NATURE OF THE FACILITATIVE EFFECT OF LOCOMOTION

THE NATURE OF THE FACILITATIVE EFFECT OF LOCOMOTION ON SCENE RECOGNITION

By

MARK WADE, B.Sc.

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AUTHOR: Mark Wade, B.Sc. (McMaster University)

SUPERVISOR: Professor Hongjin Sun

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Abstract

Scene recognition performance is reduced when an observer undergoes a viewpoint shift. However, the cost of a viewpoint shift is less when it is caused by observer locomotion around a scene compared to scene rotation in front of a stationary observer - a phenomenon called the facilitative effect of locomotion. The present dissertation examined the characteristics of the facilitative effect of locomotion, and the mechanism underlying its existence. In each of six experiments, participants learned a spatial arrangement of five identical objects positioned on top of a rotatable table. Participants were then blindfolded and one object was relocated. Simultaneously, participants underwent a viewpoint shift of various magnitudes. The blindfold was then removed and participants identified which object had been moved. Chapter One showed that the facilitative effect of locomotion is robust across a wide range of viewpoint shifts (Experiment 1a), and that visual cues in the surrounding environment cannot account for this effect (Experiment 1b). The results of Chapter Two suggest that active control over the viewpoint shift may partially account for the benefit of locomotion (Experiment 2a), specifically by providing participants with explicit knowledge regarding the magnitude and direction of the viewpoint shift (Experiment 2b). Finally, Chapter Three showed that body-based cues available during locomotion (i.e. proprioceptive, vestibular, etc.) facilitate performance beyond actively controlling the viewpoint shift alone, and that those cues must be reliable and undisrupted to confer a scene recognition advantage (Experiment 3a). On the other hand, simply remaining oriented within one's environment could not fully account for the facilitative effect of locomotion (Experiment 3b). These results provide an integrative account of the characteristics and mechanism associated with the facilitative effect of locomotion. Results are also discussed in the context of current views on egocentric and object-based mental transformations.

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General Introduction

Defining the Facilitative Effect of Locomotion

In order to perform everyday tasks – such as navigation or reaching for objects - it is imperative that we monitor the spatial relationships between ourselves and objects in the environment. This spatial information must often be retained in memory and subsequently used to guide actions. During such periods of retention, viewpoint shifts invariably lead to changes in the spatial relationships between oneself and objects in the environment. Two modes through which a viewpoint shift can occur are observer locomotion to a new viewing perspective, or by an angular rotation of the scene while the observer remains stationary. For example, consider a scene that consists of multiple passengers sitting in a bus. When an observer walks past the bus, or when the bus moves in front of a stationary observer, the spatial relationships between the observer and the passengers will change. In the case of locomotion, accurate spatial information must be maintained via a continuous updating process (Rieser, 1989). This ability to keep track of changing spatial relationships while moving through the environment is termed spatial updating (Amorim, Glasauer, Corpinot, & Berthoz, 1997; Farrell & Thomson, 1998; Waller, Montello, Richardson, & Hegarty, 2002). Spatial updating has been demonstrated across a range of spatial tasks, and assists in both navigation and wayfinding. In contrast, when the observer remains stationary and the viewpoint shift is caused by rotation of a configuration of objects about some fixed vertical axis (i.e. scene rotation), individuals cannot necessarily update their spatial representations by means of the same online updating process involved during locomotion (since they are stationary). Instead, in the case of scene rotation, individuals likely rely on a different mental process to recover object spatial relations following a viewpoint shift (e.g. Hegarty & Waller, 2004). Despite these differences between locomotion and scene rotation with regard to the way in which individuals monitor spatial relations, these two modes can be experimentally manipulated such that they result in equivalent changes in self-to-object spatial information (i.e. equivalent viewpoint shifts). This allows researchers to determine how observer locomotion and scene rotation differentially affect spatial processing.

A substantial area of research has aimed at determining differences in spatial performance between viewpoint shifts caused by observer locomotion and viewpoint shifts caused by scene rotation. Early studies by Huttenlocher and Presson (1973; 1979) have shown that participants' directional judgments are superior when they imagine locomoting to a new viewing position compared to imagining scene rotations. Further evidence for a distinction between locomotion and scene rotation is derived from literature that compares how changing an individual's orientation differs from changing their position. For example, Easton and Sholl (1995) have shown that individuals have difficulty when required to point to surrounding objects after imagining facing a different direction, yet pointing becomes easier when they imagine locomoting to that point of observation while facing the same direction (see also Presson & Montello, 1994).

In general, these results suggest that imagining orientation changes (such as scene rotation) is more difficult than imagining translation changes (such as locomotion).

As an extension, past research has also aimed to test whether viewpoint shifts caused by physical movement facilitate spatial recall compared to imagined shifts of the same magnitude. In a pioneering study by Rieser (1989), participants learned a spatial layout of objects in a room. Following this learning phase, blindfolded participants were required to either physically rotate their body a given magnitude, or they stood still and were asked to imagine rotating. Participants were then instructed to point to one of the objects. The results showed that participants who physically rotated their body had lower pointing error and responded quicker than those who imagined rotating (see also Presson & Montello, 1994). These results highlight the importance of physical movement on updating spatial representations when undergoing a viewpoint shift.

The studies mentioned above have typically measured participants' directional judgments of objects relative to themselves when they are located within the scene. However, in order to gauge the contribution of physical movement (i.e. locomotion) when experiencing a viewpoint shift, it is useful to employ a design in which viewpoint shifts can be made *identical* regardless of whether they are caused by locomotion or scene rotation. This can be achieved with the use of scene recognition tasks in which the entire scene can be physically manipulated. In these tasks, participants are required to detect changes to smallscale spatial scenes - usually table-top arrays of objects - after undergoing a viewpoint shift that is caused by locomotion around the scene or rotation of the entire display in front of a stationary observer (e.g. Simons & Wang, 1998; Wang & Simons, 1999).

In an attempt to determine how physical movement affects spatial performance relative to scene rotation, Wang and Simons (1999) presented participants with a scene that was comprised of five common objects on a circular, rotatable table. During the *learning phase*, participants briefly viewed the spatial arrangement of objects. The scene was then blocked from participants' view. In the *retention phase*, the experimenter moved one of the objects to a new position on the table. Concurrent with this change, participants experienced a viewpoint shift. In the *Subject Move* condition, participants walked to a new viewpoint that was 40° from their original learning position, and the table did not rotate. Alternatively, in the *Table Rotate* condition, participants remained stationary and the experimenter rotated the table by 40°. In the *test phase,* participants viewed the scene and indicