A main effect of orientation was not observed [$F(1,23) = 3.55, MS_e = 0.01, p = .07; M_{aligned} = 0.86, M_{contra\text{-}aligned} = 0.90$]. In addition, an interaction between learning condition and orientation was not observed [$F(1,23) = 0.69, MS_e = 0.01, p > .05$]. Therefore, no alignment effect was observed in either the RE or the VE condition.

Discussion

The results of Experiment 2 suggest that an orientation-free representation is developed through learning in both an RE and a VE. Orientation-free representations developed through RE navigational learning are consistent with commonly reported results for spatial learning in large-scale spaces, even though other studies did not limit the participants' body orientation to one (e.g., Rossano & Moak, 1998; Rossano et al., 1999; Sholl, 1987; Thorndyke & Hayes-Roth, 1982).

In Experiment 1 and in many other previous studies in which real-world navigation was used, during the learning phase, participants had the opportunity to assume many different body orientations. Thus, it is reasonable to suspect that they were more likely to build a spatial representation that consisted of multiple orientations. In Experiment 2, inasmuch as the learning path contained primarily a single body orientation, the results suggest that even without being exposed to multiple body orientations during the exploration of the environment, orientation-free representations can be generated. Consequently, Experiment 2 provided a more robust test of the qualities that lead to an orientation-free representation in real-world navigation.

The observed orientation-free representation that resulted following real-world navigation while maintaining a single body orientation is in contrast to the results reported by Presson et al. (1987). They found that when both the body and the head were maintained at a constant orientation, an orientation-specific representation was observed, but if the head and the body did not maintain a constant orientation, an orientation-free representation was observed.

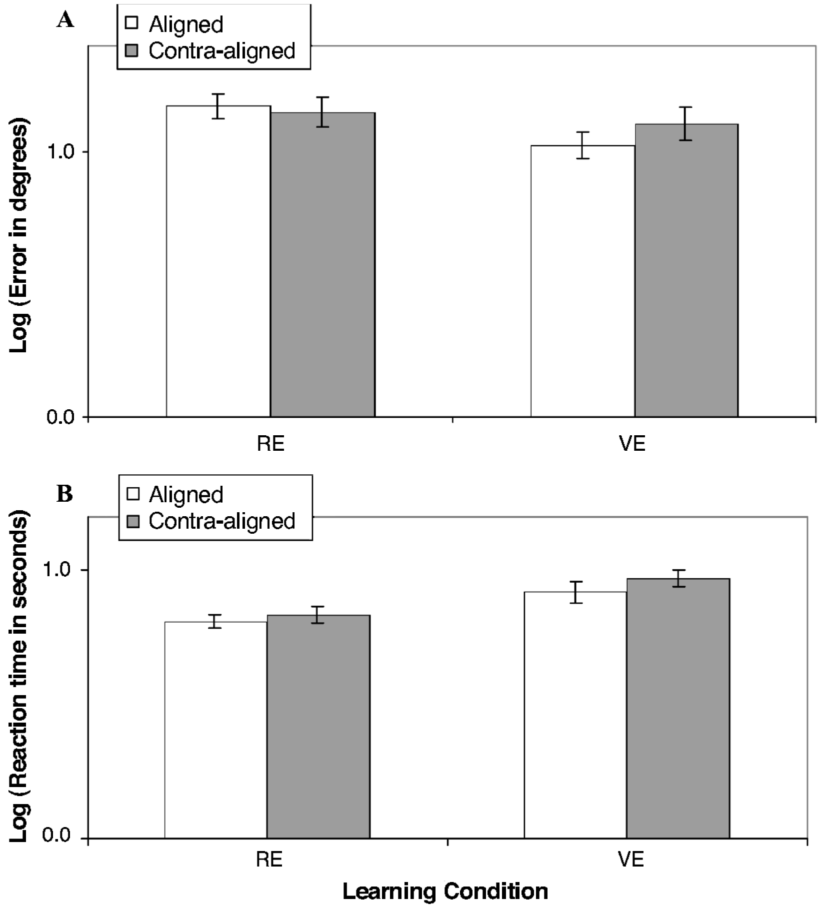


Figure 6. Experiment 2: (A) mean log pointing errors for the real environment (RE) and virtual environment (VE) conditions and (B) mean log reaction times for the RE and VE conditions. Error bars indicate standard errors.

Thus, experiencing multiple orientations by turning while walking seemed to be necessary for blindfolded participants to form orientation-free representations during navigation.

There are a number of differences between their study and ours. First, in their study, the participants had to maintain both a single body and a single head orientation, whereas in our RE condition in Experiment 2, the participants were still able to rotate their head to view landmarks outside their central field of view. In Presson et al.'s (1987) study, the participants were required to walk directly to the location of the landmarks, whereas in our study, the participants viewed the landmarks from a distance. In Presson et al.'s (1987) study, the consequence of limiting body and head orientation was that the participants, at times, were required to walk sideways in order to reach the location of the landmarks, thus forcing the participants to engage in unnatural movements that could potentially affect the way in which spatial layouts were perceived visually and nonvisually. In our experiment, the participants remained on a single path, and their body orientation was in line with the travel direction. Although our design avoided the need for unnatural movement, this resulted in the participants' having to turn their heads. Thus, it remains possible that in our RE condition, it might have been the experience of multiple head orientations that led to an orientation-free representation.

To further assess the effect of head orientation on spatial performance, we can turn to the results of our VE condition. In some respect, our VE condition shares some common features with Presson's single body/head orientation condition. In our VE condition, the participants changed their view by turning the handlebars of the bike, instead of physically turning their heads, and yet our results showed an orientation-free representation. Consequently, this suggests that multiple head orientations may not be necessary to develop an orientation-free representation.

It is important to note that whereas Presson et al.'s (1987) study required participants to learn the spatial layout through nonvisual sources only, our study provided participants with both visual and nonvisual information. It remains possible that visual learning and kinesthetic learning result in spatial representations that differ.

Despite the difference between our results and Presson et al.'s (1987) results, orientation-free representations were still observed even when the participants were required to navigate while maintaining a single body orientation. Consequently, the number of vantage points experienced during navigation may not be the determining factor in whether an orientation-free or an orientation-specific representation will be observed. Therefore, it would be more informative to examine the specific properties of active navigation that may result in different types of spatial representations.

EXPERIMENT 3

Inasmuch as an alignment effect was not observed in Experiments 1 and 2 in both the RE and the VE conditions, it is important to examine what particular aspects of navigation lead to orientation-free representations. One such factor, as proposed by Presson and Hazelrigg (1984), involves the idea that navigation requires participants to directly interact with the environment. In order to test this theory, one would have to examine situations in which participants do not interact directly with their environments but still passively receive the equivalent spatial information.

Few studies have examined orientation specificity following passive learning. Rossano and Moak (1998) and Rossano et al. (1999) used a computer display to present visual information experienced during navigation. What is interesting is that the resulting spatial representation differed, depending on the way the test environment was presented. If, during test, visual information specifying location was made available, an orientation-free representation was found. However, if the participants were required to simply imagine themselves facing a particular orientation, without any visual or nonvisual feedback, an orientation-specific representation was found.

In Experiment 3, we manipulated the extent to which a participant interacted with the environment and evaluated how this, in turn, affected the type of representation that was observed following learning. We compared conditions in which the participants actively navigated through a VE with conditions in which the participants passively viewed the same visual scene.

Method

Participants

Sixteen undergraduate students from McMaster University participated in this study and were compensated with course credit or money. All had normal or corrected-to-normal visual acuity.

Material

Equipment and paths were the same as those in the VE condition of Experiment 2.

Procedure

All the participants completed two conditions: (1) the active condition and (2) the passive condition. For both conditions, the learning phase and the testing phase were conducted in the VE. The active condition was essentially the same as the VE condition in Experiment 2. In the passive condition, the participants sat on the bike and wore the HMD, just as in the active condition. They were presented with the same visual scene, recorded during a typical active navigation; however, they did not pedal the bike but, instead, passively viewed the visual display. The participants were provided with the same instructions during learning in both the active and the passive conditions.

All the participants learned and were tested in the active condition, using one of the horizontal paths (e.g., H1) and one of the vertical paths (e.g., V1). All the participants learned and were tested in the passive condition for the remaining horizontal (e.g., H2) and vertical (e.g., V2) paths. For half of the participants, V1/H1 were tested in the active condition, whereas V2/H2 were tested in the passive condition, and vice versa for the remaining participants. The method used to measure the participants' pointing response estimations was the same as that used in the VE condition of Experiment 2. Pointing direction and reaction time were recorded.

Results

There was no significant difference between the performance of the participants who completed the active condition first and that of those who completed the passive condition first [order effect: $F(1,14) = 0.035, p > .1$], and therefore, the data were collapsed across learning order to simplify the results.

The raw score distribution of absolute pointing errors for the active and passive conditions are shown in Figures 7A and 7B, respectively. Similarly, the raw score distributions of reaction times for the active and passive conditions are shown in Figures 7C and 7D, respectively. All the distributions were unimodal. In the active condition, with regard to both error and reaction time, the distributions for the aligned and the contra-aligned orientations were similar. This served to verify that there was minimal difference across the entire range of pointing errors and reaction times across all the participants. However, in the passive condition, with regard to both errors and reaction times, the distribution for the contra-aligned orientation (Figures 7B and 7D) showed a higher proportion of large errors and a higher proportion of long reaction times, as compared with those for the aligned orientation. There was no apparent peak in response error around 180º, indicating that the participants were not simply unable to adjust for contra-aligned judgments.

Both pointing errors and reaction times were subject to a log transformation to normalize the distribution before statistical analysis. A 2×2 repeated measures ANOVA (2 learning conditions [active and passive] $\times$ 2 orientations [aligned and contra-aligned]) was conducted on the mean log pointing error and the mean log reaction time. Figures 8A and 8B illustrate mean log pointing error and mean log reaction time collapsed across participants in each learning condition and each testing orientation.

Pointing Error

With regard to pointing error, a main effect of learning condition was observed [$F(1,15) = 11.10, MS_e = 0.04, p < .05$; $M_{Active} = 0.93$, $M_{Passive} = 1.09$]. A main effect of orientation was not observed [$F(1,15) = 2.97$, $MS_e = 0.03$, $p = .11$; $M_{aligned} = 0.98$, $M_{contra\text{-}aligned} = 1.05$]. An interaction between learning condition and orientation was observed [$F(1,15) = 7.07, MS_e = 0.02, p < .05$].

In the active condition, a Tukey post hoc test of comparison between aligned orientation and contra-aligned

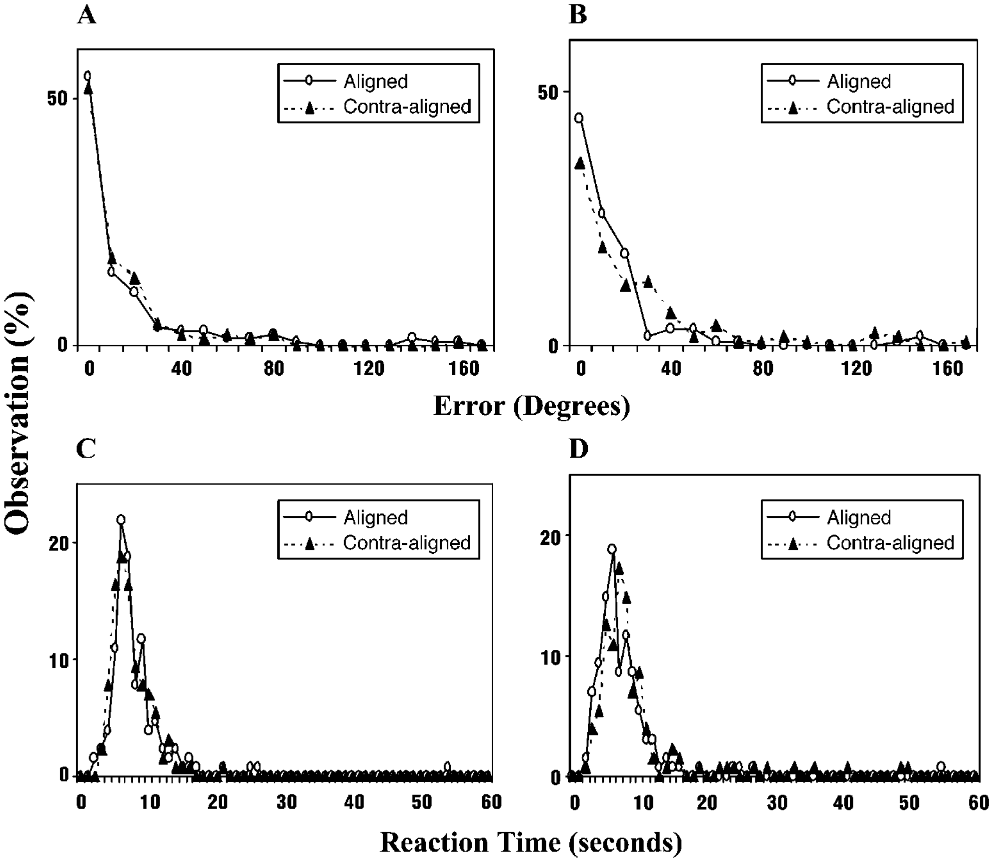


Figure 7. Experiment 3: pointing error distributions for (A) the active condition and (B) the passive condition and reaction time distributions for (C) the active condition and (D) the passive condition.

orientation was not significant, thus failing to demonstrate an alignment effect. However, in the passive condition, a Tukey comparison between aligned orientation and contra-aligned orientation was significant. This demonstrated an alignment effect in the passive condition only. Furthermore, a Tukey comparison between the active-aligned orientation and the passive-aligned orientation was not significant.

Reaction Time

With regard to reaction time, no significant main effect of learning condition was observed [$F(1,15) = 0.049$, $MS_e = 0.01$, $p > .05$; $M_{\text{Active}} = 0.82$, $M_{\text{Passive}} = 0.83$], nor was a main effect of orientation observed [$F(1,15) = 1.55$, $MS_e = 0.01$, $p > .05$; $M_{\text{aligned}} = 0.81$, $M_{\text{contra-aligned}} = 0.84$]. However, a significant interaction effect was observed between learning condition and orientation [$F(1,15) = 6.45$, $MS_e = 0.01$, $p < .05$].

In the active condition, a Tukey post hoc test of comparison between aligned orientation and contra-aligned orientation was not significant, thus failing to demonstrate an alignment effect. In the passive condition, a Tukey comparison between aligned orientation and contra-aligned orientation was significant. This indicated an alignment effect in the passive condition only.

Discussion

Experiment 3 demonstrated that active navigational learning leads to an orientation-free representation, whereas experiencing the path passively leads to an orientation-specific representation. Across conditions, pointing error and reaction time were highest for the passive condition, when tested from a contra-aligned orientation. However, pointing error and reaction time for both the active and the passive conditions were comparable for an aligned orientation. Therefore, the comparable performance between the passive-aligned and the active-aligned conditions suggests that the observed alignment effect in the passive condition was not due to poor overall performance. This lessens the possibility that during the passive condition, the participants attended less to the spatial information or were less motivated to perform the task.

When people actively navigate, they encode both the visual information of the spatial layout and the nonvisual information that is simultaneously available. The availability of concordant information from multiple inputs may enable participants to develop stronger and more accessible spatial knowledge. Such multisensory interactions may allow one to more effectively integrate spatial information obtained from different views, thus forming a unified

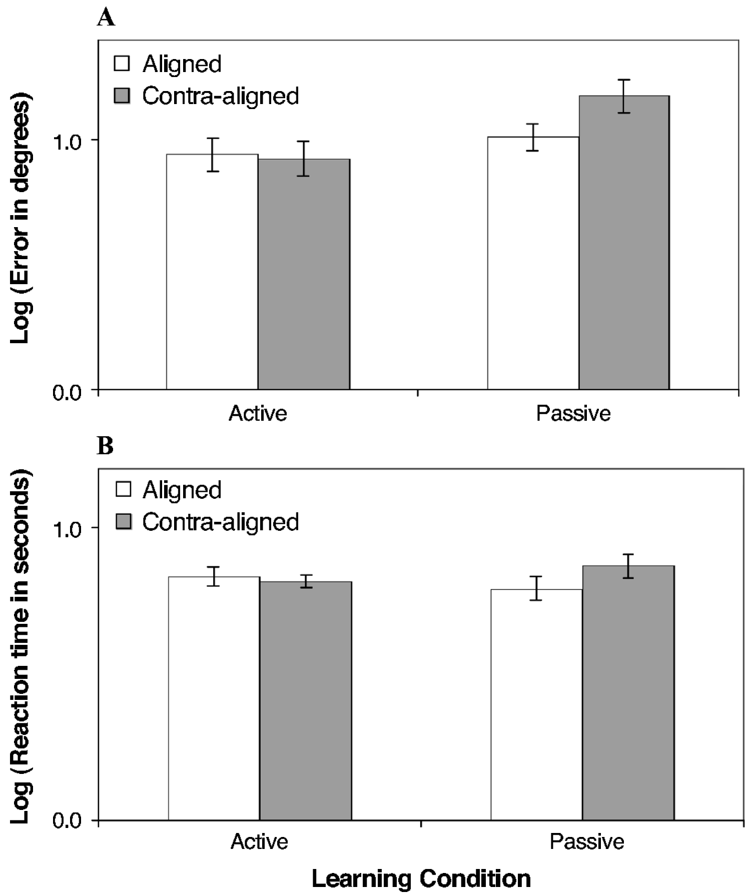


Figure 8. Experiment 3: (A) mean log pointing errors for the active and passive conditions and (B) mean log reaction time for the active and passive conditions. Error bars indicate standard errors.

knowledge of space independently of their own position in space (Presson et al., 1989). In contrast, in the passive condition, when one receives only a visual display of the movement trajectory in the absence of proprioceptive cues, the spatial information gained may be encoded as discrete and specific visual events and may be restricted or biased toward the originally learned orientation (Rossano et al., 1999).

As was previously mentioned, Rossano and Moak (1998) conducted an experiment involving a condition similar to our passive condition. The orientation-free representation observed following passive learning in Rossano and Moak's experiment was in contrast to the results of the present study. It is possible that, in our study, since our participants were traveling only one straight pathway, they were more susceptible to forming a spatial representation related to the orientation of the movement path.

In terms of general spatial performance (not in the context of orientation specificity), few studies have compared performance in a directional pointing task following active learning with performance following passive learning (Wilson, 1999; Wilson, Foreman, Gillett, & Stanton, 1997). In these studies, investigators failed to observe a difference between active conditions and passive conditions. This is inconsistent with our results, which showed that pointing errors in the active condition were significantly lower than those in the passive conditions. The discrepancy between these results could be due to the type of VR interface and the quality of the visual simulation implemented. For example, whereas the participants from the previous studies used keyboards to navigate in the virtual environment, the participants in our study controlled their navigation in a more natural way (pedaling a bike).

Although overall aligned performance was comparable for both the active condition and the passive condition in the present study, an important difference was revealed when we examined learning in the context of orientation specificity—that is, when the participants were tested from a contra-aligned orientation. The alignment effect observed in the passive condition indicates that it is the *active* nature of navigation that leads to the development of an orientation-free representation. It is therefore important to further understand the mechanisms that underlie active navigation.

EXPERIMENT 4

The concept referred to here as *active* navigation may actually encompass a subset of factors that may potentially influence the spatial representations that one ultimately develops. Intuitively, it would seem that the sensorimotor information available during active navigation would be the determining factor. In a typical navigation task, participants receive proprioceptive information during locomotion. Extensive literature has demonstrated that proprioceptive information is useful for updating egocentric representations of distance traveled, direction of movement, and relative location of nearby landmarks in the real world (Farrell & Thomson, 1998; Klatzky et al., 1998; Loomis, Klatzky, Golledge, & Philbeck, 1999; Simons & Wang, 1998; Sun, Campos, Chan, Young, & Ellard, 2004) and in VR (Bakker, Werkhoven, & Passenier, 1999, 2001; Chance et al., 1998; Kearns et al., 2002; Klatzky et al., 1998; Sun, Campos, & Chan, 2004). A number of studies have examined the question of nonvisual updating in the context of orientation specificity (Easton & Sholl, 1995; Farrell & Robertson, 1998; Presson & Montello, 1994; Rieser, 1989). For example, Rieser required blindfolded participants to point toward remembered target locations. Results demonstrated that directional judgments were better when the participants physically moved to the testing location than when they merely imagined themselves positioned in that same testing location. Rieser claimed that when visual information is not available, spatial updating is achieved through the proprioceptive information generated by self-movement. Although proprioceptive information plays a large role when visual information is not available, it remains to be tested whether such information is still important if vision is made available.

The results of Experiment 3 indicated that the complete lack of proprioceptive information led to an orientation-specific representation. It would, therefore, be interesting to test whether different levels of proprioceptive information would lead to different types of spatial representations. For instance, one could compare conditions in which participants are provided with natural proprioceptive information during navigation (e.g., leg movements) with conditions in which only minimal proprioceptive information is provided (e.g., hand movements). Such results would complement findings from the literature on nonvisual updating by identifying the minimal information required to achieve the same nonvisual updating as that revealed in real movement.

In Experiment 4, in order to determine which components of active navigation lead to an orientation-free representation, we compared conditions in which realistic proprioceptive information was available with conditions in which minimal proprioceptive information was available. The participants were required to navigate through the VE by either pedaling a bike or operating a computer mouse. The computer mouse allowed the participants to retain a sense of control over their movement trajectory but remained an unnatural form of navigation and provided minimal proprioceptive information.

Method

Participants

Forty undergraduate students from McMaster University participated in this study and were compensated with either course credit or money. All had normal or corrected-to-normal visual acuity.

Materials

The equipment and the paths were the same as those used in the VE condition of Experiments 2 and 3. However, one of the two conditions (the mouse condition) required the participants to navigate by operating a computer mouse instead of riding a bike.

Procedure

All the participants completed two conditions: (1) the bike condition and (2) the mouse condition. The learning phase and the testing phase involved the same VR interface as that in Experiment 2. The bike condition was essentially the same as the active condition in Experiment 3 and the VE condition in Experiment 2. The mouse condition also followed the same procedure as the bike condition; however, the participants navigated through the environment by operating a computer mouse instead of pedaling a bike. The participants moved forward through the environment by pressing and holding down the middle mouse button. They turned right by scrolling the mouse to the right and turned left by scrolling the mouse to the left. The participants stopped turning when they centered the mouse in the middle of the computer display. For both conditions, the participants were tested immediately following the completion of the learning phase, and testing was conducted in the same manner as in Experiment 3, with the exception that in the mouse condition, pointing was done via the mouse. The method used to measure the participants' pointing response estimations was the same as that used in the VE condition of Experiment 2. Pointing direction and reaction time were recorded.

Results

There was no significant difference between the performance of the participants who completed the bike condition first and the performance of those who completed the mouse condition first [order effect: $F(1,38) = 0.226, p > .1$], and therefore, the data were collapsed across learning order to simplify the results.

The raw score distributions of absolute pointing errors for the bike and the mouse conditions are shown in Figures 9A and 9B, respectively. Similarly, the raw score distributions of reaction times for the bike and the mouse conditions are shown in Figures 9C and 9D, respectively. All the distributions were unimodal. With regard to both errors and reaction times, in both the bike and the mouse conditions, the distributions were indistinguishable between aligned and contra-aligned orientations. This served to verify that there was minimal difference across the entire range of pointing errors across all the participants.

Both pointing errors and reaction times were subject to a log transformation to normalize the distribution. A 2×2 repeated measures ANOVA (2 learning conditions [bike and mouse] $\times$ 2 orientations [aligned and contra-aligned]) was conducted on the mean log pointing error and the mean log reaction time. Figures 10A and 10B illustrate mean log

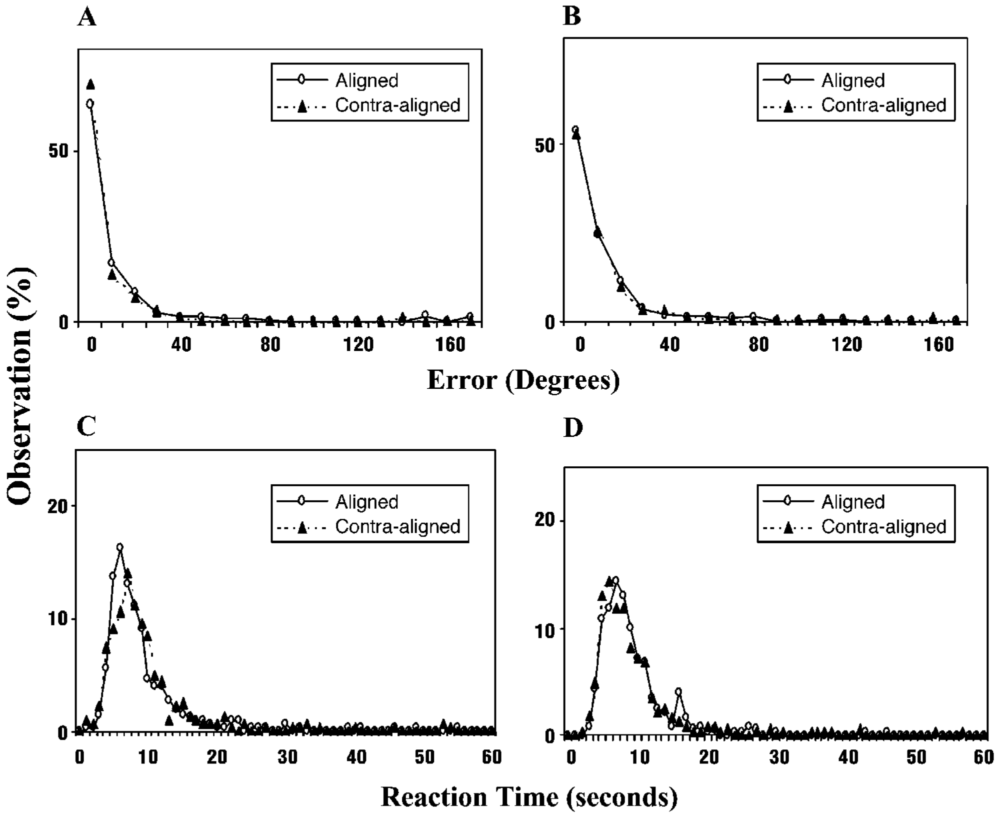


Figure 9. Experiment 4: pointing error distributions for (A) the bike condition and (B) the mouse condition and reaction time distributions for (C) the bike condition and (D) the mouse condition.

pointing error and mean log reaction time collapsed across participants in each learning condition and each testing orientation.

Pointing Error

With regard to pointing error, a main effect of learning condition was observed [$F(1,39) = 8.54$, $MS_e = 0.07$, $p < .05$; $M_{Bike} = 0.75$, $M_{Mouse} = 0.87$]. A main effect of orientation was not observed [$F(1,39) = 0.42$, $MS_e = 0.05$, $p > .05$; $M_{aligned} = 0.82$, $M_{contra\text{-}aligned} = 0.80$]. Furthermore, an interaction effect between learning condition and orientation was not observed [$F(1,39) = 2.24$, $MS_e = 0.04$, $p > .05$]. Therefore, no alignment effect was observed in either the bike or the mouse condition.

Reaction Time

With regard to reaction time, a main effect of learning condition was not observed [$F(1,39) = 0.45$, $MS_e = 0.01$, $p > .05$; $M_{Bike} = 0.88$, $M_{Mouse} = 0.89$]. A main effect of orientation was not observed [$F(1,39) = 0.15$, $MS_e = 0.01$, $p > .05$; $M_{aligned} = 0.88$, $M_{contra\text{-}aligned} = 0.89$]. Furthermore, an interaction effect was not observed between learning condition and orientation [$F(1,39) = 1.21$, $MS_e = 0.01$, $p > .05$]. Therefore, no alignment effect was observed in either the bike or the mouse condition.

Discussion

Since no alignment effect was observed in either the mouse condition or the bike condition, it would seem that active navigation, regardless of the level of proprioceptive information provided, is sufficient for the development of an orientation-free representation.

The results from our mouse condition can be compared with results from other VR studies that have employed simple input devices, such as keyboards. For instance, Tlauka and Wilson (1996) investigated whether an alignment effect would be observed after participants had learned and were tested in a VE via keyboard navigation. They then compared performance in this task with performance in another task in which learning occurred by examining a 2-D map. It was concluded that the reaction time of the directional judgments following training and testing in the VE did not demonstrate an alignment effect, whereas an alignment effect *was* demonstrated in the map condition. Although the conclusions they drew from their results were in agreement with what we found in our mouse condition, one needs to interpret such consistent findings with caution. The unique experimental design employed in their study makes it difficult to compare their findings with those from most other studies in which the alignment effect was examined, because their designation of the test orientation

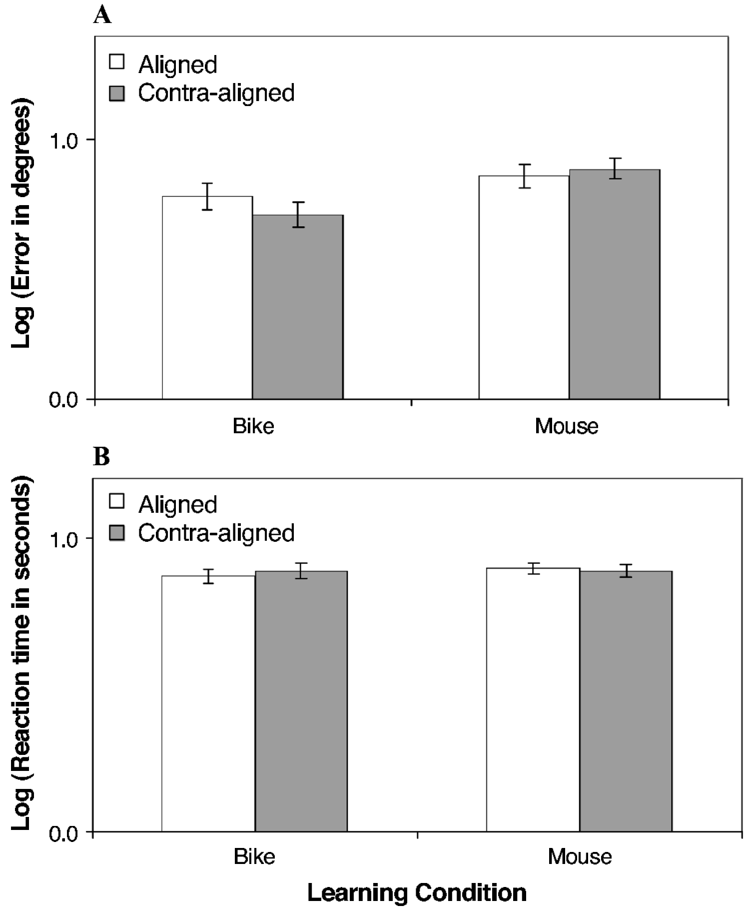


Figure 10. Experiment 4: (A) mean log pointing errors for the bike and mouse conditions and (B) mean log reaction time for the bike and mouse conditions. Error bars indicate standard errors.

as being aligned or contra-aligned was different from what is commonly used in the literature.

There may be a number of factors that may explain why an orientation-free representation was developed following active navigation in our study. During sighted navigation, what is experienced visually is tightly linked to the cues associated with self-motion, and thus the encoding of the environment may be enhanced as a result of this visual–sensorimotor interaction. For example, one's self-generated movements could enable one to anticipate the changing visual information that typically results from movement. During navigation, there are events that are particularly important for developing spatial knowledge of a specific environment—for instance, when changing directions. By actively controlling one's own movements, one may allocate more *attentional* resources to these critical events. Even the general sense of control during active movement could potentially enhance the learning experience.

It is conceivable that the predicted enhanced spatial knowledge that results from information gained from the simultaneous visual–sensorimotor interaction, as described above, does not require motor behavior to be executed in a manner that is identical to that in real-world navigation—that is, walking. Any motor behavior would serve the same purpose as long as it enables participants to interact with the environment. Therefore, we would predict that even a degraded form of motor behavior would result in a similar type of spatial representation. The results of Experiment 4 confirmed this supposition, so that an orientation-free representation was developed in both the mouse and the bike conditions.

It is important to note that although orientation-free representations were observed for both the bike condition and the mouse condition, the overall spatial performance in the bike condition was significantly more accurate than that in the mouse condition. In other words, proprioceptive information appeared to enable more precise spatial processing. This is consistent with a number of studies in which spatial performances have been compared using different types of VR interfaces (Arthur & Hancock, 2001; Lathrop & Kaiser, 2002; Waller, Hunt, & Knapp, 1998). In these studies, researchers assessed how accurately and consistently participants could point to or move toward previously learned targets. Participants were significantly more accurate and more consistent in the real-world condition than in other conditions that did not involve a natural form of movement. In addition, Chance et al. (1998) found that when the visual display was updated in response to full body movements, spatial knowledge acquisition was facilitated, in comparison with conditions in which this updating was not possible.

GENERAL DISCUSSION

These experiments suggest that in both RE and VE active navigation conditions, participants consistently developed orientation-free representations, which is in contrast to the orientation-specific representations observed for both the map condition and the VE passive condition.

Validating the Evidence Supporting Orientation-Free Representations

The conclusions drawn with respect to any orientation-free representations observed were drawn from the lack of statistically significant differences observed between performances in aligned conditions and contra-aligned conditions. As is the case whenever one attempts to generate assumptions on the basis of null findings, it is important to ensure that the generalizations based on such results reflect a true phenomenon and not simply a statistical artifact. In order to verify the validity of nonsignificant results, one must ensure both that an effective control is available for comparison and that a sufficient number of observations are included.

In the present discussion, there are a number of different factors indicating that the nonsignificant main effects reported here were not simply failures to reach significance. In Experiment 1, the null result reported for the VE condition is meaningful when this condition is compared with the RE and map conditions consisting of the same number of comparisons. The orientation-free and orientation-specific representations observed in the RE and map conditions reflect the typically observed and generally accepted dissociation. With regard to Experiment 2, it is justifiable to compare the null results reported for both conditions (RE and VE) with the null results observed for similar conditions in Experiment 1 since a within-subjects design was used in Experiment 2 (as opposed to the between-subjects design used in Experiment 1) and an increased number of observations were included in Experiment 2, thus making it a more sensitive measure.

Experiment 3 was particularly informative, since the results demonstrate that it is indeed possible for an alignment effect to be observed following passive learning in a VE. Not only does this serve to verify the statistical power observed for the null results in the active condition of Experiment 3, but also it serves as a comparison for the VE condition in Experiment 2 and the bike condition in Experiment 4, which were all essentially equivalent. Thus, the null results obtained in all of these experiments can be interpreted as indicating the absence of an alignment effect, and not simply as reflecting a failure to reveal the effect.

For this same reason, if concern remains about the possibility that the lack of statistical significance observed in each of these conditions is due to an insufficient number of participants in each condition, the results of each of these equivalent conditions (VE in Experiment 2, active in Experiment 3, and bike in Experiment 4) could be combined, forming a total of 80 participants. Furthermore, with regard to Experiment 4, a substantial number of participants were included in the mouse condition, thus providing ample opportunity for the null hypothesis to be rejected. The fact that it failed to be rejected speaks to the strength of the result.

The general trend of failing to observe an alignment effect in the equivalent VE conditions (VE in Experiment 2, active in Experiment 3, and bike in Experiment 4) is not without exception. In Experiment 2, with regard to the reaction time results, the main effect of orientation showed a trend that approached statistical significance ($p = .07$). It is conceivable that with additional observations, a significant difference between performances for aligned and contra-aligned orientations could be observed.

Even if such reaction time results were to turn out to be statistically significant, one must interpret these results in the context of the following related issues. First, as was indicated above, the measurement sensitivity for Experiment 2 should be stronger than that of Experiment 1, which demonstrated the lack of an alignment effect typically observed for the RE and VE conditions and a strong alignment effect for the map condition. The pointing error results observed for both the RE and the VE conditions in Experiment 2 are consistent with what was found in Experiment 1. Second, the fact that no interaction effect was observed with regard to reaction time in Experiment 2 provides evidence that VE learning, like RE learning, results in orientation-free representations. Third, because the small effect of orientation observed in Experiment 2 applies only to reaction time, it is possible that the differences in reaction time in Experiment 2 may represent a reaction time/accuracy tradeoff.

Empirical Test for the Two Theories for Spatial Representation

In our study, we empirically tested two theories that attempt to specify the particular factors that lead to the development of orientation-free representations versus orientation-specific representations. Our series of experiments addressed a number of issues that had not been thoroughly examined previously. Issues of particular interest to this discussion include the degree to which the number of vantage points experienced during navigation affects spatial representations, the effect of actively versus passively experiencing a path on the resulting spatial knowledge, and how different levels of proprioceptive information differentially affect the development of spatial representations.

The Multiple Vantage Points Theory

As was previously mentioned, the differences observed following map learning, as compared with learning via navigation, have been attributed to the number of vantage points participants are exposed to during learning (Evans & Pezdek, 1980). The notion of vantage points could potentially include nonvisual components (i.e., body and head orientation), as well as visual components. With regard to the nonvisual components, by comparing the results of Experiments 1 and 2, we were able to determine how performance in situations in which participants were allowed only a single body orientation differed from that in those conditions that allowed participants to experience multiple body orientations. Inasmuch as orientation-free representations were observed in both of these experiments, these results provided compelling evidence that experiencing multiple body orientations during navigation is not required for developing orientation-free representations.

It is important to note that in the RE condition of Experiment 2, the participants were still able to rotate their heads to view landmarks outside their direct field of view. Therefore, it remains possible that even though the participants were required to maintain a single body orientation, the fact that they were still able to turn their heads enabled the development of an orientation-free representation. Direct evidence regarding the effect of head orientation could be provided by comparing the results of Experiment 2 with a real-world navigation task in which both body and head orientation are held constant. Although this was not tested explicitly in the present study, the orientation-free representations observed following VE navigation, in which the participants did not experience multiple head orientations, suggest that multiple head orientations may not be necessary.

Vantage points can be experienced through nonvisual means, and they can also be experienced visually. One can, therefore, question the effect that multiple *visual* vantage points would have on the resulting spatial representation. We can address this issue by examining the results of the passive condition in Experiment 3, in which the participants experienced only visual information. If the multiple-viewpoint theory holds true, we would expect that in the passive condition, an orientation-free representation would develop. However, in our study, an orientation-specific representation developed despite the fact that multiple vantage points were experienced—in this case, visually.

Collectively, this series of experiments clearly challenges the multiple vantage points theory. If the possibility that orientation-free representations are developed simply as a result of the greater number of vantage points is ruled out, the next logical explanation relates to the intrinsic properties of active navigation.

Active Navigation and Its Possible Constituent Components

When theories that account for the causal factors leading to the development of an orientation-free/specific representation are evaluated, our results strengthen the underlying assumptions of the primary learning theory. The main premise of this theory relies on the notion that different spatial representations are developed depending on the degree to which one interacts with their environment during learning.

The present study was the first to compare active learning to passive learning in the context of orientation specificity. It was demonstrated that the participants developed an orientation-specific representation when learning their environment passively, whereas an orientation-free representation was developed following active learning. Consequently, it would seem that there is something unique about the active nature of navigation that leads to the development of orientation-free representations.

After having determined that active navigation results in spatial representations that differ from passive learning, in Experiment 4 we sought to gain insight into the exact constituent components that make up active navigation. To do this, we first explored whether the degree of kinesthetic or proprioceptive input that was experienced affected the resulting spatial representations. The orientation-free representations that were developed in both the bike and the mouse conditions demonstrated that only a minimal level of proprioceptive information is necessary to build an orientation-free representation, provided that participants actively control their own movements. This result also demonstrates that the *type* of proprioceptive information that is provided is irrelevant, whether it is naturally linked to locomotion (i.e., legs) or not (i.e., hands). That said, one might argue that the bike setup of our VR interface does not provide completely natural proprioceptive information. However, the fact that the same type of representation was observed following RE and VE navigation in Experiment 2 makes this speculation insignificant. Therefore, it seems that overall, regardless of the amount or quality of proprioceptive information that was provided, the same type of spatial representation was developed.

Orientation Specificity and Its Implications for Understanding Spatial Representations

It is important to examine the degree to which one's spatial representation is orientation specific, as identified by whether or not spatial memory is dependent on the original orientation in which the spatial layout was learned. This property of spatial representations is one of the very few concrete properties that one can measure empirically and, thus, provides one of the major clues regarding how spatial representations are developed. Identifying the factors that cause observers to form orientation-free or orientation-specific representations of their external world is important in understanding the mechanisms that underlie spatial processing.

In terms of the functional properties of orientation-free and orientation-specific representations, each of these types of spatial representations may potentially serve a different purpose. When one forms an orientation-specific representation, it may be that spatial information is encoded as discrete picture-like events that are organized in terms of an egocentric, or viewer-centered, frame of reference. Such spatial knowledge can be retrieved with high accuracy only if it is recalled in the same orientation as that in which it is initially learned.

In contrast, when orientation-free representations are developed, observers are able to integrate spatial information over space and time and consequently form a unified knowledge of space independently of their body position and orientation (Presson et al., 1989). The spatial representations revealed in this case would appear to be based on an exocentric, or environment-centered, frame of reference. Indeed, an orientation-free representation would offer an advantage to the observer. Such representations are flexible enough that they provide one with the capability to more easily recognize scenes learned from a number of different perspectives and allows for the continuous updating of spatial knowledge during further environmental exploration. More important, flexible knowledge about an overall spatial layout would be useful in guiding locomotion in situations in which a novel path is chosen to reach a destination.

Conclusions

Orientation specificity is an important concept in the discussion of spatial processing. Orientation-free versus orientation-specific representation is one of the few functional distinctions between different ways humans represent spatial information. VR technology provides a unique testing tool to complement traditionally employed real-world navigation tasks and map-learning paradigms in evaluating human spatial representations. Such paradigms assist in one's understanding the nature of the mechanisms underlying the development of particular spatial representations. The key findings in this study indicate that orientation-free representations are developed to a large extent as a consequence of the interaction of information from different modalities and that this interaction occurs most effectively during active navigation.

REFERENCES

Arthur, E. J., & Hancock, P. A. (2001). Navigation training in virtual environments. *International Journal of Cognitive Ergonomics*, **5**, 387-400.

Bakker, N. H., Werkhoven, P. J., & Passenier, P. O. (1999). The effects of proprioceptive and visual feedback on geographical orientation in virtual environments. *Presence: Teleoperators & Virtual Environments*, **8**, 36-53.

Bakker, N. H., Werkhoven, P. J., & Passenier, P. O. (2001). Calibrating visual path integration in VEs. *Presence: Teleoperators & Virtual Environments*, **10**, 216-224.

Chance, S. S., Gaunet, F., Beall, A. C., & Loomis, J. M. (1998). Locomotion mode affects the updating of landmarks encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration. *Presence: Teleoperators & Virtual Environments*, **7**, 168-178.

Easton, R. D., & Sholl, M. J. (1995). Object-array structure, frames of reference, and retrieval of spatial knowledge. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **21**, 483-500.

Eichenbaum, H., & Cohen, N. J. (2001). *From conditioning to conscious recollection: Memory systems of the brain.* Oxford: Oxford University Press.

Evans, G. W., & Pezdek, K. (1980). Cognitive mapping: Knowledge of real-world distance and location information. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **6**, 13-24.

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

Farrell, M. J., & Thomson, J. A. (1998). Automatic spatial updating during locomotion without vision. *Quarterly Journal of Experimental Psychology*, **51A**, 637-654.

Golledge, R. G. (1999). *Wayfinding behavior.* Baltimore: Johns Hopkins University Press.

Kearns, M. J., Warren, W. H., Duchon, A. P., & Tarr, M. J. (2002). Path integration from optic flow and body senses in a homing task. *Perception*, **31**, 349-374.

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

Lathrop, W. B., & Kaiser, M. K. (2002). Perceived orientation in physical and virtual environments: Changes in perceived orientation as a function of idiothetic information available. *Presence: Teleoperators & Virtual Environments*, **11**, 19-32.

Levine, M., Jankovic, I. N., & Palij, M. (1982). Principles of spatial problem solving. *Journal of Experimental Psychology: General*, **111**, 157-175.

Loomis, J. M., Blascovich, J. J., & Beall, A. C. (1999). Immersive virtual environment technology as a basic research tool in psychology. *Behavior Research Methods, Instruments, & Computers*, **31**, 557-564.

Loomis, J. M., Klatzky, R. L., Golledge, R. G., & Philbeck, J. W. (1999). Human navigation by path integration. In R. G. Golledge (Ed.), *Wayfinding behavior* (pp. 125-151). Baltimore: Johns Hopkins University Press.

May, M., Peruch, P., & Savoyant, A. (1995). Navigating in a virtual environment with map-acquired knowledge: Encoding and alignment effects. *Ecological Psychology*, **7**, 21-36.

Palij, M., Levine, M., & Kahan, T. (1984). The orientation of cognitive maps. *Bulletin of the Psychonomic Society*, **22**, 105-108.

Peruch, P., & Lapin, E. A. (1993). Route knowledge in different spatial frames of reference. *Acta Psychologica*, **84**, 253-269.

Presson, C. C., DeLange, N., & Hazelrigg, M. D. (1987). Orientation-specificity in kinesthetic spatial learning: The role of multiple orientations. *Memory & Cognition*, **15**, 225-229.

Presson, C. C., DeLange, N., & Hazelrigg, M. D. (1989). Orientation specificity in spatial memory: What makes a path different from a map of the path? *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **15**, 887-897.

Presson, C. C., & Hazelrigg, M. D. (1984). Building spatial representations through primary and secondary learning. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **10**, 716-722.

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

Presson, C. C., & Somerville, S. C. (1985). Beyond egocentrism: A new look at the beginnings of spatial representation. In H. M. Wellman (Ed.), *Children's searching: The development of search skill and spatial representation* (pp. 1-26). Hillsdale, NJ: Erlbaum.

Richardson, A. E., Montello, D. R., & Hegarty, M. (1999). Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Memory & Cognition*, **27**, 741-750.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **15**, 1157-1165.

Roskos-Ewoldsen, B., McNamara, T. P., Shelton, A. L., & Carr, W. (1998). Mental representations of large and small spatial layouts are orientation dependent. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **24**, 215-226.

Rossano, M. J., & Moak, J. (1998). Spatial representations acquired from computer models: Cognitive load, orientation-specificity and the acquisition of survey knowledge. *British Journal of Psychology*, **89**, 481-497.

Rossano, M. J., & Warren, D. H. (1989). Misaligned maps lead to predictable errors. *Perception*, **18**, 215-229.

Rossano, M. J., West, S. O., Robertson, T. J., Wayne, M. C., & Chase, R. B. (1999). The acquisition of route and survey knowledge from computer models. *Journal of Environmental Psychology*, **19**, 101-115.

Sholl, M. J. (1987). Cognitive maps as orienting schemata. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **13**, 615-628.

Sholl, M. J., & Bartels, G. P. (2002). The role of self-to-object updating in orientation-free performance on spatial-memory tasks. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **28**, 422-436.

Sholl, M. J., & Nolin, T. L. (1997). Orientation specificity in representations of place. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **23**, 1494-1507.

Siegel, A. W. (1981). The externalization of cognitive maps by children and adults: In search of ways to ask better questions. In L. S. Liben, A. Patterson, & N. Newcombe (Eds.), *Spatial representation and behavior across the life span: Theory and application* (pp. 167-194). New York: Academic Press.

Simons, D. J., & Wang, R. F. (1998). Perceiving real-world viewpoint changes. *Psychological Science*, **9**, 315-320.

Sun, H.-J., Campos, J. L., & Chan, G. S. W. (2004). Multisensory integration in the estimation of relative path length. *Experimental Brain Research*, **154**, 246-254.

Sun, H.-J., Campos, J. L., Chan, G. S. W. Young, M., & Ellard, C. (2004). The contributions of static visual cues, nonvisual cues, and optic flow in distance estimation. *Perception*, **33**, 49-65.

Thorndyke, P. W., & Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology*, **14**, 560-589.

Tlauka, M., & Wilson, P. N. (1996). Orientation-free representations from navigation through a computer-simulated environment. *Environment & Behavior*, **28**, 647-664.

Waller, D., Hunt, E., & Knapp, D. (1998). The transfer of spatial knowledge in virtual environment training. *Presence: Teleoperators & Virtual Environments*, **7**, 129-143.

Warren, D. H., Rossano, M. J., & Wear, T. D. (1990). Perception of map environment correspondence: The roles of features and alignment. *Ecological Psychology*, **2**, 131-150.

Wilson, P. N. (1997). Use of virtual reality computing in spatial learning research. In N. Foreman & R. Gillett (Eds.), *A handbook of spatial research paradigms and methodologies: Vol. 1. Spatial cognition in the child and adult* (pp. 181-206). Hove, U.K.: Psychology Press.

Wilson, P. N. (1999). Active exploration of a virtual environment does not promote orientation or memory for objects. *Environment & Behavior*, **31**, 752-763.

Wilson, P. N., Foreman, N., Gillett, R., & Stanton, D. (1997). Active versus passive processing of spatial information in a computer-simulated environment. *Ecological Psychology*, **9**, 207-222.

(Manuscript received December 19, 2002;
revision accepted for publication August 14, 2003.)

Chapter Three

Chan, G. S. W., Byrne, P., Becker, S., and Sun, H-J. (in preparation). Differential encoding of environmental features in spatial representation of room-sized environment.

Foreword

The results from Chapter 2 revealed the importance of non-visual information for learning targets along a route in a large, complex building. Importantly, the findings also reveal the fact that different frames of reference are possible for the same learned environment. Our results showed that, at least prima facie, there is support for the possible existence of two different frames of reference in large-scale environments - egocentric and allocentric. However, because the environment used in Chapter 2 was a large, complex environment, it was difficult to tightly control the different variables subjects experienced during their travels in comparison, for instance, to a smaller, modifiable, room-sized environment. While the large environment used in Chapter 2 was necessary in order to assess the importance of natural non-visual information, it is not an ideal setting with which to specifically address how different visually-defined features of the environment affect spatial representations. The use of an environment that can be viewed entirely from one position while keeping the observer static helps create a more controlled experimental scenario compared to a large, multifaceted environment that requires navigation to access all of the necessary spatial information. Past research has shown that different environmental features may in fact be processed using different frames of reference (Wang & Spelke, 2000; Holmes & Sholl, 2005). For instance, previous studies have shown that environmental objects may be processed more egocentrically, while structural aspects of the environment like the corners of the room may be processed more allocentrically (Wang & Spelke, 2000). This further prompted us to evaluate what effect environment features had on the types of spatial representations developed. In order to achieve this, in Chapter 3, we utilized a small room environment to observe the nature of features of the environment and their effects on frames of reference. Specifically, we observed the difference between objects and corners with analysis through configuration error to assess the quality of their spatial representation across different viewpoints.

RUNNING HEAD: DIFFERENTIAL ENCODING OF ENV FEATURE

Differential Encoding of Environmental Features in Spatial Representation of Room-Sized Environment

George S. W. Chan, Patrick Byrne, Suzanna Becker, and Hong-Jin Sun

McMaster University

Abstract

Originally demonstrated by Wang and Spelke (2000), it has since been shown that different features of an environment may be encoded either allocentrically or egocentrically. Following this line of research, we studied subject's directional judgments of environmental features (objects and corners) from an imagined viewpoint that was either aligned or misaligned with the originally learned viewpoint. Subjects were first brought to a fixed learning position in a four-sided, irregularly shaped room and learned the locations of four corners and four different objects relative to two testing viewpoints (aligned or misaligned). They were then blindfolded, disoriented (Exp 1) or brought out of the room (Exp 2-4), and required to point in the directions of the corners and objects while imagining themselves at one of the two testing viewpoints. Four experiments were conducted: different objects placed in the middle of the room (Exp 2); different objects placed against the wall (Exp 1 & 3); and identical objects placed against the wall (Exp 4).

The results showed that absolute error for both corners and objects and configurational error for corners (Exp 1-4) and objects with the same identity (Exp 4) were higher from the misaligned viewpoint compared to the aligned viewpoint. However, the configurational error for objects with different identities was similar between viewpoints (Exp 1-3). The fact that configuration errors were different relative to different viewpoint under particular circumstances (e.g., environmental features) argues against a definitive frame of reference based on configuration error alone. Thus, disregarding important variables such as viewpoint can potentially misrepresent the true nature of spatial representations. The authors interpret the results by proposing that

learning of spatial features with or without uniquely different identities could lead to two different types of allocentric representation.

Differential Encoding of Environmental Features in Spatial Representation of Room-sized Environment

The ability to encode and memorize our surroundings is necessary for basic survival and daily functioning. During spatial learning, mental representation of the environment may be formed using different frames of reference (FR). Observers may rely on their position and orientation within the environment to encode observer-to-feature relations that result in an egocentric spatial FR (e.g. Diwadkar & McNamara, 1997; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Shelton & McNamara, 1997; Sholl, 1987; Tarr, 1995; Tarr, Buelthoff, Zabinski, & Blanz, 1997; Tarr & Pinker, 1989). It is also possible that the observer may encode feature-to-feature relations resulting in an allocentric spatial FR (; Tolman, 1948; O'Keefe & Nadel, 1978; Sutherland & Dyck, 1984; Gallistel, 1990).

An influential study by Wang and Spelke (2000) examined the FR of our representation by measuring subjects' recall of the direction of environmental features before and after disorientation. In their study, participants were brought into a room-sized environment where they learned the position of a few objects outside of the room. They were then led to the centre of the room blindfolded and were either rotated by a small amount or were completely disoriented. Participants then had to point blindfolded in the directions of where they thought the target features were. The experimenters measured pointing angles in terms of absolute error (AE) and calculated configuration error (CE). AE was calculated as the average unsigned error between participant's response and the actually direction of the target features. In comparison, CE was calculated as the standard deviation of the signed errors between participant's response and the actual direction of the target features.

Essentially, it is argued that while AE provides a measure of the average error of pointing response, it does not take into account whether or not the error measured was a reflection of subject's spatial representation being distorted or simply being askew in comparison to the actual environment. In such an example, the learned allocentric representation of the environment may not be distorted but rather may reflect other variables manipulated in the experiment such as subject's inability to shift imagined viewpoint between learning and testing. It is possible that an increase in AE may be a systematic shift of the overall spatial representation by a set degree while still being similar in terms of the feature-to-feature spatial dimension to the learned spatial environment. CE however, takes into account the signed error of participant's response. An increase in CE would demonstrate an increase in distortion between the actual spatial environment and the environment subjects encoded. Essentially, an increase in CE would demonstrate a distortion of subject's allocentric representation of the environment and not simply a systematic shift in comparison to the actual environment. Therefore Wang and Spelke argue that an increased CE after disorientation would suggest that the feature-to-feature relation of the observer's representation was not retained, whereas similar CEs before and after disorientation would suggest that the feature-to-feature relation was retained.

An interesting result from the Wang & Spelke (2000) study was their comparison between different features within the environment. Specifically they compared CEs between objects and corners with or without disorientation. Without disorientation, participants performed equally well for objects and corners. Whereas, after disorientation participants demonstrated significantly higher CEs for objects compared to corners. They therefore argued that after disorientation, feature-to-feature relations were retained for corners but not for objects. Through these results, Wang and Spelke argue that corners may be encoded allocentrically while objects may be encoded egocentrically. This experiment therefore suggests that different types of features experienced by observers at the same time can be processed differently.

In a similar study, Holmes and Sholl (2005) had subjects learn a set of buildings (considered large objects which they argue are therefore more comparable to corners) outside of a room and the corners in that room. With or without disorientation, subjects' pointing performance was relatively the same for both buildings and corners. In fact, when Holmes and Sholl tried to replicate the Wang and Spelke's study with objects inside the room, they found the trend of their CEs for corners was even higher than that of the objects. That such possible difference between objects and corners may be observed hints towards potentially different types of representations existing simultaneously.

Regardless the type of behavioural difference discovered in the literature, the difference between processing of corner and object/landmark have been interpreted from the angle that corners are parts of a fixed structure (connecting extended surface - the wall) while the objects are typically isolated and movable (Wang & Spelke, 2000; Gouteux & Spelke, 2001; Wang & Spelke, 2002). While the ecological or functional interpretation could be a contributing factor in the performance difference found in corner and objects, one critical difference that has been missed in the literature is the that different objects in the real world or in most spatial experiments typically have uniquely difference appearance or identities, while different corners of a room typically do not have very uniquely different identities.

It has been well documented that in spatial memory task, object positions and object identities can be processed separately. For example, studies have posited that participants may encode three specific aspect of spatial information: 1) the positions where the feature is located; 2) the identity of the feature at that position and; 3) the integration of both sources of information (Postma & de Haan, 1996; Postma, Izendoorn, & de Haan, 1998). The research suggests that there are dissociable mechanisms involved between tasks that relies more on identity information in comparison to those that relies more on visual position information. Other studies supported this by demonstrating that articulatory suppression can prevent verbal processing while not affecting other ongoing visual spatial processes (e.g., Logie, Zucco, & Baddeley, 1990).

Following this logic, it is reasonable to speculate that processing of the location information of spatial features with different identities (such as everyday objects) could be different from processing spatial features without different identities (such as corners). This factor could possibly affect how corners and objects in a room can be processed differently, in particular, in different frame of reference.

In examining the frame of reference used in the mental representation of space, one of many important approaches is to examine the change of spatial performance when observers take a different view point from that during learning. When situated in a stationary position, we see the world from a singular viewpoint. This viewpoint not only tells us where we are in relation to our environment, but it also dictates the best imagery we can recall later of what we learned. One functional distinction between different forms of mental representations involves the degree to which the observer is viewpoint dependent. This is the phenomenon in which an observer recalls an environment better from a viewpoint aligned with the first view of the environment compared to any other viewpoints. The observer therefore takes into account his/her own position and orientation during spatial processing (Palij, Levine, & Kahan, 1984; Presson & Hazelrigg, 1984; Sholl, 1987; Rossano & Warren, 1989; Presson, Delange, & Hazelrigg, 1989; Warren, Rossano, & Wear, 1990; ; Peruch & Lapin, 1993; Diwadkar & McNamara, 1997; Palij, Roskos-Ewoldsen et al., 1998; Sholl & Bartels, 2002; Sun, Chan, & Campos, 2004). Often, the measurement taken in these studies is the absolute error (AE) in directional judgments of learned features. AE is defined as the absolute difference between the participant's directional judgments and the actual direction of the target feature. Most studies have looked at viewpoint dependence across different context as a tool for understanding change in spatial memory in relation to specific physical and mental demands (e.g. Rieser, Guth, & Hill, 1986; Shelton & McNamara, 1997; Wang & Brockmole, 2003; Avraamides & Kelly, 2005; May, 2007; Waller, Lippa, & Richardson, 2008; Hodgson & Waller, 2006). However, none have studied the underlying mental/cognitive mechanisms as to why such viewpoint dependence exists. There are two different errors that AE calculations can represent. First, participants can fail to take the new viewpoint, thus the direction judgment will be a fixed error term for all objects in the layout. Second, participants can have a distorted representation of the layout once taking a new viewpoint, which can lead to an increase in configuration errors. One way to dissociate these two types of errors is to have additional error measures such as CE which specifically captures the distortion of relative layout.

Current Study

In the current study, we followed-up the study by Wang and Spelke (2000) by adopting a similar paradigm with a slightly different objective. Specifically, our focus was on the effect of manipulating the observers' viewpoint at the time of testing. We evaluated viewpoint dependency of the CE as well as the CE magnitude change before and after disorientation in order to pinpoint the relative contribution of egocentric and allocentric FR.

In the learning phase of all four experiments, participants were brought into an irregularly shaped room where they learned the location of four objects and four corners inside the room. After learning, participants experienced some form of orientation change. During the testing phase, participants were blindfolded and had to imagine themselves in an orientation either aligned with their initial learning orientation or misaligned with their initial learning orientation. From these testing orientations, participant's pointing responses towards the remembered object and corner locations was measured. Results were analyzed in terms of AE and CE.

In Experiment 1, we examined the effect of disorientation on AE and CE from multiple viewpoints. Following learning of four uniquely different objects and four corners, participants were either brought to the middle of the room or were disoriented by spinning and then led on a meandering path to the middle of the room. In Experiments 2 to 4, before testing, to create similar effects of disorientation we led participants out of the room and positioned them in a new orientation. In Experiment 2, we positioned objects on the floor in the middle of the room. In Experiment 3, we moved the same four objects against the wall to make them more comparable to corners in order to address the results demonstrated in Experiment 2. Finally, in Experiment 4, we manipulated the spatial properties of the objects by making their identity uniform in order to test which underlying spatial property between objects and corners caused the difference observed in the previous 3 experiments.

Experiment 1

In our first experiment, we wanted to re-evaluate the effect of disorientation using a modified paradigm of Wang and Spelke’s (2000) study by testing subjects from two viewpoints. In the Wang and Spelke (2000) study, a within subject design was used in which subjects first performed in the "eye closed" condition followed by a disorientation condition. We utilized a between subject design between these two conditions to provide more comparable retention duration between the two conditions and to avoid any potential bias of an order effect.

In the learning phase, participants were instructed by the experimenter to remember the location of the corners and objects in an irregularly shaped room designed by the experimenter. Immediately after learning, subjects were blindfolded and led to the middle of the room (retention phase). Half of the participants were disoriented and led on a meandering path to the middle of the room. This was used to disrupt the use of non-visual information, such as proprioceptive and vestibular information for spatial updating similar to the Wang and Spelke (2000) study. In comparison, the rest of the subjects walked in a straight path to the middle of the room right after learning. They were then physically rotated towards the testing viewpoints. This would provide subject with non-visual information for spatial updating. During the testing phase, subjects pointed to the features (objects and corners) from two orientations: 1) aligned with the viewpoint experienced during learning and 2) misaligned with the viewpoint experienced during learning. Data was analyzed in terms of AE and CE from aligned and misaligned viewpoints. It was expected that the misaligned viewpoint would increase AE in comparison to the aligned viewpoint for both objects and corners. However, what needed to be determined was if the misaligned viewpoint would increase CE in comparison to the aligned viewpoint for either objects or corners. If CE increased then this would suggest that the allocentric representation of either the objects or corners was distorted. Whereas, if CE was comparable between viewpoints than this would suggest that the allocentric representation was maintained. Any increase in AE would simply be a result of a systematic bias or failure in shifting the imagined testing viewpoint to that of the learned viewpoint.

Method

Participants

Thirty-two students from McMaster University's first year psychology course (16 males, 16 females) participated in our study. Half of the students (8 males, 8 females) were disoriented before testing and the rest were not.

Materials

An irregularly shaped, four-sided room was created with four corners of different angles (see Figure 1). Three of the walls were made from a black cloth hung on seven foot tall wooden frames, while the last wall consisted of the white wall of the laboratory. This allowed us to enclose subjects in a well-controlled environment without any other stable features present in a typical room (e.g., doors). Two learning positions were designated. From each learning position in the direct line of sight to the opposite wall passing through the centre of the room a colored "x" was mounted at eye height. A compass consisting of a large laminated piece of paper with a circle with angles measured and marked on it was placed in the centre of the room. A large circular cloth with a small circle marked in the middle covered the compass during learning.

Four objects were placed on wooden stands at roughly chest height against the wall of the room - a kettle, a two liter soda bottle, a book, and a lamp (consistent with the types of objects used in Shelton & McNamara, 1997). The layout of the objects relative to each other roughly matched the configuration of the corners. Participants were required to wear a plumb line (a string with a weight suspended at the end) on the index finger of their right hand.

Insert Figure 1 here

Procedure

Prior to the experiment, while outside of the constructed small room, subjects were informed that they would be required to remember certain features of the constructed room which would be specified once they were brought in. They were then given practice and feedback on the pointing task.

Subjects were informed that during the learning phase that they may move their head and torso in order to see all the features in the room, but that they could not move their feet. During testing, subjects were placed directly on the centre of the compass. Again, their feet could not move but their head and torso could move. Before pointing to an imagined direction of a feature, they were required to turn their head as if looking straight at the feature. Their pointing arm (always their right arm) had to remain parallel to the ground. A plumb line was attached to subject's index finger. If subjects pointed to a feature behind them, they were told that they were allowed to twist their body (but not their feet) in whichever direction until they were comfortable. This was to allow the experimenter to measure the direction of the plumb line relative to the centre of the subject's body.

Learning phase. Half of the participants were instructed to remember the locations of the objects first, while the other half were instructed to remember the location of the corners first. Subjects were blindfolded and led into the room to one of two learning viewpoints. For both groups (objects and corners), half of the participants learned from a pre-specified position (location LP1 in Figure 1) directly facing the blue "x" while the other half learned from another pre-specified position (location LP2 in Figure 1) directly facing the red "x". The combination of the two pre-specified learning positions and the order of the features learned first (objects or corners) were balanced across subjects.

Subjects were instructed to remember where the two "x"s were located and also the location of the spot on the circular cloth in the middle of the room. They were also informed that after learning they would be blindfolded and brought to the spot in the middle of the room (which corresponded to the centre of the compass). Participants were then given four minutes to remember the location of the features.

Before the learning phase ended, practice pointing was given in which subjects were instructed to point (with their eyes open) from their current position (LP1 or LP2) towards the four target features in a clockwise direction starting from the feature to their immediate left. Note that the experimenter did not give any verbal labels of the target feature to subjects, rather subjects were informed to start with the "object closest to their immediate left" or the "corner closest to their immediate left". After pointing to the last feature clockwise they were asked to point to the last feature again but this time to point counterclockwise until they pointed back to the first feature. This ensured that subjects were paying attention to the correct features. Participants were then blindfolded, the cloth in the middle of the room was removed, and subjects were led onto the centre of the compass in one of the following manners.

Retention phase. Half of the participants were disoriented before testing. This was achieved by spinning participants three times before leading them on a convoluted path to the centre of the compass. Once on the compass, participants were spun three more times and then stopped facing a random direction. Participants were then asked if they knew which direction they were facing. If participants answered yes (independent of whether or not they were actually correct), they were spun again until they were unsure of which direction they were facing. When this was achieved, subjects were instructed to imagine facing one of the colored "x" even though their body faced a random direction unknown to the subject.

The rest of the participants were not disoriented, which meant that immediately after the learning phase they were blindfolded and led to the centre of the compass via a straight path. Subjects were instructed to imagine facing one of the colored "x's" and were also physically oriented so that they were actually facing that imagined "x".

Testing phase. After the retention phase subjects were instructed to assume an aligned and a misaligned imagined viewpoint. An example of subjects assuming an aligned viewpoint would be when they learned from a position facing the blue "x" and were instructed to imagine facing the blue "x" during testing. Whereas an example of subjects assuming a misaligned viewpoint would be when they learned from a position facing the blue "x" and were instructed to imagine facing the red "x" during testing. The order of these viewpoints (aligned or misaligned) was balanced across subjects.

Participants then performed the pointing task as instructed earlier from the centre of the compass. Afterwards, the subjects who were not disorientated were physically rotated to face the other "x" and the pointing task was repeated. This is unlike the disoriented subjects who were spun three times until they faced another random direction and were asked to imagine facing the other colored "x" before the pointing task was repeated.

Data Analysis

For the calculation of AE (absolute value of participant's angular response minus actual angles of the feature) and CE (standard deviation of the signed value of participant's angular response minus actual angles of the feature), we used the averaged data across clockwise and counterclockwise pointing responses for each feature. We then conducted a general ANOVA for both AE and CE across viewpoints and features.

In addition, following the data analysis of Wang and Spelke (2000), we also calculated the "pointing error" which is the standard deviation of the pointing response to each individual feature. While CE is a description of the variance among multiple features, "pointing error" is a description of the variance within each individual feature. Any difference in CE between oriented and disorientated conditions may be a result of a simple difference in pointing error. To correct for this, we calculated the predicted difference in CE between oriented and disoriented conditions by dividing the increase in pointing error by the square root of the number of pointing responses measured (Wang & Spelke, 2000). We then performed a t-test between the observed CE differences with the predicted difference. Further, because this contamination is also relevant across viewpoints, we calculated a predicted difference in CE across viewpoints in much the same way and performed a similar t-test.

Results

A 2 (orientation: disoriented vs. oriented) by 2 (feature: objects vs. corners) X 2 (viewpoints: aligned vs. misaligned) ANOVA was conducted on the AE and CE. Only the disorientation variable was a between subject variable. No significant difference was observed between males and females, therefore the data was collapsed across sex.

Absolute Error

A significant main effect of disorientation was observed with disorientated participants having a higher error than oriented ($M_{disoriented} = 22.25$, $M_{oriented} = 13.10$, $F(1, 30) = 12.62$, $p < 0.05$). A main effect of feature was not observed ($M_{objects} = 16.90$, $M_{corners} = 18.45$, $F(1,30) = 0.99$, $p = 0.33$). A main effect of viewpoint was not observed ($M_{aligned} = 15.38$, $M_{misaligned} = 19.97$, $F(1,30) = 2.66$, $p = 0.11$).

A significant two-way interaction between orientation and viewpoint was observed, moreover as evidenced by the trend of the means, viewpoint dependence in the predicted direction was only observed when participants were disoriented ($M_{disoriented\text{-}aligned} = 17.02$, $M_{disoriented\text{-}misaligned} = 27.47$, $M_{oriented\text{-}aligned} = 13.74$, $M_{oriented\text{-}misaligned} = 12.46$, $F(1,30) = 4.35$, $p < 0.05$). A three-way interaction was not observed among disorientation, features, and viewpoints. In fact, Figure 2 clearly demonstrates that the viewpoint dependence observed in the two-way interaction is comparable between the two features ($M_{disoriented\text{-}objects\text{-}aligned} = 17.58$, $M_{disoriented\text{-}objects\text{-}misaligned} = 25.50$, $M_{disoriented\text{-}corners\text{-}aligned} = 16.48$, $M_{disoriented\text{-}corners\text{-}misaligned} = 28.45$, $M_{oriented\text{-}objects\text{-}aligned} = 13.14$, $M_{oriented\text{-}objects\text{-}misaligned} = 11.39$, $M_{oriented\text{-}corners\text{-}aligned} = 14.33$, $M_{oriented\text{-}corners\text{-}misaligned} = 13.54$, $F(1, 30) = 0.63$, $p = 0.43$).

Insert Figure 2 and 3

<u>Configuration Error</u>

A significant main effect of orientation was observed with the disoriented condition having a higher error than the oriented condition ($M_{disoriented} = 20.41$, $M_{oriented} = 14.47$, $F(1, 30) = 6.01$, $p < 0.05$). A main effect of feature was not observed ($M_{objects} = 16.77$, $M_{corners} = 18.11$, $F(1,30) = 1.23$, $p = 0.28$). A main effect of viewpoint was not observed ($M_{aligned} = 17.02$, $M_{misaligned} = 17.86$, $F(1,30) = 0.12$, $p = 0.73$).

Statistically significant interaction effects were not observed among disorientation, features, and viewpoints ($M_{disoriented-objects-aligned} = 19.60$, $M_{disoriented-objects-misaligned} = 20.82$, $M_{disoriented-corners-aligned} = 17.54$, $M_{disoriented-corners-misaligned} = 23.68$, $M_{oriented-objects-aligned} = 13.96$, $M_{oriented-objects-misaligned} = 12.69$, $M_{oriented-corners-aligned} = 16.98$, $M_{oriented-corners-misaligned} = 14.26$, $F(1, 30) = 1.90$, $p = 0.18$).

A closer inspection of Figure 3 shows trends that suggest that when participants were disoriented, corners may have had higher CEs from the misaligned viewpoint compared to the aligned viewpoint. However, such a trend was not obvious for object's CE values. The Tukey t-tests in the disoriented conditions revealed marginally significant difference for corners (Tukey's $T_{corners}(1,15) = 1.86$, $p > 0.05$) but not for objects (Tukey's $T_{objects}(1,15) = 0.36$, $p > 0.05$).

To take into account the contribution of variance due to intrinsic pointing error in the overall CE, we conducted t-tests between the predicted CE increase and the observed CE increase. Across viewpoints, objects and corners showed no significant differences (Oriented: $\text{t-test}_{objects} = 1.21$, $p = 0.12$; $\text{t-test}_{corners} = 1.04$, $p = 0.15$; Disoriented: $\text{t-test}_{objects} = 0.09$, $p = 0.46$; $\text{t-test}_{corners} = -0.66$, $p < 0.26$).

Planned Comparisons for Only the Aligned Viewpoint Data and for Only the Misaligned Viewpoint Data

We further examined the data for only the aligned viewpoint. We did not observe a main effect across orientation ($F(1,30) = 2.14$, $p = 0.15$), nor did we observe a significant two-way interaction between orientation and features ($F(1,30) = 2.43$, $p = 0.13$). However, when we break down the analysis to individual features, planned comparisons revealed a significant effect of orientation for objects ($F(1,30) = 4.26$, $p = 0.048$ [$p < 0.05$]) but not for corners ($F(1, 30) = 0.47$, $p = 0.83$).

We also examined the data for only the misaligned viewpoint. We observed a marginal significance across orientation ($F(1,30) = 4.11$, $p = 0.051$). We did not observe a significant two-way interaction between orientation and features ($F(1,30) = 0.14$, $p = 0.71$). However, again when we break down the analysis into individual features, planned comparisons revealed a marginal significance of orientation for both objects ($F(1,30) = 3.70$, $p = 0.064$) and corners ($F(1, 30) = 3.47$, $p = 0.072$).

Planned Comparisons for Only the Oriented Data and for Only the Disoriented Data

We further examined the data for only the oriented condition. We did not observe a main effect across viewpoints ($F(1,30) = 0.35$, $p = 0.56$), nor did we observe a two-way interaction between features and viewpoints ($F(1,30) = 0.20$, $p = 0.66$). We also examined the data for only the disoriented condition. Again, we did not observe a main effect across viewpoint ($F(1,30) = 1.18$, $p = 0.29$). However, we did observe a marginal two-way interaction between features and viewpoint ($F(1,30) = 2.27$, $p = 0.15$). When we break down the analysis into individual features, planned comparisons revealed a marginal significance for corners ($F(1, 30) = 2.57$, $p = 0.12$) but not for objects ($F(1,30) = 0.11$, $p = 0.74$).

Discussion

Absolute error was generally higher when subjects were disoriented compared to when they were oriented. It should be noted that in the oriented condition, subjects were told to imagine from a specific viewpoint which was also consistent with the orientation of their body-based cues. Whereas, in the disoriented condition, subjects were told to imagine from a specific viewpoint, but were not provided with useful body-based cues. This difference between oriented and disoriented conditions demonstrates the effect of spatial updating in maintaining our memory of a previously learned spatial layout. When we examined the orientation conditions individually, for AE, when participants were oriented, their performance demonstrated low angular error and in fact viewpoint dependence was not even observed. This suggests that participants have a relatively robust memory of where the features are and can perform the pointing task accurately while blindfolded. Again, a lack of viewpoint dependence seems to be a result of spatial updating being available to participants. In comparison, when participants were disoriented, AE revealed viewpoint dependence for both objects and corners as evidenced by the significantly higher error in the misaligned viewpoint compared to the aligned viewpoint.

Following disorientation, the object CE increased, but the increase was comparable for aligned and misaligned viewpoints. Since the viewpoint dependence was seen for AE but not CE, this suggests that at least, to some degree, the larger AE in the misaligned condition was caused by errors in assuming the correct viewpoint as well as the distortion of the representation of the spatial layout. This illustrates the limitation of using only AE in analyzing the alignment effect in many traditional approaches.

Our Experiment 1 is an extension of Wang and Spelke's (2000) study. One methodological difference between our study and theirs is that we provide subjects with specific viewpoints to imagine during testing. In comparison, Wang and Spelke simply allowed subjects to assume any imagined viewpoint they want during testing. It is very likely that if participants were completely disoriented and were left to their own devices (e.g., instructed to assume an imagined viewpoint of their own choosing), they would pick an imagined viewpoint that is easiest to recall, which would arguably be a viewpoint aligned with the first experienced viewpoint. Therefore, Wang and Spelke's task is most likely comparable with our aligned viewpoint condition. In fact, the results in both our aligned condition and Wang and Spelke's task showed similar CEs that increased following disorientation for objects but not for corners. Because CE is a direct measure of subject's memory of the spatial layout, an increase in CE would reflect a distortion in the feature-to-feature relations. Consequently, for both ours and Wang and Spelke's results, if we follow their logic, the increase in CE for objects (but not corners) suggests that objects were encoded from an egocentric FR. However, when we also examine our data from just the misaligned viewpoint condition, the overall pattern reveals a different story. Across the orientation conditions, both objects and corners were observed to have similar increases in CE. Based on Wang and Spelke's logic, this would suggest that both objects and corners are actually egocentrically processed. Therefore, we would arrive at contradictory conclusions based on the results from the aligned and misaligned conditions. This calls for a new interpretation of previous results. A more reasonable interpretation is to propose that subjects encode both objects and corners from both egocentric and allocentric FRs. During retrieval, the two types of FRs may be re-weighted.

One type of representation would be a very high fidelity egocentric representation. This representation is maintained even after a small body movement is introduced and does not degrade after a mental and physical transformation to a misaligned viewpoint evidenced by low AE and CE. However, any disorientation may degrade this egocentric representation very easily. The existence of this representation would explain the results from the oriented condition and why AE and CE increased after disorientation.

The other type of representation would be an allocentric representation. This allocentric representation may take two slightly different forms for objects and for corners. Objects may be encoded in a low fidelity manner. Such a representation would produce a fairly high CE but it would not be viewpoint dependent. Whereas, Wang and Spelke would have argued that the increase in CE after disorientation should be interpreted as evidence for a purely egocentric representation, we put forth that subjects simply shifted the weighting from an egocentric representation to a crude allocentric representation. Specifically, in our oriented condition subjects relied more heavily on an egocentric representation possibly due to its high reliability and accessibility. However, following disorientation, egocentric representations becomes unreliable due to the body-based information being unavailable to use for orientation. Therefore subjects shifted their weighting to rely more on an allocentric representation.

Corners may be encoded allocentrically as well, but in a relatively higher fidelity manner, as if subjects took a global snapshot of the environment. Therefore, the feature-to-feature relations would be well-maintained. The existence of this representation would explain why disorientations had no effect on the corners' CE in the aligned condition. However, subjects may have difficulty accessing this representation from different viewpoints thus the slight increase in CE in the misaligned condition after disorientation.

Although the results from Experiment 1 were informative, we needed to conduct additional experiments to substantiate the difference between viewpoints for corners and especially the lack of difference for objects following disorientation. Therefore, in the subsequent experiments we concentrated only on the viewpoint difference following the disorientation manipulation.

Experiment 2

As we have demonstrated in experiment 1, when participants were not disoriented, performance was clearly different than when participants were disoriented. While the disorientation procedure was intended to remove body based orientation cues, other effects may have been unintentionally introduced. For example, participants may have felt discomfort, loss of motivation or even confidence in performing the task. This may potentially disrupt spatial performance resulting in a less sensitive measure. Therefore, in experiment 2, we seek an alternative method to disorientation.

One of the purposes of experiment 2 was to try and engage participants to rely more on their spatial memory and less on cues that may influence them if they remain inside the room. To do this, following the learning phase, we led blindfolded participants directly outside of the room to the compass for testing while physically orienting them to a novel direction (did not match the imagined aligned or misaligned viewpoint during testing). Also, the objects were not placed on wooden stands against the walls but simply on the floor in the middle of the room in order to make them as uniquely different from the corners as possible. If a difference can be observed between objects and corners this would markedly pronounce this effect. Again, if the misaligned viewpoint would increase AE in comparison to the aligned viewpoint for both objects and corners. However, what needed to be determined was if the misaligned viewpoint would increase CE in comparison to the aligned viewpoint for either objects or corners. If CE increased then this would suggest that the allocentric representation of either the objects or corners was distorted. Whereas, if CE was comparable between viewpoints than this would suggest that the allocentric representation was maintained. Any increase in AE would simply be a result of a systematic bias or failure in shifting the imagined testing viewpoint to that of the learned viewpoint.

Method

Participants

Sixteen students (8 males and 8 females) from McMaster University's first year psychology course participated for credit.

Materials

A constructed small room designed with dimension and layout similar to experiment 1 was used. The compass and the cloth covering it in the middle of the room used in experiment 1 were removed. To maximize the effect of viewpoint dependence, instead of testing participants from one location in the middle of the room with two orientations (aligned and misaligned), participants now had to learn two locations in the room that corresponds to an aligned or misaligned viewpoint therefore adding an additional imaginary translation during testing. From each learning position in the direct line of sight to the opposite wall passing through the centre of the room, two markers were placed. A colored marker "x" was mounted at eye height on the wall and a spot of the same color was placed on the ground 3 feet in front of the learning position (i.e., a red "x" corresponding to a red spot and a blue "x" corresponding to a blue spot). These spots would serve as the imagined testing locations.

The objects were placed on the ground about 4 feet from the wall and altogether formed an irregularly shaped formation. The objects were not in front of any corners relative to the imaginary testing locations. The same compass used in experiment 1 was placed 4 feet outside of the room in a location directly between the two learning position.

Insert Figure 4

Procedure

The learning phase was exactly the same as in experiment 1,except participants had to also remember the location of the colored spots on the floor.

It was explained to subjects that later they would be brought out of the room and had to imagine themselves back inside standing on top of a spot facing the correspond colored "x" (e.g., "imagined yourself standing on the red spot facing the red "x"). The two learning positions (3 feet behind either of the colored spot), oriented subjects so that they are facing the corresponding colored "x". This meant that if subject's learning position were behind the blue spot, then the aligned testing viewpoint in that case would be for the experimenter to ask participants to imagined themselves standing on the blue spot facing the blue "x" whereas the red spot facing the red "x" would be the misaligned testing viewpoint.

Following learning participants were not spun around, instead before the testing phase participants were led outside of the room onto the compass while blindfolded. Participants were oriented so that they were facing away from the centre of the constructed room. The pointing task was exactly the same as in experiment 1.

Results

A 2 (features: objects vs. corners) X 2 (viewpoints: aligned vs. misaligned) ANOVA was conducted on the AE and the CE. No significant difference was observed between males and females, therefore data was collapsed across sex.

Absolute Error

A main effect of features was not observed ($M_{objects} = 28.03$, $M_{corners} = 25.14$, $F(1,15) = 0.56$, $p = 0.47$). A main effect of viewpoint was observed showing the misaligned viewpoint to have significantly higher error than the aligned viewpoint demonstrating viewpoint dependence ($M_{aligned} = 19.47$, $M_{misaligned} = 33.69$, $F(1,15) = 7.04$, $p < 0.05$).

An interaction effect was not observed between features and viewpoints. Both features (objects and corners) demonstrated viewpoint dependence in AEs, paralleling each other in terms of magnitude (see figure 5a).

Insert Figure 5

<u>Configuration Error</u>

A main effect of feature was not observed ($M_{objects} = 21.04$, $M_{corners} = 19.18$, $F(1,15) = .97$, $p = 0.34$). A main effect of viewpoint was not observed ($M_{aligned} = 18.23$, $M_{misaligned} = 22.00$, $F(1,15) = 2.27$, $p = 0.15$).

An interaction effect was not observed between features and viewpoints, however the graph of the two-way interaction shows trends that suggest that corners had a much lower error in the aligned viewpoint in comparison to the misaligned viewpoint. This trend was not observed for objects. ($M_{objects\text{-}aligned} = 20.35$, $M_{objects\text{-}misaligned} = 21.74$, $M_{corners\text{-}aligned} = 16.11$, $M_{corners\text{-}misaligned} = 22.26$, $F(1, 15) = 1.48$, $p = 0.24$). Further, a tukey HSD test showed a significant difference between aligned and misaligned viewpoint for corners (tukey's $T_{corners}(1,15) = 4.43$, $p < 0.05$) but not for objects (see figure 5b). T-tests between predicted CE increase and observed CE increase across viewpoint showed a significant difference for corners ($t\text{-}test_{corners} = -2.46$, $p < 0.05$) but not for objects.

Discussion

Our results suggest that AE and CE reveal dichotomous trends in the data demonstrating differential behavior. In terms of AE, we again observe viewpoint dependence for both objects and corners as in experiment 1 when participants were disoriented. In terms of the CE, similar to the disorientation condition in experiment 1, for corners we observed lower CE for the aligned viewpoint compared to the misaligned viewpoint. However, this trend was not observed for objects.

Our ANOVA did not show the main effect of CE between aligned and misaligned viewpoint to be significantly different, considering the trend observed in figure 3b, we wished to examine the extent of the viewpoint difference for corners and objects separately. A more sensitive, although less robust analysis (the Tukey HSD), was used. Our two separate Tukey tests demonstrated a significant difference between misaligned and aligned viewpoint for corners but not for objects.

Although the pattern of response for objects and corners are quite different, the nature of this difference is unclear. It is possible that the fact that the objects were placed on the ground (and being closer to the participant during learning) could be the key contributing factor for the observed difference.

Spatial Updating From Inside to Outside of the Environment

In experiment 1, we compared the difference between disorientation and lack of disorientation. In experiment 2, following learning, we brought participants outside the testing room through a few segments of movement involving both direction and position change. The results showed that the simple relocation of participants from the learning environment even without drastic disorientation resulted in behavior similar to participants being disoriented as shown in Experiment 1. This method is more advantageous than disorientation because disorientation may introduce some level of internal error to performance from the sheer stress of it, potentially masking or reducing the sensitivity of the pointing task. In our study, the comparable results found for testing in the same room following disorientation and testing outside learning environment is consistent with notion that there seems to be an online/offline type of spatial processing when participants switch between environment (Wang & Brockmole, 2003; Kelly, Avraamides, & Loomis, 2007). This switch seems to be dependent on the observer's relative location in their environment.

By demonstrating that being outside of the learned environment or being disoriented can result in viewpoint dependence, in conjunction with our analysis of CE we go beyond simple behavioral interpretation. We demonstrate a dissociation in the mental mechanisms and processing reflected by the different source of error observed in CE between objects and corners in spatial memory.

Experiment 3

The goal of experiment 3 is to test participants' performance when objects and corners are made more comparable. Objects were placed against the wall at chest height on wooden stands. We are again interested in whether or not CE would reveal similar dichotomy in performance when participants are simply led out of the room.

Method

Participants

Sixteen students (6 males, 10 females) from McMaster University's first year psychology course participated for credit. Two participant's data (1 male and 1 female) were later dropped because their error suggested that they were unable to learn the environment.

Materials

The room and the objects in the room was the same as that used in experiment 2 (coke bottle, book, lamp, and kettle). However, the objects were now placed back on wooden stands. In addition, the objects on the wooden stands are placed flushed against the wall at distances and angles similar to that of corners relative to subject's learning position and imagined testing position. We still retained experiment 2's two testing location.

Procedure

The procedure for learning and testing was exactly the same as in experiment two.

Results

A 2 (feature: objects vs. corners) X 2 (viewpoints: aligned vs. misaligned) within factors ANOVA was conducted on the AE and the CE. No significant difference was observed between males and females, so data was collapsed across sex.

Absolute Error

A main effect of features was not observed ($M_{objects} = 27.80$, $M_{corners} = 28.97$, $F(1,13) = 0.51$, $p = 0.49$). A main effect of viewpoint was observed showing the misaligned viewpoint to have significantly higher error than the aligned viewpoint demonstrating viewpoint dependence ($M_{aligned} = 20.51$, $M_{misaligned} = 36.26$, $F(1,13) = 8.42$, $p < 0.05$).

An interaction effect was not observed between features and viewpoints. Both features (objects and corners) demonstrated viewpoint dependence in AEs, paralleling each other in terms of magnitude (see figure 6a).

Insert Figure 6

Configuration Error

A main effect of feature was not observed ($M_{objects} = 21.33$, $M_{corners} = 18.84$, $F(1,13) = 1.64$, $p = 0.22$). A main effect of viewpoint was not observed ($M_{aligned} = 18.06$, $M_{misaligned} = 22.11$, $F(1,13) = 2.14$, $p = 0.16$).

An interaction effect was observed between features and viewpoints, with the data demonstrating lower error for the aligned viewpoint in comparison to the misaligned viewpoint for corners but not for objects ($M_{objects\text{-}aligned} = 21.47$, $M_{objects\text{-}misaligned} = 21.19$, $M_{corners\text{-}aligned} = 14.64$, $M_{corners\text{-}misaligned} = 23.03$, $F(1, 13) = 5.79$, $p < 0.05$) (see figure 6b). A tukey HSD test showed a significant difference between aligned and misaligned viewpoint for corners (tukey's $T_{corners}(1,13) = 3.11$, $p < 0.05$) but not for objects.

T-tests between predicted CE increase and observed CE increase across viewpoint showed no significant differences for objects ($test_{objects} = 0.24$, $p = 0.40$). However, the difference approached significance for corners ($t\text{-}test_{corners} = -1.46$, $p = 0.08$).

Discussion

In experiment 3, we replicated experiment 1 and 2's result. Again, we demonstrated that simply being outside of an environment could lead to differential spatial performance. In terms of the AE, we again observe both features to have viewpoint dependence of roughly equal magnitude. Importantly, in terms of the CE, our ANOVA demonstrated a significant interaction effect between features and viewpoints. Specifically, we observe similar performance between misaligned and aligned viewpoints for objects whereas for corners, aligned viewpoint had a significantly lower error than the misaligned viewpoint. Through this results and those of experiment 1 and 2, the observed different performance patterns for objects and corners suggests different type of spatial processing. Again, this illustrates the importance of multiple viewpoints as a tool to compare across features.

In comparison, between experiment 2 to experiment 1 and 3, the position of the objects did not seem to affect participant's performance. This suggests that position property of objects is not the determining factor leading to the difference in mental representation between objects and corners. Another candidate that makes objects distinctly different from corners is the unique identity among the objects but not observed for corners.

Experiment 4

The goal of experiment 4 is to test whether or not salient identity may lead to different performance between objects and corners. To do this we removed the identity of the objects by only using wooden stands with the same shape (those used in the previous experiments) placed in the same location as in Experiment 3.

Method

Participants

Sixteen students (8 males, 8 females) from McMaster University's first year psychology course participated for credit.

Materials

The room was the same as that used in Experiment 3. However, the wooden stands were used as objects.

Procedure

The procedure was the same as in Experiment 3.

Results

A 2 (features: objects vs. corners) X 2 (viewpoints: aligned vs. misaligned) within factors ANOVA was conducted on the AE and the CE. No significant difference was observed between males and females, so data was collapsed across sex.

Absolute Error

A main effect of features was not observed ($M_{objects} = 39.32$, $M_{corners} = 32.90$, $F(1,15) = 1.77$, $p = 0.20$). A main effect of viewpoint was observed showing the misaligned viewpoint to have significantly higher error than the aligned viewpoint demonstrating viewpoint dependence ($M_{aligned} = 24.34$, $M_{misaligned} = 47.88$, $F(1,15) = 32.33$, $p < 0.05$).

An interaction effect was not observed between features and viewpoints. Both features (objects and corners) demonstrated viewpoint dependence in AEs, paralleling each other in terms of magnitude (see figure 7a).

Insert Figure 7

Configuration Error

A main effect of feature was not observed ($M_{objects} = 28.54$, $M_{corners} = 20.85$, $F(1,15) = 2.39$, $p = 0.14$). A main effect of viewpoint was observed with misaligned viewpoint having a significantly higher error than the aligned viewpoint ($M_{aligned} = 19.47$, $M_{misaligned} = 29.92$, $F(1,15) = 6.50$, $p < 0.05$). An interaction effect was not observed between features and viewpoints, with the data demonstrating CE to be smaller from the aligned viewpoint in comparison to the misaligned for both corners and objects ($M_{objects\text{-}aligned} = 21.06$, $M_{objects\text{-}misaligned} = 26.01$, $M_{corners\text{-}aligned} = 17.88$, $M_{corners\text{-}misaligned} = 23.83$, $F(1, 15) = 2.25$, $p = 0.15$) (see figure 7b). A Tukey HSD test for the corners showed that the difference between aligned and misaligned viewpoint approached significance (Tukey's $T_{corners}(1,15) = 2.39$, $p = 0.11$). Interestingly, the Tukey HSD test for the objects now shows the difference between aligned and misaligned viewpoint to be significant (Tukey's $T_{objects}(1,15) = 3.38$, $p < 0.05$).

T-tests between predicted CE increase and observed CE increase across viewpoint showed a significant differences for objects ($\text{t-test}_{objects} = -2.81$, $p < 0.01$). Also, the difference for corners approached significance ($\text{t-test}_{corners} = -1.23$, $p = 0.11$).

Discussion

In this experiment we replaced the original objects with four objects without uniquely different identities among them. Again, viewpoint dependence was observed in the AE for both objects and corners. However, in addition to the corners, we now observe a higher CE in the misaligned viewpoint in comparison to the aligned viewpoint for objects also. In fact, the magnitude of this difference in CE between aligned and misaligned viewpoint was even larger for objects than for corners. This suggests that the nature of the difference between objects and corners lies with the identity information provided by uniquely different objects.

General Discussion

Our experiments highlight the use of multiple measures in spatial performance and the incorporation of participants' viewpoint in the design. Through this, we are able to critically explore the underlying process involved in our spatial representation. Traditional viewpoint dependence measured in AE revealed the behavioral and cognitive characteristic of our spatial memory, but it is the analysis of the related CE from multiple viewpoints that paints a better picture of the underlying processes.

In experiment 1, when subjects were not disoriented, they could spatially update their position and orientation accurately in relation to objects and corners. In fact, they were so accurate that there was no significant difference between aligned and misaligned viewpoints for both AE and CE. However, when participants were disoriented, directional judgment of corners and objects demonstrated viewpoint dependence in terms of AE. In comparison, different patterns of CE were observed across viewpoints between objects and corners. Similar to Wang and Spelke's (2000) results, we observed significant CE increase after disorientation for objects but not for corners. This observation was limited to only the aligned viewpoint condition. However, when we analyze within the disorientation condition, there was a trend showing lower CE for the aligned viewpoint than the misaligned viewpoint for corners but not for objects. Although performance between viewpoints for corner did not reach statistical significance, we felt this was a good initial starting point for further exploration.

In experiment 2, in order to increase the difficulty of the memory task and to avoid potential detrimental effect of disorientation, we introduced two novel manipulations: 1) we brought subjects outside of the learning environment, consequently testing them in a novel location and orientation; and 2) the objects were removed from the wooden stand and placed away from the wall towards the middle of the room on the floor in order to make them more "object" like. Viewpoint dependence in AE was observed for both objects and corners. For CE, different patterns were observed across viewpoints between objects and corners. Similar to experiment 1's disorientation condition, CE was lower for the aligned viewpoint in comparison to the misaligned viewpoint for corners. However, for objects, CE was comparable between the two viewpoints.

In experiment 3, we made objects more comparable to corners by placing them back on the wooden stands (at chest height) and against the wall. The pattern of results was identical to that of experiment 2 for both AE and CE. This suggests that the position of the features did not seem to affect the differential performance between objects and corners. One of the factors contributing to the differential effect observed maybe the unique identity among the objects.

In experiment 4, we removed the unique identity of the objects by simply using the identical wooden stands used in experiment 3 so that both objects and corners have uniform identity information. Again, in terms of AE, we observe viewpoint dependence for objects and corners. However, in terms of CE, the trend showed the aligned viewpoint to be lower in comparison to the misaligned viewpoint for both objects and corners. This result suggests that the unique identity of the objects led to the comparable CE between viewpoints in experiment 1, 2, and 3.

It is important to point out the consistency of the data observed across all four experiments when subjects were disoriented (experiment 1) or were tested outside the learning room (experiment 2, 3, and 4). For AE, viewpoint dependence was always observed. For CE, corners were observed to be lower in the aligned viewpoint compared to the misaligned viewpoints (experiment 1, 2, 3, and 4). For objects, when they are uniquely different from each other, aligned viewpoint was comparable to misaligned viewpoint (experiment 1, 2, and 3). However, when the unique identity was removed, then similar to corners, objects' CE for the misaligned viewpoint became higher than the aligned viewpoint (experiment 4).

Related Results in the Literature

While we observed and measured AE and CE through multiple viewpoints, other studies utilized a single viewpoint and arrived to different conclusions about the FR used between different features. Specifically, both Wang & Spelke's (2000) and Holmes &

Sholl (2005) measured both AE and CE in their studies of different features. In both studies, participants were instructed to assume an imagined viewpoint of their choice while performing a pointing task blindfolded. When the average AE and CE were compared between objects and corners, Wang & Spelke (2000) demonstrated that CE is higher for objects than for corners. They conclude that object-to-object relations are less stable than corner-to-corner. In comparison, Holmes and Sholl (2005) performed similar experiments but did not observe the same trend in terms of CE between objects and corners.

Our results in our aligned viewpoint condition are consistent with Wang and Spelke's (2000) results: CE for objects was consistently higher than corners'. However, our use of multiple viewpoints demonstrated that CE for corners decreased when participants imagined an aligned viewpoint whereas CE for objects generally did not. Higher CE for objects in comparison to corners in Wang and Spelke's (2000) study could be a result of participants being allowed to assume their own imagined viewpoint. We speculate that they may automatically try to imagine a viewpoint aligned with their first experience of that environment.

FRs Revealed Through CE and Viewpoint

Wang and Spelke (2000) interpret the preservation of the feature-to-feature relations following disorientation (lack of CE increase) as an indication for an allocentric FR. In contrast, an increase in CE is an indicator of an egocentric FR. Based on this logic, it appears that our results reveal a contradicting pattern. For objects, Exp 1 showed that CE increased after disorientation which is consistent with the finding Wang and Spelke

(2000). This can be interpreted as an indication of egocentric representation. However, it is generally assumed performance following egocentric representation typically exhibit viewpoint dependency (performance cost in misaligned viewpoint), but we did not observed that in CE. For corners, CE did not increase significantly after disorientation which is consistent with evidence from Wang and Spelke (2000). One might want to interpret this as the evidence for allocentric presentation. However, a viewpoint difference was found for corner throughout the study. Therefore, it appears that it is problematic if one only use CE variable alone to generate conclusion about frame FR.

In Wang and Spelke (2000), an underlying assumption in inferring FR based on the change of CE value after disorientation is that subjects learn the environment from either an egocentric or an allocentric FR and that the same FR is used during retrieval under any circumstances. While their "either egocentric or allocentric FR" interpretation of the CE may be possible, it is also possible that subjects do not learn the environment from only one FR, but may utilize both egocentric and allocentric FRs, although they do not have to use different FR exactly the same time. During retrieval, subjects may use different combinations or weightings of the two FRs depending on what is manipulated during retention. One factor that can affect how FRs can be re-weighted is the amount of body perturbulance manipulated. Egocentric FR is usually more salient and accessible and therefore is heavily relied upon whenever possible. A small shift in the body may still allow subjects to use their egocentric FR. However, a large shift in the body (e.g., disorientation) may make the egocentric FR less accessible and reliable, forcing subjects to depend more on their allocentric FR. In addition, egocentric representations are transient and may be vulnerable to temporal delay (Wang & Spelke, 2000). Again, a short time delay may still allow subjects to use their egocentric FR, while a long time delay may force subjects to depend more on their allocentric FR.

The examination of CE under different viewpoint in our series of four experiments suggests that all features in our environment are processed via egocentric and allocentric FRs. It is during retrieval that the weighting of the FRs can be revealed. Such weighting depends upon the spatial property of the feature and the quality of spatial updating during retention. The analysis of CE argued by Wang and Spelke is that the degree to which CE increase should reveal the extent that egocentric representation being used. We argue that this may be too simplistic a view in understanding the meaning of CE. Although CE captures the quantitative relation between feature-to-feature, an increase in CE may not extend the idea that different representation may be retrieved in either a more egocentric or allocentric manner. It is important to review the underlying assumptions that differentiate egocentric and allocentric FR.

The simplest (and perhaps best) assumption that defines an egocentric FR is that the observer is relating the features in the environment to themselves. In comparison, an allocentric FR is defined as when the observer is relating the features in the environment to each other. It is much more likely that disorientation re-weights subject's FR tendency. When spatial updating is interrupted, egocentric FR should be made much less accessible resulting in subjects re-weighing the representation used for the task to be more allocentrically dependent. We therefore argue that instead of different features being revealed through disorientation to be processed either egocentrically or allocentrically, that disorientation would result in behavior that is primarily based on subject's allocentric representation.

We offer an alternative interpretation of the FR used in our task based on the CE value under different viewpoint conditions. We first summarize our results. Following spatial learning, when subjects perform a small body rotation the CE did not increase and did not appear to vary much between features and viewpoints. In other words, the fidelity of the internal representation was extremely high for both sets of features and viewpoints. After disorientation or relocation to outside testing space, the CE for objects increased but did not vary across viewpoint, until the unique identity was removed. For corners, after disorientation, in the aligned condition, the CE did not increase, but in the misaligned condition, CE increased slightly.

Based on these results we speculate that there are three underlying representations.

1) A very high fidelity egocentric representation of both objects and corners. This representation is very accurate that, when relying on it, the only CE comes from the ability of subjects to point and researchers' ability to measure. Furthermore, small rotation following learning would not degrade this representation enough to show errors above this pointing variance. The existence of this egocentric representation would explain the control results from Exp 1 and why such uniformly low CE did not appear after disorientation. However, any dramatic self-motion or disorientation would degrade this representation to a very high degree.

2) An allocentric representation that is ONLY formed for spatial features without uniquely different identities (e.g. corners). This would be a process that encodes geometry

of the space around the observer. The existence of this representation would explain why disorientation had little effect on CE values for the corners in the aligned condition. In other words, accessing this representation might be easier when doing so from the a real/imagined point of view from which the observer recorded it (Bryne, Becker, Burgress, Psych Review 2009). Therefore, a slight increase in errors in the misaligned condition was observed.

In the case of the corners in which the identity information was not uniquely different from each other, the spatial relation between features becomes more salient. This may prime subjects to processes the corners in a more wholistic fashion, resulting in a relatively global manner of processing. Such a global process would be similar to a generating a panoramic snapshot of the entire scene, producing low CE. We suspect the exceptionally low CE observed in the aligned condition for corners may be a result of such a grouping strategy. Whereas, the relatively higher CE observed in the misaligned condition may be a result of the snapshot being less easily accessible as verbal strategy is not available.

3) A low fidelity cognitive/linguistic allocentric representation for objects with uniquely different identities (i.e. remembering object A was to the left of object B which is about twice the distance to object C). Such a representation would lead to fairly high CE because of its approximate nature, but it would obviously not be viewpoint dependent. The salient identity of the objects would provide subjects with a potential verbal strategy, which may allow for higher cognitive processes resulting in the observed comparable error across different viewpoints.

Having proposed that behavioural difference between corners and objects could be contributed by the identity of the spatial features, other contributing factors could still be involved. For example, corners are part of the extended surface of the environment, connects by the walls, whereas objects always consist of a group of stand alone entities. It is important to acknowledge that corners may be "special" in a number way. First, corners are connected by the walls and are essentially part of the larger environment. Second, corners are navigationally relevant and therefore may be processed uniquely.

Conclusion

To the author's knowledge, this is the first study to incorporate CE and viewpoint dependence in understanding FR. Through four experiments we illustrate the importance of experimentation from multiple viewpoints (via viewpoint dependence) and with multiple levels of analyzes.

In the opinion of the authors, we feel that the disorientation data is best explained by the multiple allocentric representation interpretation. The reason being that it best explains all the pattern data. This is especially true for the comparatively lower CE in the aligned viewpoint for the corners in comparison to the objects.

In conclusion, our results calls for the importance in the understanding of the role of feature identify in spatial learning. Feature identity may be a fundamental component involved in governing the rules in which spatial information is being structured. This would consequently reveal the FR tendency involved.

Reference

Avraamides, M. N. and Kelly, J. W. (2005). Imagined perspective-changing within and across novel environments. Spatial Cognition. Vol. 4. 245-258

Byrne, B., Becker, S., and Burgess, N. (2007). Remembering the past and imagining the future: A neural model of spatial memory and imager. Psychological Review.Vol. 114(2) 340-375

Diwadkar, V. A. and McNamara, T. P. (1997). Viewpoint dependence in scene recognition. Psychological Science. Vol. 8(4). 302-307

Gallistel, C R. (1990). Representations in animal cognition – An introduction. Cognition. Vol. 37(1-2). 1-22

Gouteux, S., and Spelke, E. S. (2001). Children's use of geometry and landmarks to reorient in an open space. Cognition, 81(2). 119-148

Hodgson, E. and Waller, D. (2006). Lack of set size effects in spatial updating: Evidence for offline updating. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 32(4). 854-866

Holmes, M. C. and Sholl, M. J. (2005). Allocentric coding of object-to-object relations in overlearned and novel environment. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 31(5). 1069-1087

Kelly, J. W. , Avraamides, M. N., and Loomis, J. m. (2007). Sensorimotor alignment effects in the learning environment and in novel environments. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 33(6). 1092-1107

Logie, R. H., Zucco, G. M., and Baddeley, A. D. (1990). Interference with visual short-term memory. Acta Psychologica. Vol. 75(1). 55-74

May, M. (2007). Imaginal repositioning in everyday environments: Effects of testing method and setting. Psychological Research. Vol. 71. 277-287

O'Keefe, J. and Nadel, L. (1978). The Hippocampus as a Cognitive Map. Oxford: Clarendon

Palij, M., Levine, M., and Kahan, T. (1984). The orientation of cognitive maps. Bulletin of the Psychonomic Society. Vol. 22(2). 105-108

Peruch, P. and Lapin, E. A. (1993). Route knowledge in different spatial frames of reference. Acta Pscyhologica. Vol. 84(3). 253-269

Postma, A. and DeHaan, E. H. F. (1996). What was where? Memory for object locations. Quarterly Journal of Experimental Psychology Section A – Human Experimental Psychology. Vol. 49(1). 178-199

Postma, A., Izendoorn, R., and De Haan, E. H. F. (1998). Sex differences in object location memory. Brain and Cognition. Vol. 36. 334-345

Presson, C. C., and Hazelrigg, M. D. (1984). Building spatial representations through primary and secondary learning. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 10. 716-722

Presson, C. C., Delange, N., and Hazelrigg, M. D. (1989). Orientation specificity in spatial memory: What makes a path different from a map of the path? Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 15(5). 887-897

Rieser, J. J., Guth, D. A., and Hill, E. W. (1986). Sensitivity to perspective structure while walking without vision. Perception. Vol. 15(2). 173-188

Roskos-Ewoldsen, B., McNamara, T. P ., Shelton, A. L., and Carr,W. (1998). Mental representations of large and small spatial layouts are orientation dependent. Journal of Experimental Psychology: Learning, Memory, and Cognition, Vol. 24. 215-226

Rossano, M. J., and Warren, D. H. (1989). Misaligned maps lead to predictable errors. Perception, Vol.18. 215-229

Shelton, A. L. and McNamara, T. (1997). Multiple views of spatial memory. Psychonomic Bulletin and Reviews. Vol. 4(1). 102-106

Sholl, M. J. (1987). Cognitive maps as orienting schemata. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 13(4). 615-628

Sholl, M. J., and Bartels, G. P. (2002). The role of self-to-object updating in orientation-free performance on spatial-memory tasks. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 28(3). 422-436

Sun, H-J., Chan, G. S. W., and Campos, J. L. (2004). Active navigation and orientation free spatial representations. Memory and Cognition. Vol. 32(1). 51-71

Sutherland, R. J. and Dyck, R. H. (1984). Place navigation by rats in a swimming pool. Canadian Journal of Psychology. Vol. 38(2). 322-347

Tarr, M. J. (1995). Rotating objects to recognize them: A case study on the role of visual dependency in the recognition of 3-dimensional objects. Psychonomic Bulletin and Review. Vol. 2(1). 55-82

Tarr, M. J., Bulthoff, H. H., Zabinski, M., and Blanz, V. (1997). To what extent do unique parts influence recognition across changes in viewpoint? Psychological Science. Vol. 8(4). 282-289

Tarr, M. J. and Pinker, S. (1989). Human object recognition uses a viewer-centered frame of reference. Bulletin of the Psychonomic Society. Vol. 27(6). 506-506

Tolman E. C. (1948). Cognitive maps in rats and men. Psychological Review. Vol. 55. 189–208

Waller, D., Lippa, Y., and Richardson, A. (2008). Isolating observer-based reference directions in human spatial memory: Head, body, and the self-to-array axis. Cognition. Vol. 106(1). 157-183

Wang, R. F. and Spelke E. (2000). Updating egocentric representations in human navigation. Cognition. Vol. 77. 215–250

Wang, R. F., and Spelke, E. S. (2002). Human spatial representation: Insights from animals. Trends in Cognitive Sciences. Vol. 6(9). 376-382

Wang, R.F. and Brockmole, J.R. (2003) Human navigation in nested environments. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 29 (3). 398-404

Warren, D. H., Rossano, M. J., andWear, T. D. (1990). Perception of map environment correspondence: The roles of features and alignment. Ecological Psychology. Vol. 2. 131-150

Figure Caption

Figure 1. Illustration of the dimension of the environment and locations and the location of the objects, corners, learning positions, and testing positions relative to each other.

Figure 2a. Average absolute and configuration error in degrees between aligned and misaligned viewpoint for objects and corners when subjects were not disoriented and are tested from one testing position.

Figure 2b. Average pointing error between aligned misaligned viewpoint for objects and corners when subjects were not disoriented and are tested from one testing position. .

Figure 3a . Average absolute and configuration error in degrees between aligned and misaligned viewpoint for objects and corners when subjects after subjects were disoriented and are tested from one testing position.

Figure 3b. Average pointing error between aligned misaligned viewpoint for objects and corners after subjects were disoriented and are tested from one testing position.

Figure 4. Illustration of the dimension of the environment and locations and the location of the objects, corners, learning positions, and testing positions relative to each other.

Figure 5a . Average absolute and configuration error in degrees between aligned and misaligned viewpoint for objects and corners and subjects had to imagine themselves at two new testing positions and viewpoints.

Figure 1

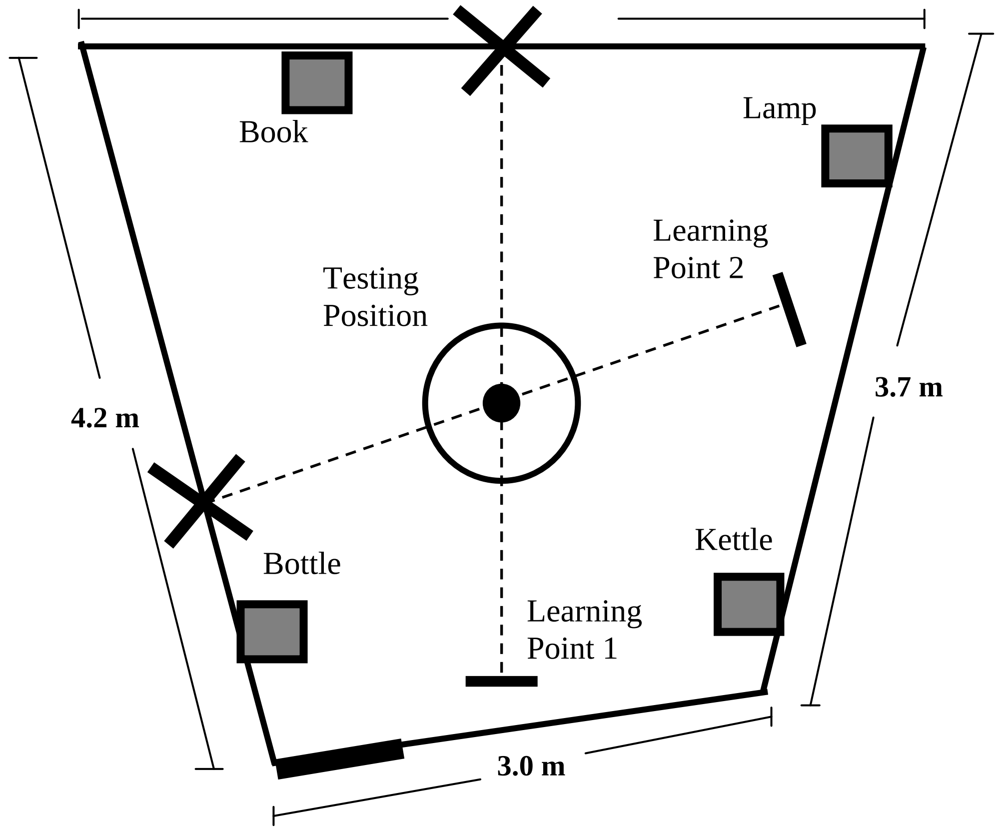
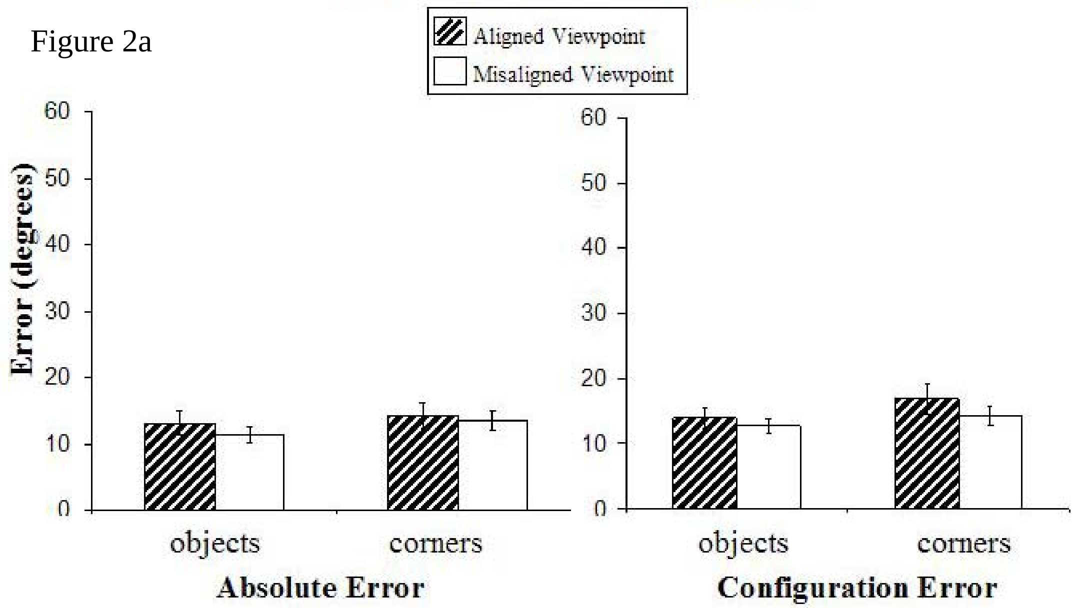

Book
Lamp
Learning
Point 2
Testing
Position
4.2 m
3.7 m
Bottle
Kettle
Learning
Point 1
3.0 m

Figure 2

Experiment 1 Absolute and Configuration Error: Features versus Viewpoints without Disorientation

Figure 2a



Experiment 1: Pointing Error Across Viewpoints for Objects and Corners Without Disorientation

Figure 2b

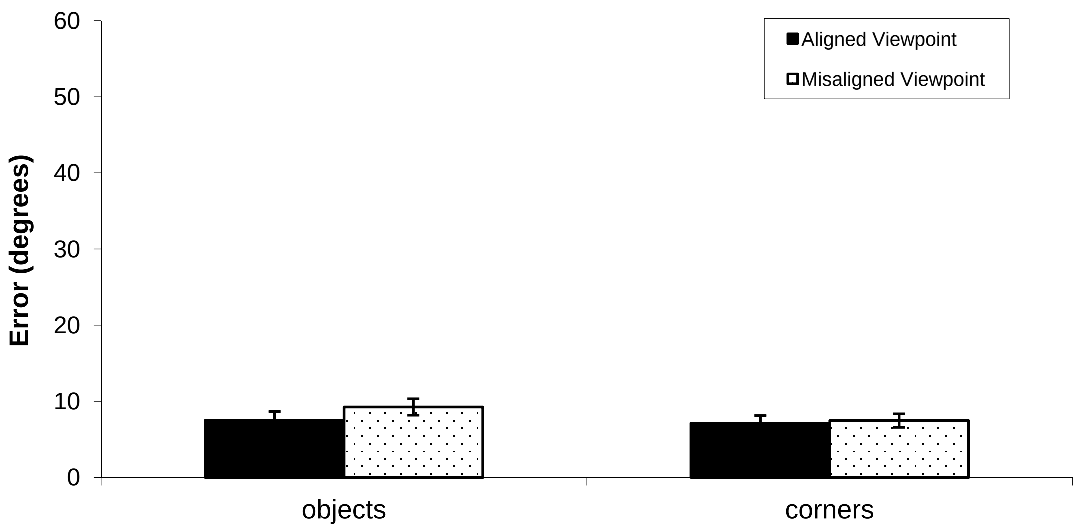
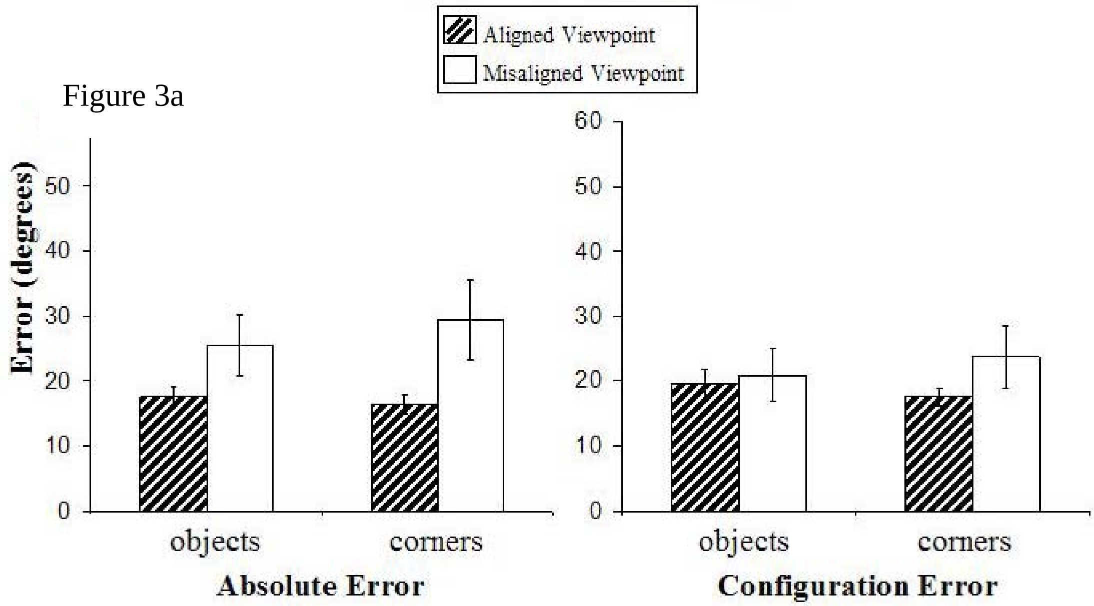


Figure 3

Experiment 1 Absolute and Configuration Error: Features versus Viewpoints with Disorientation

Figure 3a



Experiment 1: Pointing Error Across Viewpoints for Objects and Corners With Disorientation

Figure 3b

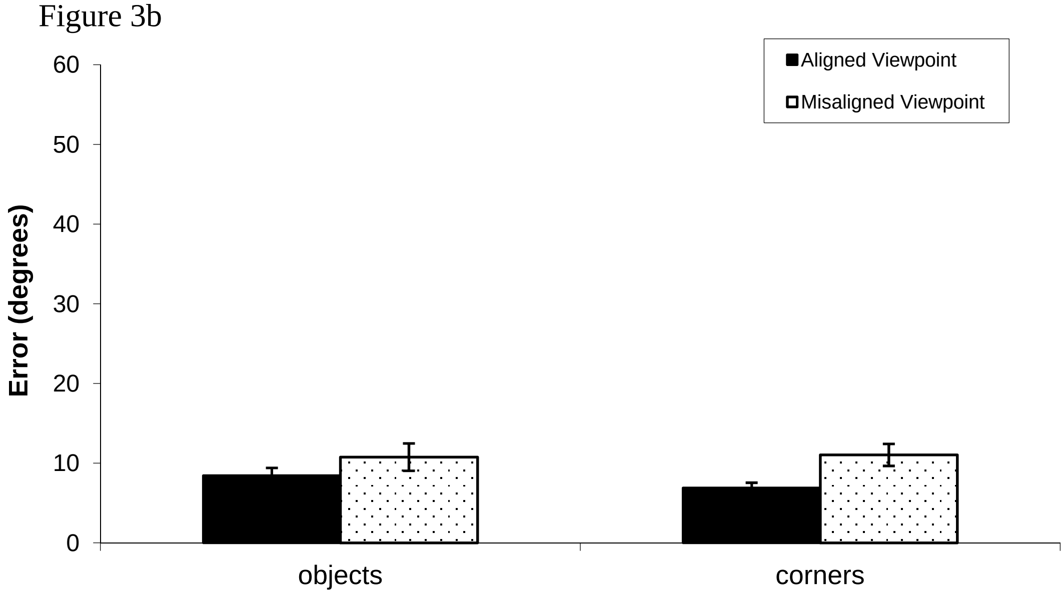


Figure 4

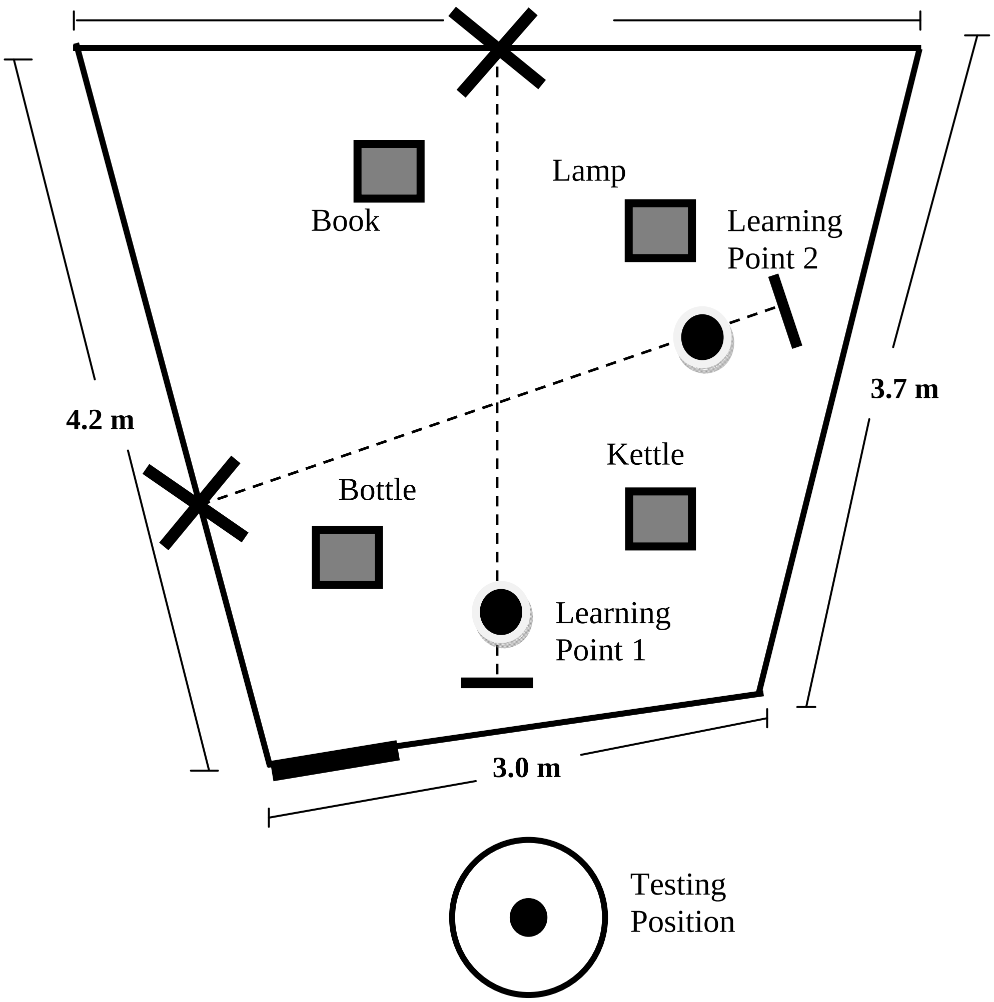
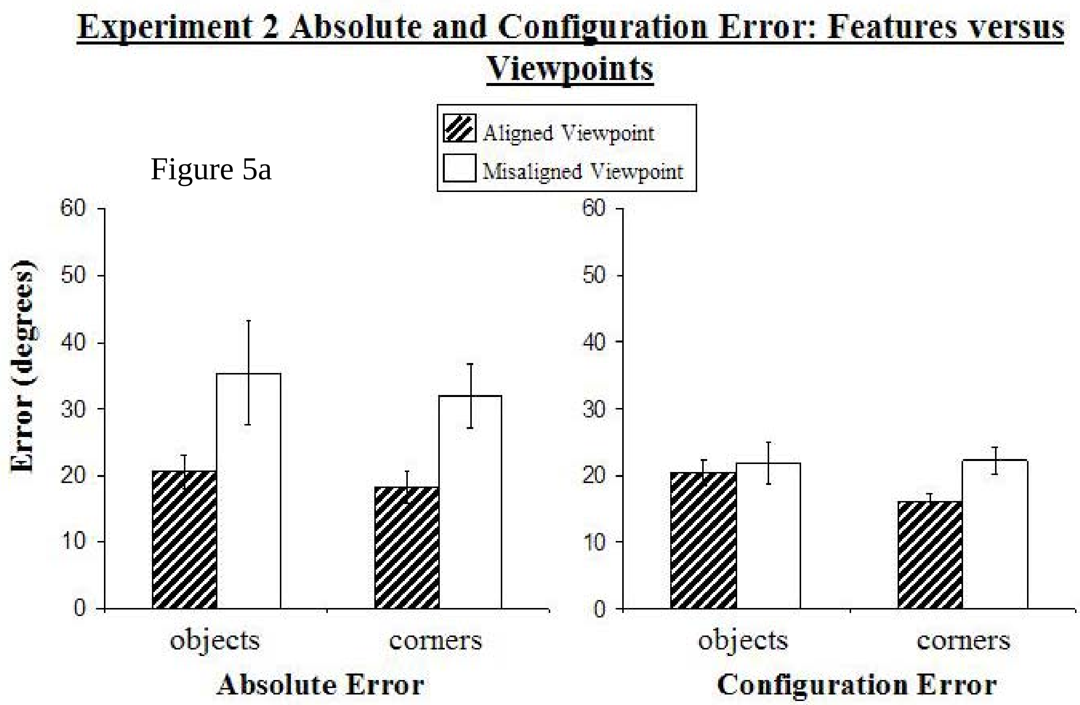

Lamp
Book
Learning
Point 2
3.7 m
4.2 m
Kettle
Bottle
Learning
Point 1
3.0 m
Testing
Position

Figure 5


Experiment 2 Absolute and Configuration Error: Features versus Viewpoints
Figure 5a
Aligned Viewpoint
Misaligned Viewpoint
Error (degrees)
60
50
40
30
20
10
0
objects
corners
Absolute Error
Configuration Error

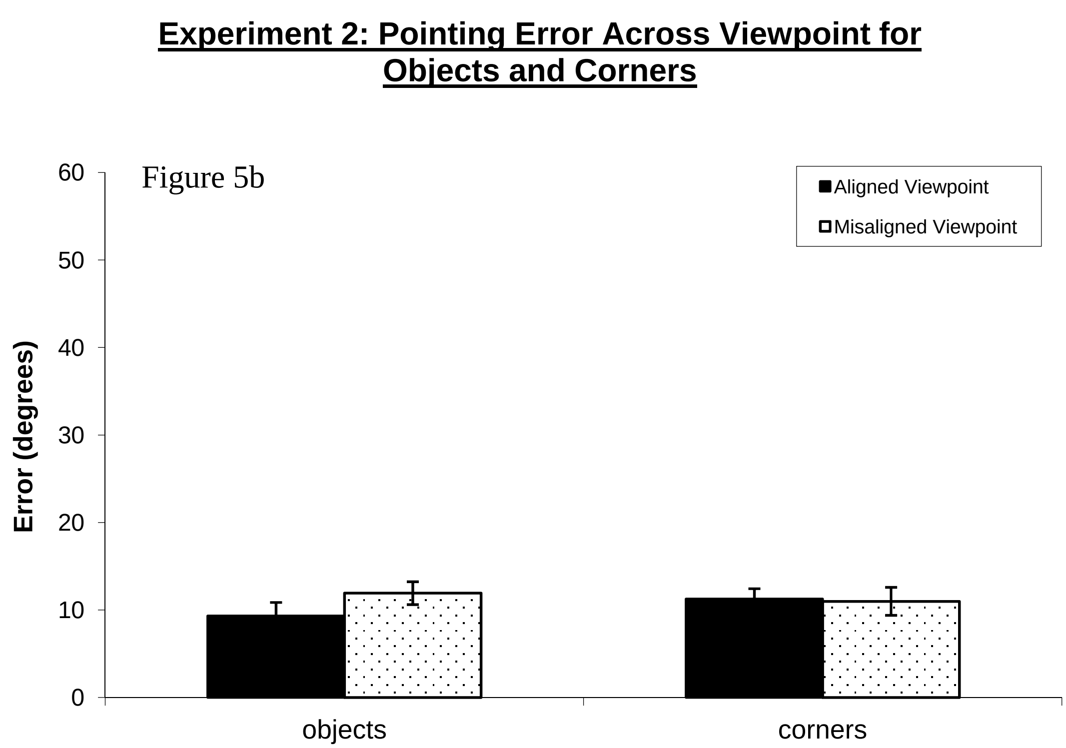
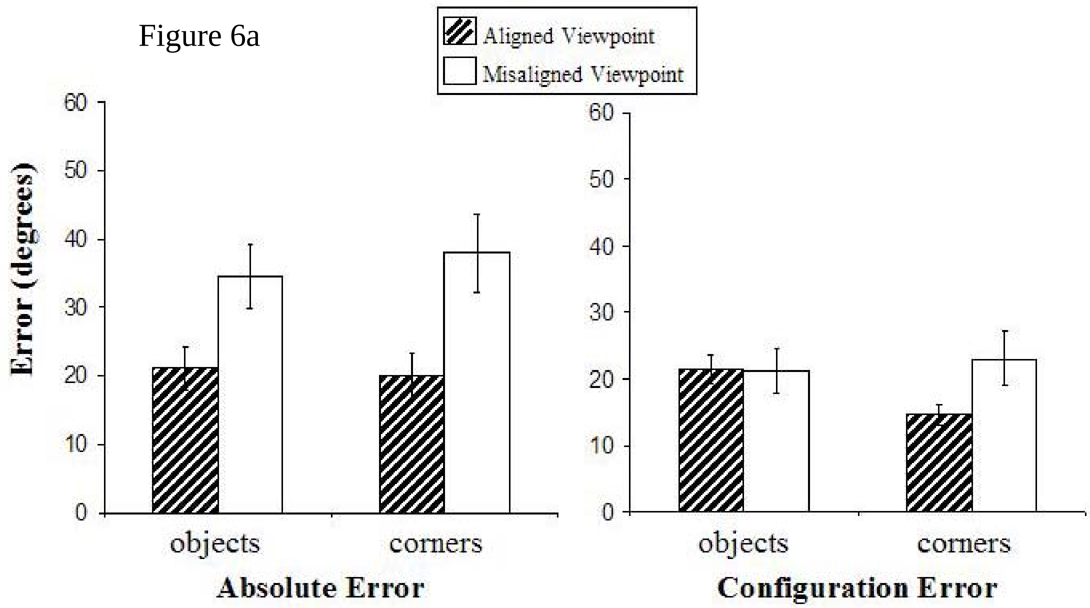

Experiment 2: Pointing Error Across Viewpoint for Objects and Corners
Figure 5b
Aligned Viewpoint
Misaligned Viewpoint
Error (degrees)
60
50
40
30
20
10
0
objects
corners

Figure 6

Experiment 3 Absolute and Configuration Error: Features versus Viewpoints



Expeirment 3: Pointing Error Across Viewpoints for Objects and Corners

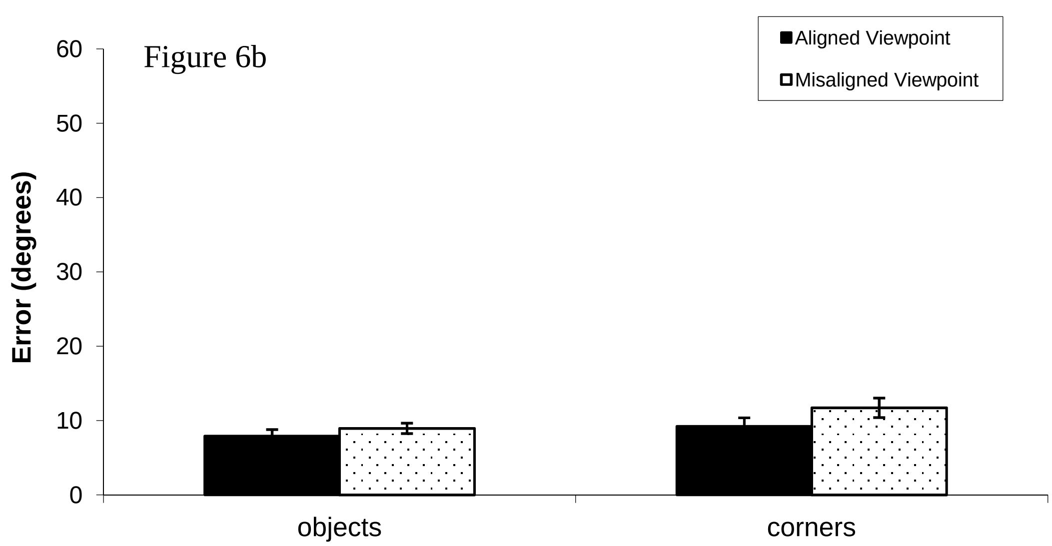
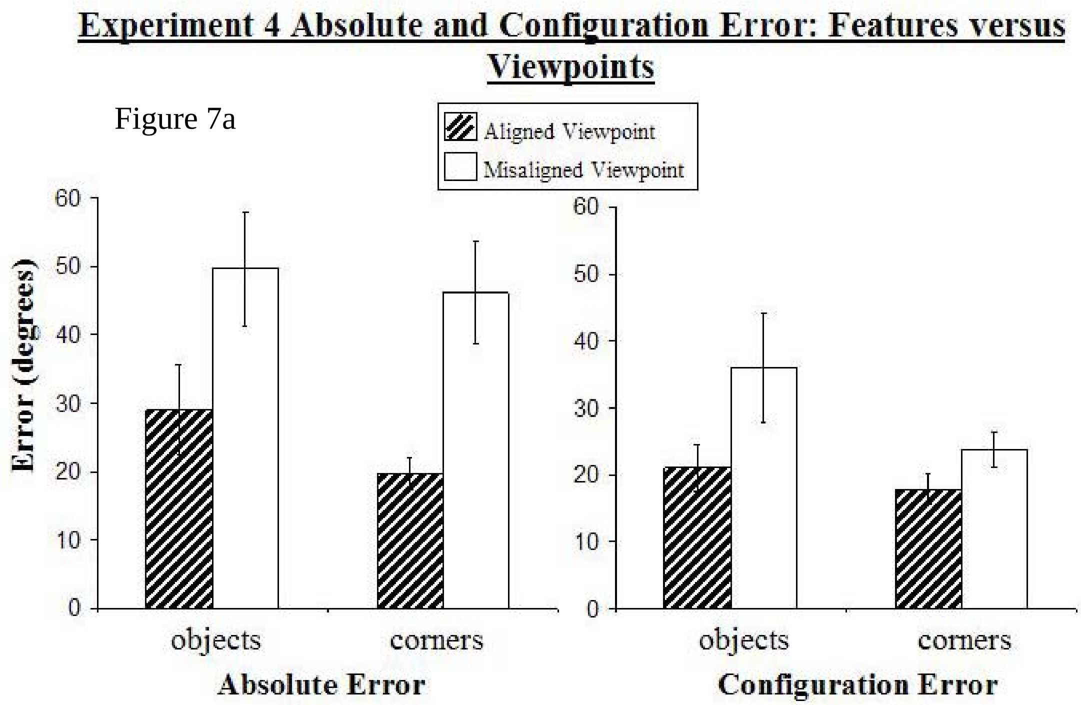
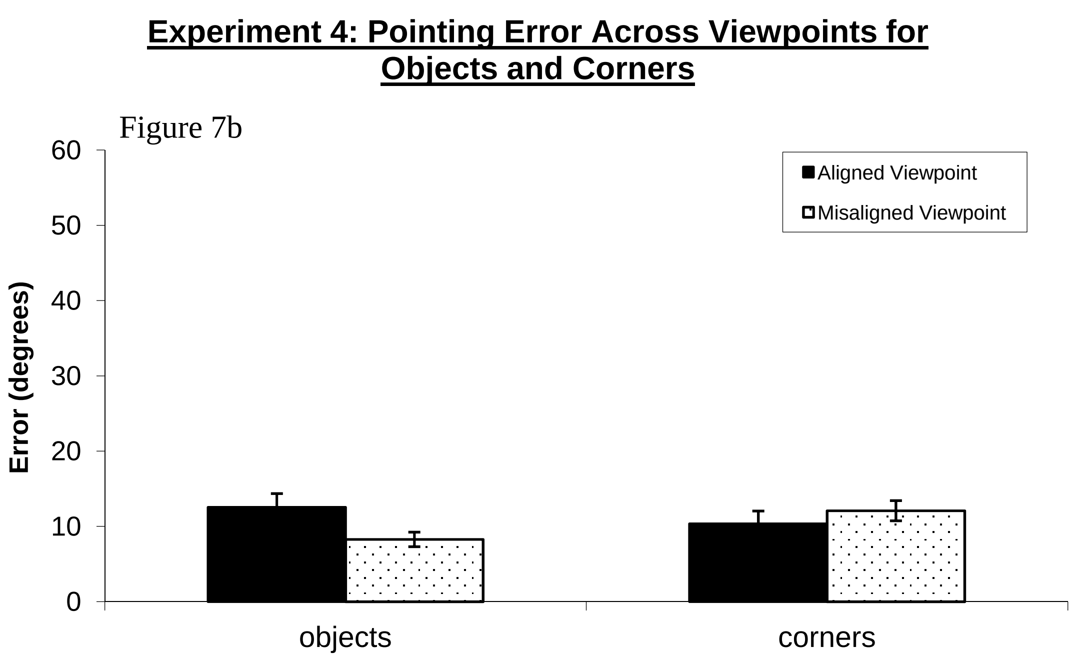


Figure 7


Experiment 4 Absolute and Configuration Error: Features versus Viewpoints
Figure 7a
Aligned Viewpoint
Misaligned Viewpoint
Error (degrees)
60
50
40
30
20
10
0
objects
corners
Absolute Error
Configuration Error


Experiment 4: Pointing Error Across Viewpoints for Objects and Corners
Figure 7b
Aligned Viewpoint
Misaligned Viewpoint
Error (degrees)
60
50
40
30
20
10
0
objects
corners

Chapter 4

Chan, G. S. W. and Sun, H-J. (in preparation). Breaking down our reference frame: The role of different spatial properties and spatial updating in a scene recognition task.

Foreword

The results and findings of Chapter 3 revealed the influence of different environmental features on observers' spatial representations; specifically it was shown that objects appear to be processed more allocentrically and corners more egocentrically. Further, the influence of different types of sensory information available to the observer on the types of spatial representations that were observed was revealed in Chapter 2. Acknowledging the importance of these two variables (sensory information available to the observer and features of the environment), we then sought to evaluate the *interaction* between observer and environmental factors. Therefore, Chapter 4 achieved this by manipulating the non-visual information available to the observer while also dissociating two visually-represented spatial properties of an object layout (i.e., identity and position). One particularly important source of non-visual information relevant to an individual's spatial representation is that found from active non-visual information (e.g., walking). Simon and Wang (1998; 1999) demonstrated the importance of non-visual information during spatial updating between learning a visual scene of an array of objects on a table and testing via a recognition task from a new viewpoint. When viewpoint change occurred by walking to the new position, response was more accurate in comparison to viewpoint change that occurred passively (i.e., the scene rotated while the subject remained stationary).

Chapter 4 utilized a scene recognition task of an array of objects on a rotatable table top similar to that of Simon and Wang (1998). Because of the nature of the small room environment in Chapter 3, it would be difficult to control for the availability of non-visual information during spatial updating while manipulating visual scene change that targets either identity information or position information. By utilizing a methodology similar to Simon and Wang (1998) while implementing two novel tasks designed to bias subjects towards identity or position information, we can study the entire spatial process of learning, retention, and testing while at the same time separating them into their individual components. This would provide the final piece tying in the intermediary process between Chapter 2 and Chapter 3.

RUNNING HEAD: Breaking down our reference frame

Breaking Down Our Reference Frame: The Role of Different Spatial Properties and Spatial Updating in a Scene Recognition Task

George S. W. Chan and Hong-Jin Sun

McMaster University

Abstract

When an observer's viewpoint of an object layout changes as a result of the movement of the layout itself, recognition performance is often poor. When the viewpoint change is the result of the observer's own movement, visual and non-visual information may serve to update the spatial representation resulting in better recognition performance. The purpose of the current experiment was to evaluate the effect of non-visual spatial updating on a scene recognition task while systematically manipulating the type of spatial information involved (identity information versus position information). Subjects had to recognize changes made to two different layouts of objects. The position task presented subjects with identical cups in which the change was the movement of one of the cups to a novel position. The identity task presented subjects with uniquely different cups in which the change was the replacement of one of the cups with a new one.

Subjects learned either the layout of five or seven objects on a rotating table. They were subsequently presented with the objects from a novel viewpoint (due to either table rotation or subject's movement around the table) and were required to identify the relevant change made. The results demonstrated that performance was more accurate when subjects moved to a new viewpoint compared to situations in which they remained stationary while the table rotated. Further, subjects were more accurate for the position task in comparison to the identity task. In addition, an interaction effect was observed in which subject's performed more accurately in the position task as long as the testing viewpoint was the same as learning viewpoint independent of the spatial updating.

However, performance in the identity task was more accurate as long as the testing viewpoint was congruent with the spatial updating provided. Our results suggest that specific spatial properties have dissociable affects that differentially interacts with non-visual information and that independent and discrete mechanisms are involved in the encoding and updating of our spatial representations.

Breaking Down Our Reference Frame: The Role of Different Spatial Properties and Spatial Updating in a Scene Recognition Task

As we move through and interact with our external environments, we experience objects and spatial layouts from perspectives that are both familiar and completely novel. Considering the multitude of spatial components that comprise a visual scene (e.g. distance, shading, and viewing angle), the exact image that is viewed at any given moment may be considerably different from those experienced in the past. The fact that we can recognize a previously experienced object or layout when viewed from a novel perspective suggests that one's mental representation of these various spatial components is flexible.

Viewpoint Dependent and Viewpoint Independent Representations

Two main theories have been proposed in an attempt to better explain humans' ability to generalize spatial knowledge gained from one perspective to interpret a scene or object from a new perspective - both of which have received considerable support. Specifically, "viewpoint dependent" hypotheses maintain that one's mental representation of an object or layout is composed of a compilation of discrete images experienced at different times across several distinct perspectives. One's ability to recognize a scene from a novel perspective occurs by comparing the new image to a series of previously stored images. Support for this account comes from neurophysiological and psychophysical evidence demonstrating that objects and scenes are more quickly and accurately recognized when they are presented from a familiar viewpoint compared to novel viewpoints (e.g. Tarr & Pinker 1989ab; Bulthoff & Edelman 1992; Biederman &

Gerhardstein, 1993, 1995; Tarr, 1995; Simons & Wang, 1998; Wang & Simons, 1999; Mou & McNamara, 2002; Wang, Simons, & Roddenberry, 2002; Wraga, Creem-Regehr, & Profitt, 2004). Further, reaction times for recognition tasks have been shown to be positively correlated with the degree of rotation, such that increasing the degree of rotation from the originally learned perspective leads to systematically increased reaction times.

The second theory, maintains a "viewpoint independent" position claiming that mental representations of objects and scene are stored as “structural descriptions” and thus, encoding a single viewpoint is sufficient for later identification of that same object from a novel viewpoint should its features be visible (Biederman, 1987; Biederman, and Gerhardstein, 1993; 1995).

Non-visual Information and Spatial Updating

Investigators have employed object and scene recognition tasks as a way of understanding how spatial information is encoded when forming a spatial representation. Traditionally these tasks have required subjects to first learn an object (or a layout of several objects) and subsequently report whether a rotated version of the object or layout is the same or different from that originally learned (Vandenberg & Kuse, 1978; Shepard & Metzler, 1988; Simons & Wang, 1998; Wang & Simons, 1999; Simons, Wang, & Roddenberry; 2002; Wraga, Creem-Regehr, & Profitt, 2004). In this task, subject's ability to compare two discrete visual presentations is used as a measure of their ability to mentally rotate the originally learned object. The interpretations of the results generated from such studies often assume that this task sufficiently simulates the viewpoint changes that are experienced during real world navigation. However, this approach essentially ignores a critical and perhaps even more frequent scenario in which viewpoint changes occur – that is, observer movement. Although it remains true that viewpoint changes can be directly attributable to object rotation while the observer remains stationary, viewpoint changes are more often the result of the movement of the observers themselves. While ultimately the retinal image that may be experienced following each of these movements (object versus self) may be identical, these two scenarios are far from equal. The critical distinction between the two perhaps is not apparent during the processes of learning or recalling, but instead involves the processing that occurs between these two phases. Specifically, when a subject is able to move from one location to another, there is a great deal of visual and non-visual information that may serve to update their mental representation and thus facilitate the recognition of a particular scene from a novel viewpoint (Simons & Wang, 1998; Wang & Simons, 1999; Simons, Wang, & Roddenberry, 2002; Waller et al., 2002; Wraga, Creem-Regehr, & Profitt, 2004). When the scene rotates independently of the observer, such updating may not be possible.

As a way of directly comparing the effects of observer movement to the effects of the movement of the stimulus array, Simons and Wang (1998) used a layout of common objects to conduct a change detection task (which object in the array changed position). Subjects either remained stationary while the entire array of objects shifted by 47 degrees, or the table remained stationary while subjects walked around the table and again viewed the entire array of objects from a position that shifted their view by 47 degrees. As result, subjects walking around the table instead of the table rotating would be provided with non-visual information to update their spatial representation. This experimental paradigm allows the experimenter to manipulate the retinal image subjects received independent of whether or not they also received spatial updating information.

The results of Simons and Wang (1998) demonstrated that when subjects moved to a novel position, they were able to perform better in detecting changes in the spatial layout compared to when the stimulus array rotated and the observer remained stationary. This experiment was one of the first to use this paradigm as a way of highlighting the importance of considering the intermediary process of updating when examining spatial representations.

Spatial Properties and Spatial Representations

In the series of experiments conducted by Simons and Wang (1998), subjects were presented with a layout of several unique objects. Their task was to detect changes in the position of the objects in the stimulus array. However, in this task subjects could potentially have used two different attributes contained in the object array: the position of the objects themselves and/or the identity of the objects. These two sources of spatial information (object position and object identity) need to be considered separately in order to reveal whether or not the brain processes them separately. Due to the design of previous studies using variations of the "object layout change detection task", it has been impossible to isolate the specific types of information that subjects are using to complete the task. Moreover, it is conceivable that spatial updating could potentially affect these two spatial properties in different ways. Support for this claim comes from many studies. For example Postma and colleagues have demonstrated, using a different paradigm (a scene reproduction task without the viewpoint changes), that positional information and identity information are processed differently (Harvey & Igel 1991; 1992; Postma & De Haan, 1996; Postma, Izendorn, & de Haan, 1998; Postma et al . 2004). Specifically, they demonstrated that memory load and articulatory suppression had differential effect on object to position assignment and position information only encoding

Current Study

Our current experiment was to assess the effects of non-visual updating on an object array recognition task, while at the same time systematically manipulating the type of information being processed (position or identity). Our goal was to better understand how and what type of information is encoded from a spatial array and if whether specific types of spatial information interact differentially with the availability of spatial updating.

We employed a scene recognition task which involved first presenting subjects with a layout of five or seven objects on a rotating table (learning phase), followed by a short period during which visual information was occluded (retention phase). During this retention phase, a change was made to the layout of objects. Subjects were then presented with the rotated object array again and were required to judge what change was made (testing phase). To test for the effect of spatial updating, we compared viewpoint change caused by display rotation with viewpoint changes caused by subjects moving around the display during the retention phase.

In addition to re-examining the effect of spatial updating via our viewpoint manipulation, we were specifically interested in examining the potentially different roles of two different spatial properties: positional information and identity information. It was predicted that the experience of actively walking to a new position before viewing the layout from a different angle would increase subjects’ ability to update their mental representation, thus facilitating their ability to detect the differences in the array. We also predicted that relative to the position task, the identity task would be affected to a lesser extent for viewpoint change due to either display rotation or subject's movement.

Another factor that can dissociate the position processing and identity processing could be through the manipulation of the number of objects presented. Such a manipulation could reveal the tendency to process different spatial properties in either a global or a local manner. If subjects process the specific spatial property in a local manner, then increasing the number of objects should deteriorate performance dramatically. However, if subjects process the spatial property in a global manner, then increasing the number of objects should not affect performance. Here we predicted that a position task using an array of identical objects would be processed in a more global manner, whereas an identity task using an array of different objects would be processed in a more local manner.

Experiment

Method

Participants. Eight male (mean age = 21.17 years, SD = 1.34 years) and eight female (mean age = 20 years, SD = 0.58 years) undergraduate students from McMaster University participated in this study. They were compensated through course credit. The study was approved by the McMaster University Research Ethics Board.

Materials. A circular table with a rotating top (122 cm diameter, 70 cm height) was used for this experiment. Ball bearings were used in the construction of the tabletop to allow for smooth rotational movements.

Cylindrically-shaped objects (drinking glasses) were chosen as a way of eliminating possible inter-object spatial cues provided by the shape of individual objects, moreover individual objects appeared identical regardless of which angle they were observed from. The object array was comprised of five or seven identical or unique objects depending on the manipulation of object numbers. In addition, for the identity condition the objects presented to subjects were drawn from a pool of 15 unique objects.

A data projector was mounted 170 cm above the table and was used to project an image of the spatial layouts that were used as a template to guide the positioning of the glasses. Each layout was generated by a program developed in Matlab. The program guided the experimenter to randomly position the objects at five or seven locations and also guided the manipulation of the object layout. Care was taken to avoid any object layout that would form any regular patterns or shape (e.g., we discarded any layout that would form the shape of a square or the letter x). Between trials and during the retention phase, a blindfold was used to occlude the subject's vision while the experimenter arranged the subsequent object layout. A wireless microphone was used as a way of recording subjects' responses and reaction times during responding. An illustration of the objects and the Matlab display is shown in Figure 1.

Insert Figure 1 About Here

Procedure. Prior to beginning the experiment subjects were provided with instructions and were given enough practice trials until they demonstrated they understood how to perform the task.

Learning phase. During the experiment the subject stood two feet away from the table. At the beginning of each trial, the subject was required to view a layout of five or seven objects on the table for five seconds. The objects were either identical or different from each other.

Retention phase. A tone was emitted to indicate the end of the five seconds at which time the subject immediately put on a blindfold for 10 seconds. During this period a manipulation was performed on the viewing conditions of the subject and on the object array.

Subject's viewing conditions was manipulated in the following four ways:

1) Subject was stationary and the display was stationary (S_{stat}/D_{stat}).

2) Subject was stationary and the display moved by rotating 47 degrees clockwise (S_{stat}/D_{move}).

3) Subject moved 47 degrees counterclockwise around the display and the display was stationary (S_{move}/D_{stat}).

4) Subjects moved 47 degrees counterclockwise around the display and the display moved by rotating 47 degrees counterclockwise (S_{move}/D_{move}).

The object array was manipulated in the following two ways:

1) When subjects were presented with an object array consisting of identical objects, one of the objects was moved to a novel location (position information only task). Figure 2a illustrates an example of a single trial of the position information only task.

Insert Figure 2a About Here

---

2) When subjects were presented with an object array consisting of different objects, one of the objects was replaced with a novel object while the overall object configuration remained the same (identity information only task). Figure 2b illustrates an example of a single trial for the identity information only task.

Insert Figure 2b About Here

Moreover, from trial to trial the objects presented to subjects were changed in order to avoid subjects gaining familiarity to the uniqueness of each object. Before the beginning of each trial, half of the objects were randomly replaced with objects picked from the pool of 15 unique objects (i.e., three objects were replaced for the five objects condition and four objects were replaced for the seven objects condition).

Test phase. At the end of the retention phase, three warning tones were emitted and at the third tone subjects were required to remove their blindfold in order to view the changed object layout. At this point our Matlab program assigned a unique letter for each object and these letters were projected directly beside the corresponding objects.

Subjects were required to determine where the change occurred. As soon as they felt they knew the answer they then spoke into the microphone, reading out the letter of the object that was projected on the table. The computer recorded the time between the third tone and when subjects spoke into the microphone, which was used as a measure of reaction time. Subjects' verbal responses were coded as being correct or incorrect. No feedback was provided throughout the experiment.

Summary of the experimental design. Three main independent variables were manipulated: viewing condition (S_{stat}/D_{stat}, S_{stat}/D_{move}, S_{move}/D_{move}, S_{move}/D_{stat}), spatial properties (position information only task and identity information only task), and number of objects (five or seven). For a summary of the entire experimental design please refer to Table 1.

Insert Table 1 About Here

Overall, every subjects participated in all possible combination of the above three independent variables (4 viewing conditions x 2 spatial properties x 2 object numbers = 16 conditions). For each of the 16 conditions, (i.e., each viewing condition, spatial property and object numbers) there were 10 trials (divided into two blocks of five trials). Subjects were presented with eight blocks of 40 trials consecutively. Each series of eight blocks consisted of the same spatial property tested (i.e., position information only task or identity formation only task) and the same number of objects (five objects or seven objects) with the manipulation of viewing conditions balanced across the series of eight blocks. Subjects performed in two sessions of 16 blocks conducted on two separate days. Each session required an hour and a half to be completed. The order in which the blocks were presented was balanced across subjects.

Results

A 4 (viewing conditions) x 2 (spatial properties) x 2 (object number) x 2 (sex) repeated measures ANOVA with one between subjects variable (sex) was conducted. Analyses were carried out on accuracy and reaction time. Accuracy was defined as the percentage of correct responses in each condition. Reaction time was measured in seconds. Overall, the difference in performance between males and females was not significantly different so the data was collapsed across sex.

Viewing Condition

In terms of accuracy, a main effect of viewing conditions (collapsing across spatial properties and object numbers) was shown (Mean (M), $S_{stat}/D_{stat} = 0.74$, M, $S_{stat}/D_{move} = 0.45$, M, $S_{move}/D_{stat} = 0.60$, M, $S_{move}/D_{move} = 0.61$, $F (3, 45) = 25.8$, $p < 0.001$). Planned comparisons revealed that subjects were significantly more accurate in the S_{stat}/D_{stat} condition as compared to all other viewing conditions and significantly less accurate in the S_{stat}/D_{move} condition as compared to all other viewing conditions.

Similar performance was observed in terms of reaction time, a main effect of viewing conditions was shown (M, $S_{stat}/D_{stat} = 4.22$, M, $S_{stat}/D_{move} = 5.32$, M, $S_{move}/D_{stat} = 4.58$, M, $S_{move}/D_{move} = 4.61$, $F (3, 45) = 13.88$, $p < 0.001$). Planned comparisons revealed that subjects were significantly faster in the S_{stat}/D_{stat} condition as compared to all other viewing conditions and significantly slower in the S_{stat}/D_{move} condition as compared to all other viewing conditions.

Importantly, we were interested in the differences in performance revealed between the following viewing conditions. When we compare the viewing conditions of

S_{stat}/D_{stat} to S_{stat}/D_{move}, as shown in the first two conditions in figure 3a and 3b, subjects performed significantly worse when the display moved (for both accuracy and reaction time) indicating the cost of mental rotation in the absence of physical movement. We also compared the viewing conditions of S_{stat}/D_{move} to S_{move}/D_{stat}. The retinal images that subjects experienced during the testing phase were identical between these two conditions. However, subjects received non-visual information for spatial updating when they moved but not when the display moved. Subjects performed significantly better when they moved around the display, indicating the benefits of non-visual spatial updating.

Insert Figure 3a and 3b About Here

Spatial Property (Identity vs Position)

In terms of reaction time, a main effect of spatial properties (collapsing across viewing condition and object numbers) was observed (M, Position = 4.48, M, Identity = 4.88, $F(1, 15) = 5.01$, $p < 0.05$). Responses in the position information only task tended to be faster than the identity task. Similar performance trends were observed with respect to accuracy but did not reach statistical significance ($p = 0.12$).

Number of Objects

In terms of accuracy, main effect of object numbers (collapsing across viewing condition and spatial properties) was shown in which subjects were more accurate when presented with five objects compared to seven objects (M, Five Objects = 0.66; M, Seven Objects = 0.54, $F(1, 15) = 32.52$, $p < 0.001$).

Similar performance was observed in terms of reaction time. A main effect of object number (five vs. seven) was shown in which subjects were faster when presented with five objects compared to seven objects (M, Five Objects = 4.33; M, Seven Objects = 5.02, $F(1, 15) = 11.51$, $p < 0.05$).

Interaction Between Spatial Property and Viewing Condition

In terms of accuracy, a two-way interaction between spatial property and viewing condition was observed ($F(3, 45) = 4.94$, $p < 0.05$). When we compare the viewing conditions of S_{stat}/D_{stat} to S_{stat}/D_{move}, as shown in the first two conditions in figure 4a, subject's accuracy for the position information only task was reduced more dramatically compared to the identity information only task.

We examined the effect of spatial updating by comparing the performance between S_{stat}/D_{move} to S_{move}/D_{stat}, as shown in the middle two conditions in figure 4a. When spatial updating is possible, although subject's accuracy for both position information only task and the identity information only task improved, the trend of this improvement in performance for the identity information only task was more evident.

Insert Figure 4a and 4b About Here

Interaction Between Viewing Condition, Spatial Property, and Number of Objects

In terms of accuracy, a three-way interaction between viewing condition, spatial property, and number of objects was observed ($F(3, 45) = 2.93$, $p < 0.05$). While figure 4a illustrates the interaction between spatial properties and viewing condition, figure 5 further breaks the data down according to the number of objects.

When we compare five objects to seven objects, subject's performance was generally worse for seven objects across all viewing conditions. However, within the S_{stat}/D_{move} condition, for the position information only task such a difference in performance was not evident.

Insert Figure 5 About Here

Discussion

Viewing Condition

Our results demonstrate that when the display rotated (comparing S_{stat}/D_{move} to S_{stat}/D_{stat}) subjects' performance dropped dramatically, consistent with the well-established observations in mental rotation studies. The more interesting finding lies in the comparison between the two conditions in which the overall visual scene was different between learning and testing due to the display rotation (S_{stat}/D_{move}) compared to the subjects' movement (S_{move}/D_{stat}). Our results demonstrated that subjects' performance was better with regards to both accuracy and reaction time, when they moved to a new viewing condition (S_{move}/D_{stat}) compared to when they remained stationary and the display rotated (S_{stat}/D_{move}). What makes this finding particularly interesting is the fact that the retinal image experienced during testing in each of these situations was identical. This means that the increase in accuracy observed in the S_{move}/D_{stat} conditions can be attributed to the non-visual information experienced during the retention phase. These findings are consistent with previous studies (e.g., Simon & Wang, 1998).

Another pair of conditions that involved identical retinal images during testing is S_{stat}/D_{stat} and S_{move}/D_{move}. Again, the only difference lies in the inclusion of non-visual information in the S_{move}/D_{move} condition. Performance was worse in situations in which both the subject and the display moved (S_{move}/D_{move}) compared to situations in which both the subject and the display remained stationary (S_{stat}/D_{stat}). This suggests that the reason for the performance difference could be a result of the inclusion of non-visual information being incongruent with the visual scene in S_{move}/D_{move} condition.

Spatial Properties and Viewing Conditions

Results demonstrated that overall, subjects were more accurate in the position only task as compared to the identity only task. Such a main effect of spatial property may be task specific and thus not very informative for revealing the underlying general principles. More importantly, our manipulation of viewing condition provides a baseline with which to reveal the interaction between spatial properties across four viewing conditions. Specifically, a two-way interaction effect was observed between spatial properties and viewing conditions with regards to accuracy. In particular, for the comparison between S_{stat}/D_{move} and S_{stat}/D_{stat} (viewpoint change without spatial updating) and the comparison between S_{move}/D_{stat} and S_{stat}/D_{stat} (viewpoint change with spatial updating), the results demonstrated that subjects' performance in the position information only task was dramatically poorer than the identity information only task in terms of accuracy. This result indicates that position information is more vulnerable to viewpoint change regardless of how the viewpoint was changed; either as a result of the display rotation or the subject's movement.

The sensitivity of position processing to viewpoint changes can also be illustrated by other comparisons. By comparing the two viewing conditions in which non-visual information was provided (S_{move}/D_{stat} and S_{move}/D_{move}), we observed that subjects performed better in the position information only task when visual information was identical between learning and testing (S_{move}/D_{move}). In other words, position processing benefited from having equivalent visual information between learning and testing, thus position processing appears to be more visually driven.

In contrast, for the identity information only task in the S_{move}/D_{move} condition, not only was there no benefit from having the equivalent visual information between learning and testing, but the trend was actually in the opposite direction. In this condition, subjects moved around the display while at the same time the display rotated the same magnitude. Consequently, the visual image did change between learning and testing. Therefore it could be that when the visual display did not match what was expected from the motor output, subjects may have had difficulty resolving such a discrepancy when they use identity information. Such a difficulty was not manifested for the position only task. A possible reason for this maybe that the mental strategy utilized for the identity task was more rigid and tightly associated with the expected display change. In comparison, the mental strategy utilized for the position task was more loosely associated with the expected display change. Therefore, when there was a discrepancy to the expected display change, for the identity task, subjects had to "un-rotate" their mental representation whereas for the position task, subject did not need to overcome such mental rigidity. This suggests that specific spatial properties may be differently influenced by non-visual information. The implication of this is that that there may be independent and discrete mechanisms involved in the encoding and updating of position and identity attributes.

Number of Objects

By manipulating the number of objects, it was revealed that in the S_{stat}/D_{move} condition, when the number of objects was higher (i.e. 7 v.s. 5), subject's performance in the identity task was dramatically worsened, whereas their performance in the position task was not affected at all. This suggests that the types of processing used in the position task may be more global in nature, whereas in the identity task it may be more local in nature. Specifically, if information is processed sequentially in an item-by-item manner, the number of objects would likely affect responding; conversely, the same is not necessarily true if the scene is processed as a whole.

Even though this clear pattern of responses was observed for the S_{stat}/D_{move} , this same pattern is not as evident in the other three viewing conditions. Considering that the S_{stat}/D_{move} condition was arguably the most challenging condition (evidenced by the lowest accuracy across both spatial properties), when it was made even more challenging by increasing the number of objects subjects may have used a more holistic processing strategy for the position task. This suggests that position attributes are processed in a more global manner while identity attributes are processed in a more local manner, providing additional evidence for the existence of dissociable mechanisms for processing different spatial properties.

General Discussion

Overall, our results complement and further the understanding of spatial updating and viewpoint dependence. Previous studies suggest that viewpoint dependence is evidence of an egocentric representation and that recalling information about an array of objects when viewing it from the originally learned viewpoint results in higher performance accuracy (Diwdkar & McNamra, 1997; Shelton & McNamara, 1997; McNamara, 2003; Mou et al., 2004). Further, it has been shown that if subjects are tested from novel viewpoints and are provided with spatial updating via non-visual cues, performance was still better from the originally learned viewpoint (Mou et al., 2004; Mou et al, 2006) Further understanding of the role of non-visual information was provided when the array of objects were presented on a rotatable table, demonstrating that subjects performed better when the viewpoint change was a result of the subject walking to the novel viewpoint compared to the table rotating the array of objects (Wang & Simons, 1998; Simons & Wang 1999; Simons, Wang, & Roddenberry, 2002; May, 1996; May, 2007). Although performance was still best from the originally learned viewpoint, the modulation of error when subjects walked to the novel viewpoint suggested that spatial updating via non-visual information did provide some benefit to spatial processing.

Other studies using fMRI have demonstrated different activation within the motor cortex when subjects imagined an object rotating compared to imagining themselves moving to a novel viewpoint (Wraga et al 2005; Wraga et al. 2010). This suggests that recognition tasks may involve different streams of processing when comparisons are made between viewpoint changes as a result of a table rotation compared to viewpoint changes due to actual physical movement to novel viewpoints. Such a situation usually do not occur as normally both our body and our mental viewpoint are congruent. However, situations in which there is incongruency between body and mental viewpoint are possible such as when we try to recall memories of where we've been such as a visual scene from past travels. One comparable example of this is to look at a possible more extreme conflicting sernsori/mental viewpoint task. Subjects may learn a visual scene from one viewpoint and then physically rotated 180 degrees so that they are facing the opposite direction. They may then be required to imagine themselves oriented along the initially learned viewpoint. The physical sensation of turning 180 degrees may automatically invoke subjects to have a different mental viewpoint. Subjects would then have to use some cognitive effort to re-orient their mental viewpoint back to the initially learned viewpoint. These different streams of processing may also interact with each other such that subjects may have difficulty ignoring sensory information that informs them that they are physically oriented in one direction while the visual scene task demands them to cognitively imagine themselves in another direction (May, 1996). This is supported by studies that demonstrate that different modes of responding may further interact with recall (de Vega & Rodrigo, 2001; Wraga, 2003; Avraamides et al., 2004; Wang, 2004; Avraamides et al., 2007). Specifically, verbal descriptions of the location of objects relative to the observer's position (e.g., front, front right, front back… etc.) during recall are less viewpoint dependent compared to physically pointing towards the direction of the objects (Kelly & McNamara, 2008). It is suggested that scene recognition tasks are inherently egocentric, especially one that studies viewpoint dependence. Pointing tasks generally rely on an egocentric body-to-object strategy, whereas verbal tasks are typically less dependent of the body. Potentially, the mode of the response may therefore invoke different frames of references during recall.

In our study, subjects always verbally responded to the change detection task, therefore subjects performance should be less egocentrically dependent. It would be expected that performance for the position information only task would be more similar to the identity information only task. However, we still demonstrated differential performance between the position information only task and the identity information only task. Extending Kelly & McNamara (2008) results, this would suggests that the influence of the visual scene may result in a more automatic egocentric FR for position information making position information being more visually captured. This provides further evidence that different stream of processing are involved between position and identity information that goes beyond difference in mode of response during recall.

In addition, our results demonstrate the benefit of non-visual spatial updating during recall, supporting the importance of spatial updating in visual scene recognition tests. This provides further evidence of possible differences between imagining viewpoint changes compared to actual physical movements resulting in equivalent viewpoint changes. In addition, we demonstrate difference in performance as a function of tasks demands; specifically, those that require subjects to attend to position information and those that require them to attend to identity information. This suggests that the neural underpinning associated with imagined versus physical movements may also interact with the types of environmental properties that are being updated.

Global versus Local Processing

Previous studies have suggested that people generally have a top-down perception of their environment such that they process spatial information globally then locally (Navron 1977; Kimchi, 1992). Specifically, observers take in the aggregate features of an environment in a holistic manner before focusing on the more local specific objects within the visual scene. In contrast, early work in spatial perception such as feature integration theory of attention, demonstrate that features in a visual scene are perceived early and in parallel across the visual field while objects are identified separately and require more attention (Treisman & Gelade, 1980). More recently, other studies have suggested that when an observer views a scene quickly, they take in the gist of it, such that they process the environment in a single global manner (Greene & Oliva, 2009; Oliva & Torralba 2006). In these spatial perception studies, a configuration of local features (e.g., the alignment of the object [Treisman & Gelade, 1980]) defines a "global" feature.

In our experiment, subjects were presented with an array of objects; were given time to learn the stimuli; and were also told beforehand what spatial property to focus on. Although the methodology is different, our results still have an impact across paradigms. We demonstrate that even given sufficient time and task specificity, changes in viewpoints had separable effects on global and local spatial perception. Contrary to general expectation, even though local processing is supposed to require more attentional resources, changes in viewpoint affect global processing more. This was true even when our experiment provided subjects with a full five seconds for learning for both position and identity information. Given the extended time in which global information had to be processed by subjects, learning of global information should have been solidified. Our task biased subjects to just process global information only, in previous experiments (see above citation), this is done within milliseconds. That increase in time duration during learning resulted in unique affects of viewpoint on global processes would suggest that other spatial processes may be ongoing. It is possible that in addition to a top-down cognitive process a bottom-up process was also on-going such as integration of local features of the visual scene.

Non-Visual Updating and the Alignment Effect

One phenomenon that is analogous to the idea of viewpoint dependence but on a much larger scale (i.e. navigable spaces) is typically referred to as the "alignment effect" (Peruch & Lapin, 1993; Rossano & Warren, 1989; Warren, Rossano, & Wear, 1990). Specifically, this effect occurs when subjects more quickly and accurately point to objects (not visible) along a previously learned route when positioned in the orientation that they originally learned the route (compared to in the opposite orientation). Although most of these studies had not considered the effect of non-visual intervening cues between learning and responding, it has been shown that if subjects learn the environment by actually traversing the trajectory, the alignment effect is not observed (Sun, Chan, and Campos, 2004), and thus reflects viewpoint independence. Recognizing that non-visual information facilitated recall in both the small-scale object array task presented in this paper, as well as our previous large-scale navigation task (Sun et al., 2004), this further supports the importance of considering the impact of non-visual information in understanding spatial representations in general.

Conclusion

It is important to take into account multiple sources of sensory information, and recognize that visual information alone may not be sufficient to explain how we access spatial information about our world. It is only recently that we have begun to understand some of the mechanism, constraints, and flexibilities of our spatial memory. However, with the current studies that have demonstrated the importance of non-visual information, it is necessary to begin looking at more complex scenarios in order to fully appreciate and understand how we perceive, learn, and store our environment and also as to how we integrate so many different source of sensory information into one cohesive story. As demonstrated, by adding an additional source of sensory information for spatial updating, we have shown that our spatial representation is much more complex than simply being viewpoint dependent or viewpoint independent.

One of the benefits of studying spatial memory is that in incorporates and integrates both low level sensory processes and high level cognitive processes as demonstrated by the position only task versus the identity only task. Importantly, both can be unconsciously manipulated by the introduction of low-level perceptual information, which an experimenter can retain a high degree of control over. This effect has an impact on not only perception, but also for processes that can be considered in the domain of experimental cognition. Future studies must take this into account and attend to the individual properties of the sum of our spatial representation in order to fully understand it.

Reference

Avraamides, M. N., Klatzky, R. L., Loomis, J. M., and Golledge, R. G. (2004). Use of cognitive vs. perceptual heading during imagined locomotion depends on response mode. Psychological Science. Vol. 15. 403-408

Avraamides, M. N., Ioannidou, L. M., and Kyranidou, M. N. (2007). Locating targets from imagined perspectives: Comparing labeling with pointing responses. Quarterly Journal of Experimental Psychology. Vol. 60. 1660-1679

Biederman, I. (1987). Recognition-by-components: A theory of human image and understanding. Psychological Review. Vol. 94. 115-147

Biederman, I. & Gerhardstein. P. C. (1993). Recognizing depth-rotated objects: Evidence and conditions for three-dimensional viewpoint invariance. Journal of Experimental Psychology: Human Perception and Performance. Vol. 19. 1162-1182

Biederman, I. & Gerhardstein. P. C. (1995). Viewpoint-Dependent Mechanisms in visual object recognition: Reply to Tarr and Bulthoff (1995). Journal of Experimental Psychology: Human Perception and Performance. Vol. 21(6). 1506-1514

Bülthoff, H. H., Edelman, S.Y. (1992). Psychophysical support for a two-dimensional view interpolation theory of object recognition. Proceedings of the National Academy of Science. Vol. 89(1). 60-64

de Vega, M. and Rodrigo, M. J. (2001). Updating spatial layouts mediated by pointing and labelling under physical and imaginary rotation. European Journal of Cognitive Psychology. Vol. 13. 369-393

Diwadkar, V. A. & McNamara, T. P (1997). Viewpoint dependence in scene recognition. Psychological Science. Vol. 8(4). 302-307

Greene, M. R. and Oliva, A. (2009). Recognition of natural scenes from global properties: Seeing the forest without representing the trees. Cognitive Psychology. Vol. 58. 137-176

Harvey, L. Igel, A., Schmidt, E. K. (1991). Gestalt self-organizing forces in vision. Perception. Vol. 20(1). 90-90

Kimchi, R. (1992). Primacy of wholistic processing and global local paradigm – A critical review. Psychological Bulletin. Vol. 112(1). 24-38

May, M. (1996). Cognitive and embodied modes of spatial imagery. Memory and Processing of Visual and Spatial Information. Conference: 5th European workshop on imagery and cognition. 418-434

May, M. (2007). Imaginal repositioning in everyday environments: Effects of testing method and setting. Psychological Research. Vol. 71. 277-287

McNamara, T. P. (2003). How are the locations of objects in the environment represented in memory? Spatial Cognition III. Vol. 2685. 174-191

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

Mou, W., McNamara, T. P., Valiquette, C. M., and Rump, B. (2004). Allocentric and egocentric updating of spatial memories. Journal of Experimental Psychology: Learning, Memory, and Cognitioin. Vol. 30(1). 142-157

Mou, W., McNamara, T. P., Rump, B., Xiao, C. (2006). Roles of egocentric and allocentric spatial representations in locomotion and reorientation. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 32(6). 1274-1290

Navron, D. (1977). Forest before trees: The precedence of global features in visual perception. Cognitive Psychology. Vol. 9. 353-383

Oliva, A. and Torralba, A. (2006). Building the gist of a scene: The role of global image features in recognition. Progress in Brain Research. Vol. 155. 23-36

Peruch, P. and Lapin, E. A. (1993). Route knowledge in different spatial frames of reference. Acta Pscyhologica. Vol. 84(3). 253-269

Postma, A. and DeHaan, E. H. F. (1996). What was where? Memory for object locations. Quarterly Journal of Experimental Psychology Section A – Human Experimental Psychology. Vol. 49(1). 178-199

Postma, A., Izendoorn, R., & De Haan, E. H. F. (1998). Sex differences in object location memory. Brain and Cognition. Vol. 36. 334-345

Postma, A., Jager, G., Kessels, R. P. C., Koppeschaar, H. P. F., & van Honk, J. (2004). Sex differences for selective forms of spatial memory. Brain and Cognition. Vol. 54. 24-34

Rossano, M. J., & Warren, D. H. (1989). Misaligned maps lead to predictable errors. Perception, Vol.18. 215-229

Shelton, A. L. & McNamara, T. (1997). Multiple views of spatial memory. Psychonomic Bulletin and Reviews. Vol. 4(1). 102-106

Shepard, S. & Metzler, D. (1988). Mental rotation: Effects of dimensionality of objects and type of task. Journal of Experimental Psychology: Human, Perception, and Performance. Vol. 14(1). 3-11

Simons, D. J. and Wang, R. F. (1998). Perceiving real-world viewpoint changes. Psychological Science. Vol. 9(4). 315-320

Simons, D. J. , Wang, R. F., & Roddenberry, D. (2002). Object recognition is mediated by extraretinal information. Perception and Psychophysics. Vol. 64(4). 521-530

Sun, H-J., Chan, G. S. W., and Campos, J. L. (2004). Active navigation and orientation free spatial representations. Memory and Cognition. Vol. 32(1). 51-71

Tarr, M. J. (1995). Rotating objects to recognize them: A case study on the role of visual dependency in the recognition of 3-dimensional objects. Psychonomic Bulletin and Review. Vol. 2(1). 55-82

Tarr, M. J. & Pinker, S. (1989a). Human object recognition uses a viewer-centered frame of reference. Bulletin of the Psychonomic Society. Vol. 27(6). 506-506

Tarr, M. J. & Pinker, S. (1989b). Mental rotation and orientation-dependence in shape recognition. Cognitive Psychology. Vol. 21. 233-282

Treisman, A. M. and Gelade, G. (1980). A feature-integration theory of attention. Cognitive Psychology. Vol. 12. 97-136

Vandenberg, S. G. and Kuse, A. R. (1978). Mental rotations, a group test of 3-dimensional spatial visualization. Perceptual and Motor Skills. Vol. 47(2). 599-604

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

Wang, R. F. (2004). Action, verbal response, and spatial reasoning. Cognition. Vol. 94. 185-192

Wang, R. F. & Simons, D. J. (1999). Active and passive scene recognition across views. Cognition. Vol. (70). 191-210

Warren, D. H., Rossano, M. J., &Wear, T. D. (1990). Perception of map environment correspondence: The roles of features and alignment. Ecological Psychology. Vol. 2. 131-150

Wraga, M. (2003). Thinking outside the body: An advantage for spatial updating during imagined versus physical self-rotation. Journal of Experimental Psychology: Learning, Memory, & Cognition. Vol. 29. 993-1005

Wraga, M., Creem-Regehr, S. H., and Proffitt, D. R. (2004). Spatial updating of virtual displays during self and display rotation. Memory and Cognition. Vol. 32(3). 399-415

Wraga, M., Shephard, J. M., Church, J. A., Inati, S., and Kosslyn, S. M. (2005). Imagined rotations of self versus objects: An fMRI study. Neuropsychologia. Vol. 43. 1351-1361

Wraga, M., Flynn, C. M., Boyle, H. K., and Evans, G. C. (2010). Effects of a body-oriented response measure on the neural substrate of imagined perspective rotations. Journal of Cognitive Neuroscience. Vol. 22(8). 1782-1793

<u>Figure Caption</u>

Table 1. Table summarizing the combination of viewing conditions, spatial properties, and object numbers, balanced through the experimental design

Figure 1. Pictures of the objects used for the Position Only Task and the Identity Only Task. Also an example of how the Matlab program projected the position of the objects onto the table in order for the experimenter to set up each trial.

Figure 2a. Illustration of the learning phase and four possible testing phases for the position only task in trials where one of the objects has moved to a different location as indicated by the arrow. All the objects are the same as indicated by the same color.

Figure 2b. Illustration of the learning phase and the four possible testing phases for the identity only task in trials where two objects has switched position as indicated by the circle. All objects in this condition were of the same color (but different shape), however, for the purpose of illustrating this task, different colors used here represents different objects.

Figure 3a . Accuracy result for all viewpoints collapsed across sex, number of objects, and spatial property.

Figure 3b. Reaction time result for all viewpoints collapsed across sex, number of objects, and spatial property.

Figure 4a. Accuracy result for the position only task and the identity only task for all viewpoints collapsed across sex and number of objects.

Figure 4b. Reaction time result for the position only task and the identity only task for all viewpoints collapsed across sex and number of objects.

Figure 5. Accuracy result of three-way interaction for viewpoint, spatial property, and number of objects collapsed across sex.

Table 1.

	Position		Identity	
5 Objects	S_{stat}/D_{stat}	S_{stat}/D_{move}	S_{stat}/D_{stat}	S_{stat}/D_{move}
	S_{move}/D_{stat}	S_{move}/D_{move}	S_{move}/D_{stat}	S_{move}/D_{move}
7 Objects	S_{stat}/D_{stat}	S_{stat}/D_{move}	S_{stat}/D_{stat}	S_{stat}/D_{move}
	S_{move}/D_{stat}	S_{move}/D_{move}	S_{move}/D_{stat}	S_{move}/D_{move}

Figure 1

Objects for the Position Only Task

Objects for the Identity Only Task

Matlab Display Used

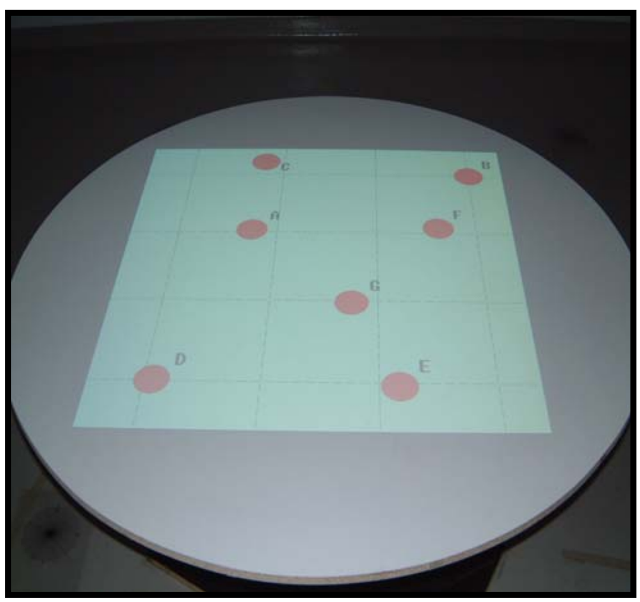


Figure 2a

Position Only Task

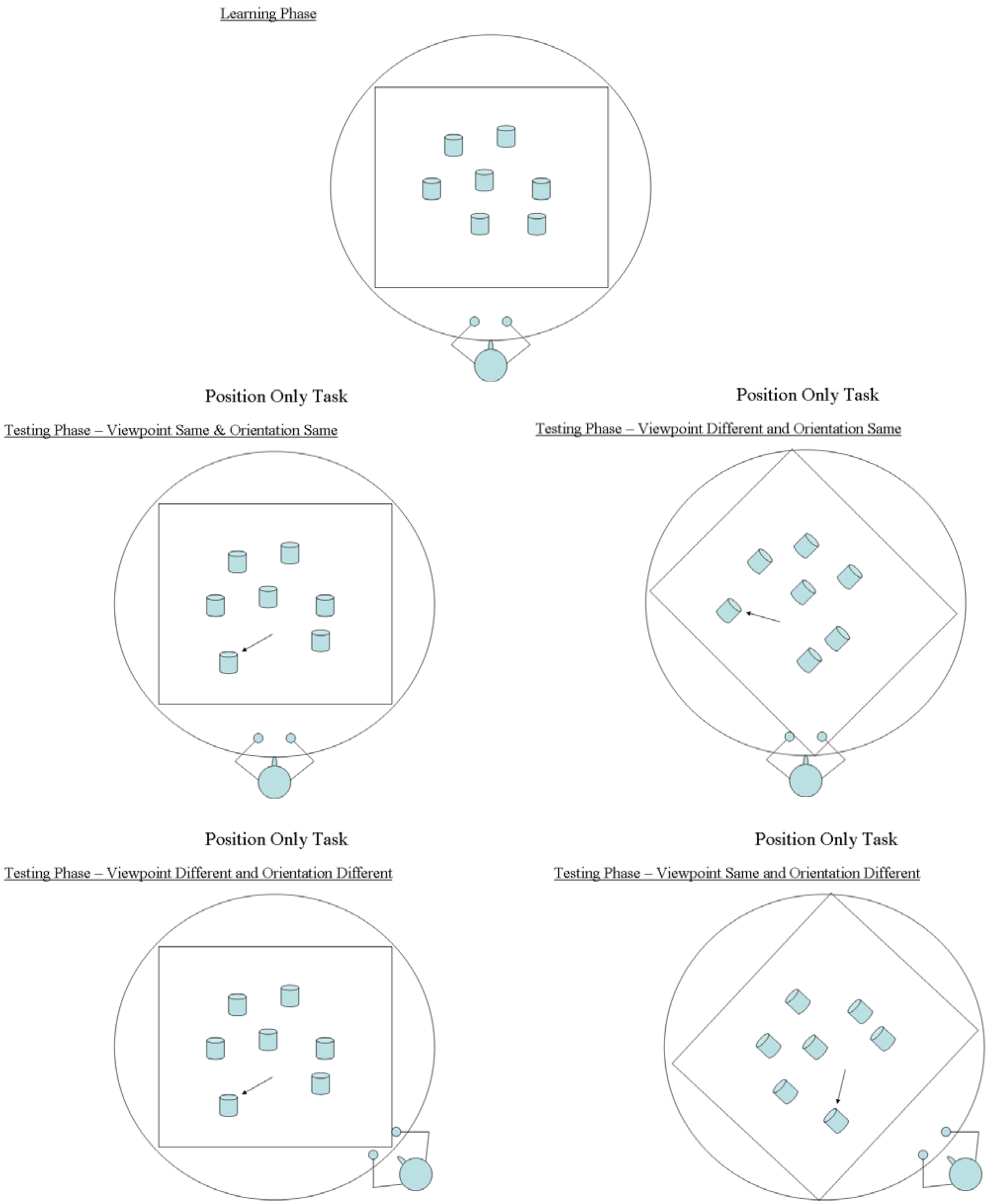


Figure 2b

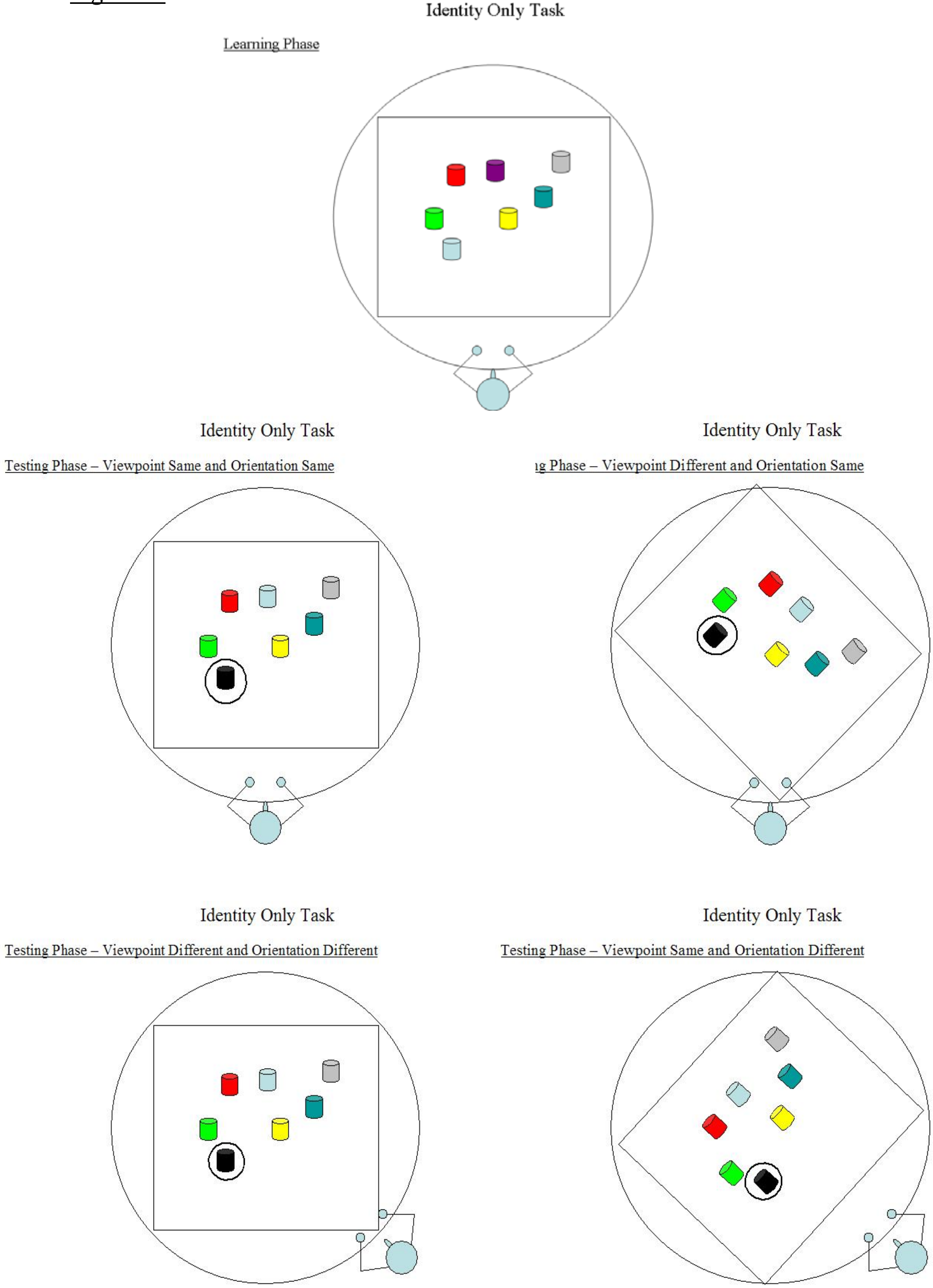

Identity Only Task
Learning Phase
Identity Only Task
Testing Phase – Viewpoint Same and Orientation Same
Identity Only Task
g Phase – Viewpoint Different and Orientation Same
Identity Only Task
Testing Phase – Viewpoint Different and Orientation Different
Identity Only Task
Testing Phase – Viewpoint Same and Orientation Different

Figure 3a

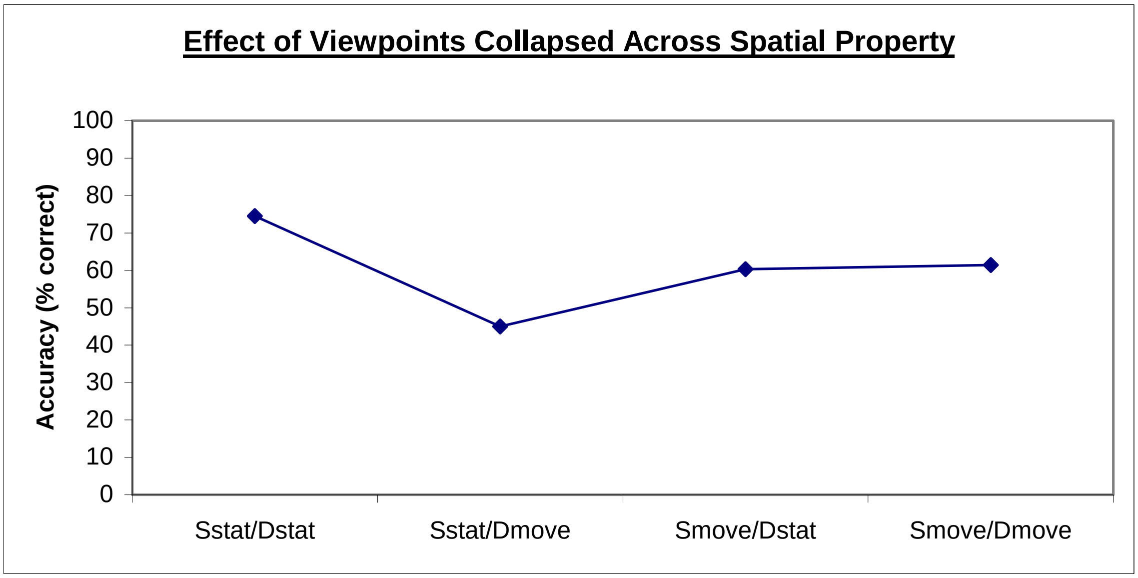


Figure 3b

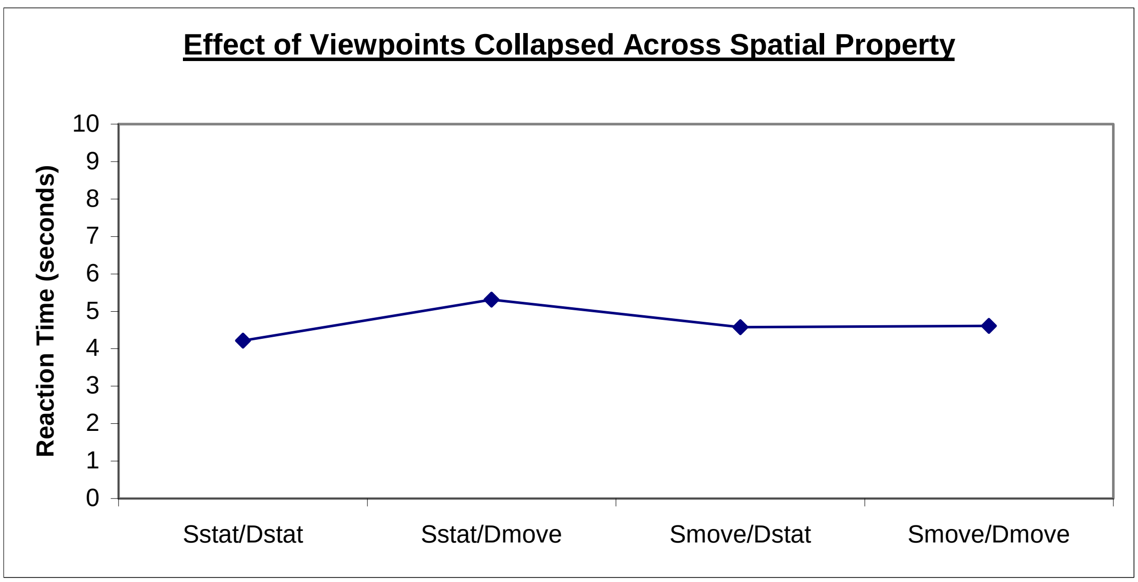


Figure 4a

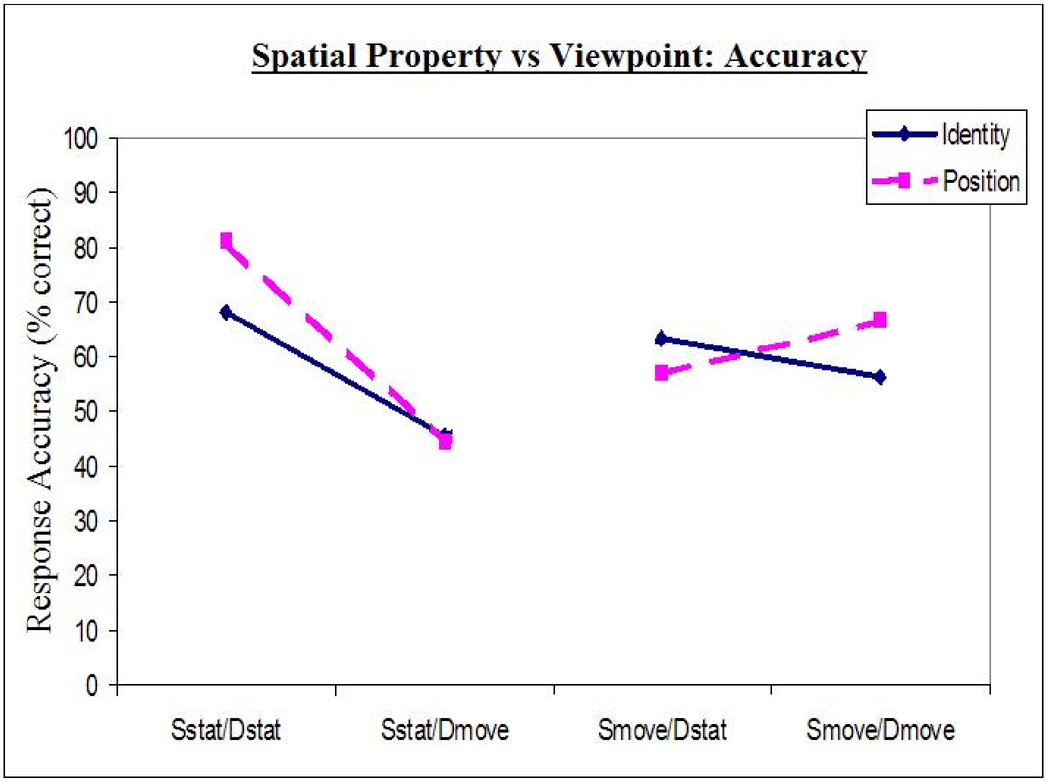


Figure 4b

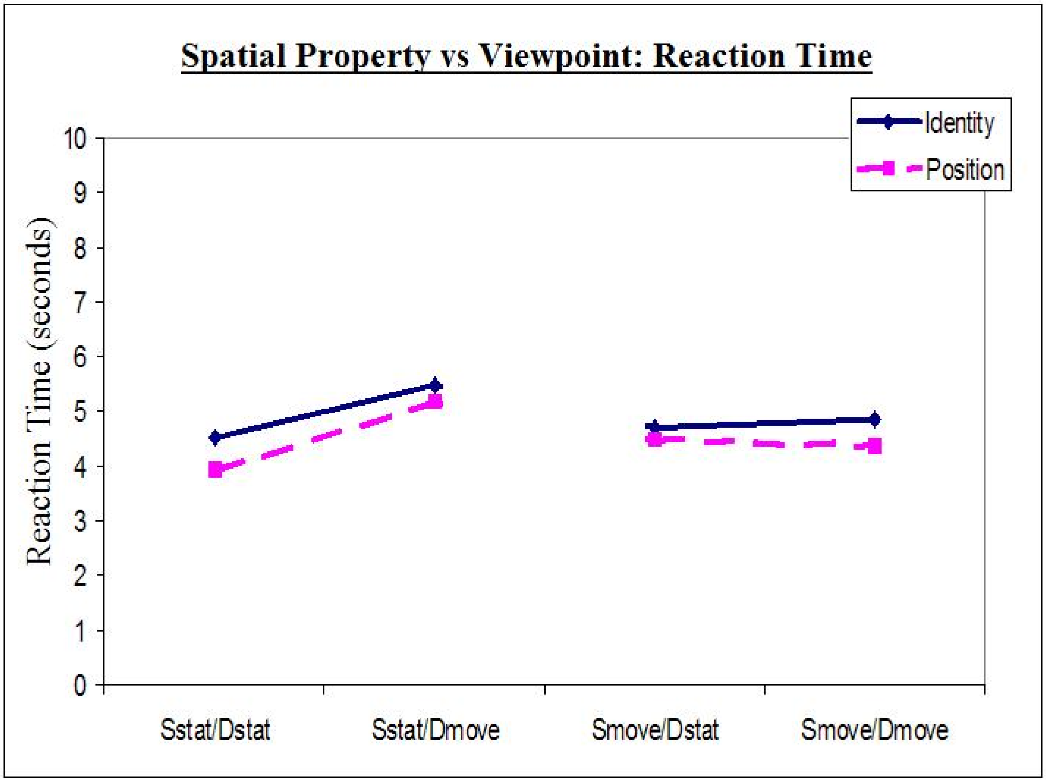
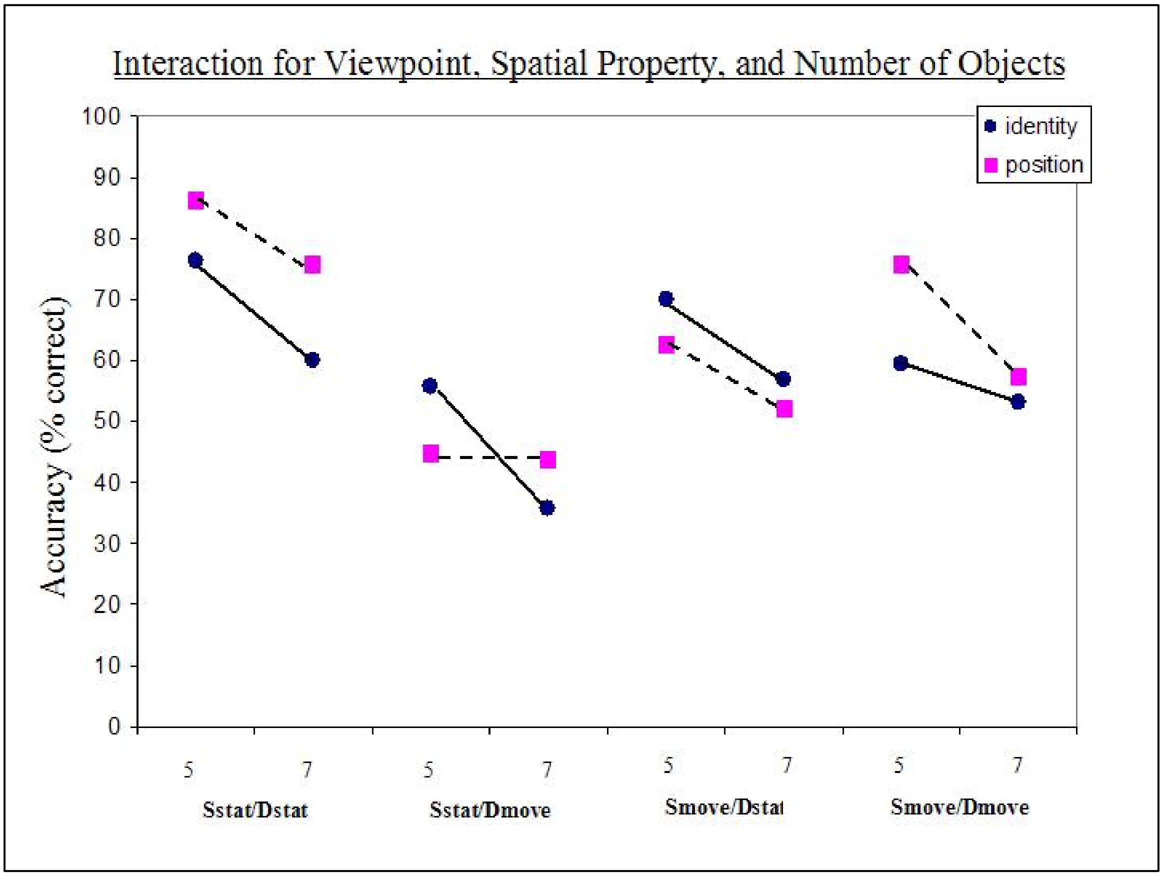


Figure 5


Interaction for Viewpoint, Spatial Property, and Number of Objects
Accuracy (% correct)
100
90
80
70
60
50
40
30
20
10
0
identity
position
5
7
5
7
5
7
5
7
Sstat/Dstat
Sstat/Dmove
Smove/Dstat
Smove/Dmove

Chapter 5

General Discussion

Throughout this thesis, a variety of evidence was brought forth supporting the complexity of spatial processing. More specifically, these experiments highlight the necessity of considering spatial processing at various environmental scales, consisting of one that is a large complex environment that can allow for full body navigation, one that is the size of a small room accessible at one glance, to with a tabletop object scene with easily manipulatable features and environmental attributes. In addition, in order to fully understand the spatial representations that are formed and their characteristics throughout the learning and recall processes, both visual and non-visual information were considered.

The main claim of this thesis is that, contrary to previous literature, egocentric and allocentric frames of references are involved simultaneously during the formation of our spatial representation. Further, whereas previous studies have simply focused on how one frame of reference is involved during learning, retention, or recall respectively, this thesis has shown evidence that both reference frames are involved throughout all three phases. Importantly, not only have we shown that is it *possible* to tease apart the weighting of both frames of reference during these three phases, but that it is also *necessary* to do so in order to fully understand the underlying mechanisms and the influence of possible variables during spatial processing. In summary, in the current thesis, we achieved this by manipulating specific visual and non-visual information during all three phases and also by systematically manipulating the size and features of the spatial environment.

Specifically, Chapter 2 immersed the observer within a complex, everyday environment with full visual and non-visual information during all three phases of spatial processing (i.e., learning, retention, and recall). We then selectively manipulated the availability of specific non-visual information during the learning phase only. It was observed that within a large, complex environment in which navigation is required to access it in its entirety, both allocentric and egocentric frames of reference are used. However, an allocentric frame of reference was only observed during recall, if the observer had active control of their own navigation during learning.

In Chapter 3, the observer remained in a single position while immersed in an environment the size of a small room. We selectively manipulated certain features of the visual information and also limited the amount of non-visual information received during the learning phase. Further, we deliberately made non-visual information unreliable during the retention and testing phase in order to single out the influence of features of the visual environment itself. We observed that features in the environment were processed more allocentrically only if they had an easily recalled verbal identity associated with them.

Finally in Chapter 4, we were guided by the objectives and findings addressed in both Chapters 2 and 3. In this study the observer was presented with an array of objects presented on a tabletop that was visually accessed from a single viewpoint during learning. The observer had to detect either identity changes or positional changes made to the array after a viewpoint change. In order to evaluate the influence of non-visual information during updating in the retention phase, observers either walked to a new position or the table was rotated. Results demonstrated multiple levels of interactions between available sensory information and environmental features.

1. Dissociating Allocentric and Egocentric Frame of References

The objective of Chapter 2 was to resolve two different theories that propose different reasons behind how we form Orientation Specific Representations (OSR) and Orientation Free Representations (OFR), through which we can further understand how egocentric and allocentric reference frames underlie spatial processing. The first theory, referred to as the “multiple vantage point theory”, suggests that when we are exposed to one view of an environment, we develop an OSR dependent on that view (Evans & Pezdek, 1980; Thorndyke & Hayes-Roth, 1982). However, if we acquire several different views of that environment, they may merge to form an OFR. The other theory, referred to as the “primary learning theory”, suggests that it is the level in which we engage with the environment that determines whether or not we develop an OSR or an OFR. If we engage the environment at a secondary level (e.g., viewing a map of the environment or viewing it from a distance) then we develop an OSR. However, if we engage the environment at a primary level (i.e., navigate through it) then we develop an OFR (Presson and Somerville, 1985). In order to resolve these two theories, Chapter 2 tested whether subjects developed an OSR after learning a realistic environment comparable to a naturally occurring scenario during which subjects were provided with multiple viewpoints during navigation or just one viewpoint. If an OSR was developed even when subjects were learning from a primary level of engagement, then this would support the multiple vantage point theory. Further, one of the advantages of our study in comparison to previous studies (e.g., Presson and Somerville, 1985) was that we had one condition consisting of a true-to-scale virtual rendition of the real environment allowing us to provide subjects with an environment capable of providing a primary level of engagement while retaining control of the visual and non-visual information subjects received in order to examine the influence of each.

Our results demonstrated that subjects developed an OSR only when non-visual information that allowed for a primary level of engagement with the environment was not available. In fact, subjects developed an OFR even when they were only presented with one vantage point as long as active, non-visual navigational control was provided (i.e., using a computer mouse to control self movement). This supports the “primary learning theory” over the “multiple vantage point theory” in that it was the level of interaction with the environment that evidenced the formation of an OFR and not necessarily having multiple viewpoints of an environment.

Chapter 2’s series of experiments measured the final spatial representation formed in terms of being orientation specific or orientation free. Aside from resolving the conflict between the two theories behind the formation of an OSR or an OFR, the representations in and of themselves reveal the underlying spatial processes to be indicative of either an egocentric or an allocentric frame of reference. Respectively, OSR would indicate that the observer was spatially processing their environment relative to themselves, whereas an OFR would indicate that the observer was spatially processing their environment independent of themselves. Therefore, it is possible that allocentric and egocentric reference frames can be dissociated with an objective, quantitative measurement (i.e., the amount of viewpoint dependence). Viewpoint dependence may go beyond being an indicator of a spatial representation's viewpoint specificity but rather, may provide a paradigm to quantitatively measure the underlying mechanisms and fundamental variables involved in our spatial processes.

Beyond the scope and purpose of Chapter 2, the results observed raise the possibility that egocentric and allocentric frames of reference may be processed simultaneously but can be dissociated. In addition, it may be possible to differentiate or examine the weighting of egocentric and allocentric frames of reference with respect to the phase of learning, retention, and testing. One of the limits of Chapter 2 is that subjects interacted with an environment that required navigation over time and space in order to experience, a very complex design. While this extended our understanding of spatial processing in real world navigation scenarios, it did not provide precise control over basic variables involved in spatial processing. One such naturally occurring scenario is a simple room which can allow the experimenter to have more precise control over the environment such as that utilized in Chapter 3. In addition, the findings of Chapter 2 suggest that non-visual and visual information interact in a complex manner for spatial processing. A more fundamental approach of dissociating the visual and non-visual variables must be taken to elucidate their independent influence on our spatial representation. Instead of simply providing subjects with an entire environment to learn, subjects can be instructed to focus on specific features categorized by potentially different spatial properties.

2. Viewpoint Dependence and Configuration Error

In Chapter 3, a large room environment was utilized in a series of experiments in order to assess and identify what features in the environment presented during learning can influence the frame of reference. In Chapter 2 we found evidence that active non-visual information generated by the observer lead to a higher weighting of an allocentric frame of reference during recall, this was determined by the absence of viewpoint dependence observed. It may be that the degree of viewpoint dependence may provide more information about the weighting of the two frames of reference. Both the experimental procedure and the method of analysis in Chapter 3 were designed to provide a more sensitive measure of the degree to which egocentric and allocentric reference frames are observed. Chapter 3 analyzed observers' recall of different features in the room-sized environment from multiple viewpoints in terms of absolute error and configuration error. Absolute error values reveal the amount of viewpoint dependence, which describes the feature-to-observer relation, whereas configuration error values reveal the degree of global structure of the feature-to-feature relation. We demonstrate that spatial representations of structural features of the environment (e.g., corners) may be centred around the observer's viewpoint, but at a cost of losing configural information about feature-relative positions. Whereas, movable features (e.g., objects) may be less egocentrically centered, while their representation relative to other objects is stronger.

Importantly, contrary to previous literature that concluded that evidence of viewpoint dependence is ipso facto evidence of the existence of an exclusively egocentric frame of reference, the exploitation of configuration error in our analysis provided evidence that even within the behavioural phenomena of viewpoint dependence, an allocentric frame of reference can be concurrently used. Consistent with previous literature, we demonstrated lower absolute error when subjects were tested from a viewpoint aligned with the learned viewpoint in comparison to a misaligned viewpoint (viewpoint dependence). Further, we replicated Wang and Spelke (2000) results of lower configuration error for corners compared to objects when we only analyzed error from the aligned viewpoint. However, when we compared the relative configuration error difference between aligned and misaligned viewpoints of objects and corners, we demonstrate that the spatial representation of objects is actually more like processing from an allocentric FR whereas corners are more like processing from an egocentric FR. We therefore extended Wang and Spelke's results by demonstrating the relative association of categorically different features within the same environment is better understood through multiple measurements from different viewpoints. This offers a new understanding of the mechanisms underlying the formation of this spatial representation by revealing different levels of configuration error for different features of the environment. Further, this is consistent with our postulation that both types of reference frames are simultaneously accessible and helps explain how previous behavioural evidence supporting either frame of reference can be misleading.

While Chapter 2 addressed the importance of non-visual information for the observer in relation their spatial representation of the environment; Chapter 3 focused more on the visual information by dissociating different visual properties. However, in both chapters viewpoint changes were made without considering the spatial processing involved during this change (retention phase) due to the nature of the experimental design. Specifically, both Chapters 2 and 3 attempted to reduce or remove any possible interactions introduced during the retention phase in order to better understand the spatial processes during the learning phase. It is important to recognize that when we interact with our environment we update our position in space when transitioning between different locations. In Chapter 2, spatial updating was not dissociated during spatial learning and in Chapter 3 spatial updating was not allowed by either disorientating participants during the retention phase or by bringing subjects out of the environment to a novel position before responding. In both chapters, spatial updating was made irrelevant in order to assess the influence of visual and non-visual information within the learning phase. To construct a better overview of the entire spatial process, it is necessary to take into account the phase that occurs between the learning phase and the testing phase; essentially the retention phase.

3. Spatial Updating and Spatial Properties

In Chapter 4, visual and non-visual properties that may underlie the processing of allocentric and egocentric reference frames during learning and retention were tested in order to address the issue of spatial updating and its interaction. Chapter 3 suggests that it is some sort of verbal identity or inherent property of being uniquely salient that allows for those features to be encoded in a much more allocentric manner. When identity information was removed by making all objects identical, this allowed the process of scene discrimination to occur only through comparing relative object position information, in which information was encoded more egocentrically. However, Chapter 4 more carefully controlled for the availability of identity information versus position information. Specifically, by presenting subjects with two different types of stimuli that required them to rely more on position or identity information, this allowed us to better assess the extent to which each feature was used to form a spatial representation and how the characteristics of these representations differed. Our results suggest that not only are position and identity information dissociable, but that they interact differently with both the complexity of the layout (i.e. the number of objects presented) and whether non-visual information was available during spatial updating. Similar to our findings in Chapter 3, position information resulted in higher error than identity information when viewpoint changed without any spatial updating, suggesting a more egocentric frame of reference for position information. However, as the environmental complexity increased, accuracy for position information did not change, while identity information resulted in lower accuracy. This suggests that position information was processed more globally whereas identity information was processed more locally.

One of the results of Chapter 4 was that when subjects experienced active spatial updating that was incongruent with the expected visual information during testing, identity information resulted in lower accuracy than position information. In fact, position information was not affected by this incongruency at all. However, when spatial updating was congruent with the expected visual information during testing, both position and identity tasks resulted in better accuracy than when spatial updating was not available at all. In fact, position information resulted in higher accuracy than identity information. This suggests that for an egocentric frame of reference the relation between expected visual and non-visual information is highly flexible, and that spatial updating can only facilitate spatial performance. Whereas for an allocentric frame of reference the relation between expected visual and non-visual information is much more rigid and that incongruencies may actually inhibit spatial performance.

4. Limitations and Future Studies

The current thesis focused on the nature of our spatial representation and broad spatial properties that may influence our spatial processing. More detailed studies of other sources of spatial influence needs to be conducted. For example, although we have developed a novel method for differentiating spatial properties as being allocentrically or egocentrically relevant, we have yet to fully define what is navigationally relevant (Foo et al., 2007). Previous studies have demonstrated that features at locations that are important for spatial recall (e.g., landmarks located at a fork in a road) to be processed differently than those that are not (e.g. landmarks located along the route that are not at decision points). This suggests that in addition to the findings of Chapters 2 and 3 indicating that identity and position information are factors that can influence our spatial processing, other features of the environment may also have a dissociable effect. Importantly, the mechanisms underlying how these variables affect spatial processing has yet to be determined. Analysis of the spatial processing of these navigationally relevant landmarks in terms of their visual and non-visual components and through both absolute and configuration error would help elucidate their respective influence.

In this thesis, we focused on objects and features within a confined environment. Animal studies have shown that boundaries are processed differently than objects (See Moser et al., 2008 for review). Two properties in which research can be more easily done are the size of the environment or even the vertical height of the bounday (i.e., corners or walls tends to be higher than the observer) and the connective enclosure in which such features usually share (e.g., corners are connected by walls which defines ones set of space as being separate from another).

An extension of this is the study of how we spatially process a natural environment such as the outdoors. Boundaries in such case can be defined by their inaccessibleness (e.g., cliffs or lakes) to large landmarks in cities. One of the problems and intriguing aspect of a naturally occurring environmental boundary is that it is difficult to operationally define it. Exploratory studies are needed just to understand how we define it. For example, how are doors or windows processed or whether or not the color of the boundary of an environment needs to be opaque as opposed to being transparent in order for it to be considered a boundary?

Finally, our research focused on relatively short term formation of spatial memories, it is important to also understand how we process and recall long term spatial memories. Longitudinal studies of subjects inexperienced with an environment to experiencing said environment on a regular basis over a length of time are necessary, with measurements of their spatial representation over a regular set of intervals (Frankenstein et al, 2009).

5. Broader Impact of the Findings of the Current Thesis

The research from this thesis provides a further understanding of how different spatial memory systems are organized, developed and used. Broader practical applications of this research range from clinical applications related to understanding the potential source of clinical spatial deficits to technological applications related to the design of robotic-based navigational aids. For instance, advances in space exploration have been achieved through the use of unmanned robots. One of biggest challenges in developing these tools is to program a robot to recognize and differentiate between natural environmental features, distances and directions of travel. Understanding how humans easily perform this can help create better programming for such robots.

A related extension of this is human-assisted robotic navigation. Currently, fully autonomous robotic navigation and exploration of a complex environment is difficult due to technological limitation in artificial intelligence and sensing (Carff et al, 2009). In addition, technology has not yet achieved the ability for teleoperation with enough sensory fidelity for long range exploration (Stoll, Wilde, & Pong, 2009). A possible solution for this is to have a person give or direct a robot with some instructions to help it better explore. One particular problem for human-robot interactions for environmental navigation is how a person can convey information that can be intelligently understood by a computer about an unmapped terrain. Analogously, when a person draws a rough map of a novel terrain for another person, even though the details are not accurate and even possibly inaccurate in certain parts of the drawn map, the person receiving such a map can usually competently utilize it. This is especially useful when accurate measurements of the environment is not easily obtainable such as if a person needs to draw a rough map for an autonomous robot to interpret and use successfully for exploring an uncharted region of Mars to an uncharted cave in the mountains of Afghanistan. The result from our thesis and its line of research helps understand how human learn or interpret secondary information about a novel environment (e.g., Chapter 2 provide data about the fallacy in human interpretation of maps for orienting towards target features in a real environment). Further, through our thesis, we demonstrate how visual and non-visual information interact along with how we mentally engage with different features in our environment. This would provide a functional general human model from which a computational model can be derived or even overcome.

A more readily useful application of our research is towards GPS systems. Throughout this thesis, we demonstrate how subjects are more able to orient themselves relative to their environment from an initially experienced viewpoint (i.e., viewpoint dependence). Through our study of the differential impact of different category of features and their spatial properties on our spatial representations, it is possible to generate better display of directional information to overcome cognitive heuristics that may lead GPS users to either being lost or fail to use the information provided optimally.

Another application of our research is with respect to informing clinically motivated research questions. For example, recent studies have discovered a condition called topographagnosia in which patients have a selective impairment in forming cognitive maps of their environment while having no other cognitive impairments (Bianchini et al., 2010). fMRI studies showed that people who suffer from this condition do not demonstrate activity in their hippocampus when they are trying to learn a novel environment. Hippocampal activity for spatial processing only occurs when they are trying to utilize spatial representations formed after very long training (Bianchini et al., 2010; Iaria et al., 2009). Understanding the cognitive mechanisms underlying egocentric and allocentric reference can help understand topographagnosia. Further, it would be of even better benefit if our future studies utilize imaging techniques during the performance of our spatial tasks (e.g., differentiating out the influence of position and identity). This may provide a neural correlate of these processes and how they might be affect the above clinical population.

6. Conclusion

Our memory of the world around us and our position throughout it is important to our very existence – where we go and where we come from. The frames of reference that we use, associating the world to us (egocentric) and associating the world around us (allocentric) underpins are critical to understanding human spatial cognition. The studies conducted throughout this thesis provide an empirical interpolation of the synthesis of both the dissociation and interaction of visual information (e.g., features in our environment) and non-visual information (e.g., active navigation). Not only does this provide an understanding of the general principle behind how humans interact with their environment, but it also highlights the complexity of our spatial reality.

Reference

Andersen R. A. and Buneo C. A. (2002). Intentional maps in posterior parietal cortex. Annual Reviews of Neuroscience. Vol. 25. 189–220

Andersen R. A., Essick G. K., and Siegel R. M. (1987). Neurons of area-7 activated by both visual-stimulated and occulomotor behavior. Experimental Brain Research. Vol. 67. 316–322

Annett, M.K. and Bischof, W.F. (2010). Investigating the application of virtual reality systems to psychology and cognitive neuroscience research. Presence: Teleoperators and Virtual Environments. Vol.19(2). 131-141

Bianchini, F., Incoccia, C., Palermo, L., Piccardi, L., Zompanti, L., Sabatini, U., Peran, P., and Guariglia, C. (2010). Developmental topographical disorientation in a healthy subject. Neuropsychologia. Vol. 48. 1563-1573

Burgess N., Spiers H. J., and Paleologou E. (2004). Orientational manoeuvres in the dark: dissociating allocentric and egocentric influences on spatial memory. Cognition. Vol. 94(2). 149-166

Burwell R. D. and Amaral D. G. (1998). Cortical afferents of the perirhinal, postrhinal, and entorhinal cortices of the rat. Journal of Computational Neuroscience. Vol. 398. 179–205

Byrne P., Becker S., and Burgess N. (2007). Remembering the past and imagining the future: a neural model of spatial memory and imagery. Psychological Review. Vol. 114. 340–375.

Carff, J., Johnson, M., El-Sheikh, E. M., and Pratt, J. E. (2009). Human-robot team navigation in visually complex environments. Proceedings of the 2009IEEE International Conference on Intelligent Robots and Systems. (*IROS '09)*, St. Louis, MO.

Cavada C. and Goldman-Rakic P. S. (1989). Posterior parietal cortex in rhesus monkey: II. Evidence for segregated corticocortical networks linking sensory and limbic areas with the frontal lobe. Journal of Computational Neuroscience. Vol. 287. 422–445

Diwadkar V. A. and McNamara T. P. (1997). Viewpoint dependence in scene recognition. Psychological Science. Vol. 8. 302–307

Easton R. D. and Sholl M. J. (1995). Object-array structure, frames of reference, and retrieval of spatial knowledge. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 21. 483-500

Epstein, R., Graham, K.S., and Downing, P.E. (2003). Viewpoint-specific scene representations in human parahippocampal cortex. Neuron. Vol. 35(5). 865-876

Evans, G.W. and Pezdek, K. (1980). Cognitive mapping: Knowledge of real-world distance and location information. Journal of Experimental Psychology: Learning, Memory, & Cognition. Vol. 6. 13-24

Foo, P., Duchon, A., Warren, W. H., and Tarr, M. J. (2007). Humans do not switch between path knowledge and landmarks when learning a new environment. Psychological Research. Vol. 71. 240-251

Frankenstein, J., Meilinger, T., Mohler, B. J., and Bülthoff, H. H. (2009). Spatial memory for highly familiar environments. Proceedings of the 31st Annual Conference of the Cognitive Science Society. (Eds.) Taatgen, N. and Van Rijn, H., Curran, Red Hook, NY, USA. 2650-2655

Fyhn M., Molden S., Witter M. P., Moser E. I., and Moser M. B. (2004). Spatial representation in the entorhinal cortex. Science. Vol. 305. 1258–64

Goodale, M.A & Milner, A.D. (1992). Separate visual pathways for perception and action. Trends in Neurosciences. Vol. 15(1). 20–5

Hafting T., Fyhn M., Molden S., Moser M. B., and Moser E. I. (2005). Microstructure of a spatial map in the entorhinal cortex. Nature. Vol. 436. 801–806

Hodgson E. and Waller D. (2006). Lack of set size effects in spatial updating: Evidence for offline updating. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 32(4). 854-866

Husain M. and Nachev P. (2007) Space and the parietal cortex. Trends in Cognitive Science. Vol. 11 30–36

Huttenlocher, J. and Presson, C.C. (1973). Mental rotation and the perspective problem. Cognitive Psychology. Vol. 4. 277-299

Huttenlocher, J. and Presson, C.C. (1979). The coding and transformation of spatial information. Cognitive Psychology. Vol. 11. 375-394

Iaria, G., Bogod, N., Fox, C. J., and Barton, J. J. S. (2009). Developmental topographical disorientation: Case one. Neuropsychologia. Vol. 47. 30-40

Jeffery, K. J. (2007). Integration of the sensory inputs to place cells: What, where, why, and how? Hippocampus. Vol. 17. 775-785

Jeffery, K. J. and Burgess, N. (2006). A metric for the cognitive map: Found at last? Trends in Cognitive Science. Vol. 10(1). 1-3

Kerr K. M., Agster K. L., Furtak S. C., Burwell R. D. (2007). Functional neuroanatomy of the parahippocampal region: The lateral and medial entorhinal areas. Hippocampus. Vol. 17. 697–708.

Lehmann, A., Vidal, M., and Bulthoff, H.H. (2008). A high-end virtual reality setup for the study of mental rotations. Presence: Teleoperators and Virtual Environments, Vol. 17(4). 365-375

May, M., Peruch, P., and Savoyant, A. (1995). Navigating in a virtual environment with map-acquired knowledge: Encoding and alignment effects. Ecological Psychology. **7**, 21-36

McNaughton, B.L., Battaglia, F. P., Jensen, O., Moser, E.I., & Moser, M-B. (2006). Path integration and the neural basis of the cognitive map. Neuroscience: Nature Reviews. Vol. 7. 663-678

Milner A. D. and Goodale M. A. (1996). The Visual Brain in Action (Oxford University Press, Oxford).

McNamara, T. (2003). How are locations of objects in the environment represented in memory. Spatial Cognition III. Vol. 2685. 174-191

Money J., Alexander D., and Walker Jr. H.T., (1965). A Standardized Road Map Test of Direction Sense. Baltimore: Johns Hopkins Press, 1965.

Moser, E. I., Kropff, E., and Moser, M-B. (2008). Place cells, grid cells, and the brain's spatial representation system. Annual Review of Neuroscience. Vol. 31. 69-89

Mou W. and McNamara T. P. (2002). Intrinsic frames of reference in spatial memory. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 28(1). 162-170

O'Keefe, J. (1976). Place units in the hippocampus of the freely moving rat. Experimental Neurology. Vol. 51. 78-109

O'Keefe, J. & Dostrovsky, J. (1971). The hippocampus as a spatial map: Preliminary evidence from unit activity in the freely moving rat. Brain Research. Vol. 34. 171-175

O'Keefe, J. & Nadel, L. (1978). The Hippocampus as a Cognitive Map. Clarendon, Oxford

Presson, C.C., DeLange, N., and Hazlerigg, M.D. (1989). Orientation specificity in memory: What makes a path different from a map of a path. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 15(5). 887-897

Presson, C.C. and Hazlerigg, M.D. (1984). Building spatial representation through primary and secondary learning. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 10(4). 716-722

Presson, C. C., & Somerville, S. C. (1985). Beyond egocentrism: A new look at the beginnings of spatial representation. In H.M. Wellman (Ed.), Children's Searching: The Development of Search Skill and Spatial Representation (pp. 1-26). Hillsdale, NJ: Erlbaum

Reiser, J.J. (1989). Access to knowledge of spatial structure at novel points of observation. Hournal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 15. 1157-1165

Rieser. J.J., Garing, A.E., and Young, M.F. (1994). Imagery, action, and young children`s spatial orientation: It`s not being there that counts, it`s what one has in mind. Child Development. Vol. 65. 1262-1278

Rieser, J.J. Guth, D.A., and Hill, E.W. (1986). Sensitivity to perspective structure while walking without vision. Perception. Vol. 15(2). 173-188

Roskos-Ewoldsen B., McNamara T. P ., Shelton A. L., and Carr W. (1998). Mental representations of large and small spatial layouts are orientation dependent. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 24. 215-226

Samsonovich, A. & McNaughton, B. L. (1997). Path integration and cognitive mapping in a continuous attractor neural network model. Journal of Neuroscience. Vol. 17. 5900–5920

Sharp, P. E. (1999). Complimentary roles for hippocampal versus subicular/entorhinal place cells in coding place, context, and events. Hippocampus. Vol. 9, 432–443

Shelton A. L. and McNamara T. P. (1997). Multiple views of spatial memory. Psychonomic Bulletin and Review. Vol. 4(1). 102-106

Shepard R. and Metzler J. (1971). Mental rotation of three dimensional objects. Science. Vol. 171(972). 701-3

Sholl, M. J. (1987). Cognitive maps as orienting schemata. Journal of Experimental Psychology: Learning, Memory, & Cognition. Vol.13. 615-628.

Sholl M. J., and Nolin T. L. (1997). . Orientation specificity in representations of place. Journal of Experimental Psychology: Learning, Memory, and Cognition Vol.23. 1494-1507

Simons D. J., and Wang R. F. (1998). Perceiving real-world viewpoint changes. Psychological Science. Vol 9. 315–320

Snyder L. H., Grieve K. L., Brotchie P., and Andersen R. A. (1998). Separate body and world referenced representations of visual space in parietal cortex. Nature. Vol. 394. 887–891

Stoll, E., Wilde, M., and Pong, C. (2009). Using virtual reality for human-assisted in-space robotic assembly. Proceedings of the World Congress on Engineering and Computer Science. Vol. 2. ISBN:978-988-18210-2-7

Taira M., Mine S., Georgopoulos A. P., Murata A., and Sakata H. (1990). Parietal cortex neurons of the monkey related to the visual guidance of hand movement. Experimental Brain Research. Vol. 83. 29–36

Thorndyke, P. W. and Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. Cognitive Psychology. Vol.14. 560-589

Tolman E. C. (1948). Cognitive maps in rats and men. Psychological Review. Vol. 55. 189–208

Vandenberg, S. G., & Kuse, A. R. (1978). Mental Rotations, A Group Test of Three-Dimensional Spatial Visualization. Perceptual and Motor Skills. Vol. 47. 599-604

Vidal, M., Lehmann, A., and Bülthoff, H.H. (2009). A multisensory approach to spatial updating: the case of mental rotations. Experimental Brain Research. Vol. 197(1). 59-68

Wang, R.F. and Brockmole, J.R. (2003) Human navigation in nested environments. Journal of Experimental Psychology: Learning, Memory, and Cognition. Vol. 29 (3). 398-404

Wang R. F. and Simons D. J. (1999). Active and passive scene recognition across views. Cognition. Vol. 70. 191–210

Wang R. F. and Spelke E. (2000). Updating egocentric representations in human navigation. Cognition. Vol. 77. 215–250

Wang R. F. and Spelke E. S. (2002). Human spatial representation: Insights from animals. Trends in Cognitive Sciences. Vol. 6. 376–382

Whitlock J. R., Sutherland R. J., Witter M. P., Moser M. B., and Moser E. I. (2008). Navigating from hippocampus to parietal cortex. Proceedings of the National Academy of Sciences. Vol. 105(39). 14755-14762

Wise S. P., Boussaoud D., Johnson P. B., and Caminiti R. (1997). Premotor and parietal cortex: Cortico connectivity and combinatorial computations. Annual Review of Neuroscience. Vol. 20. 25–42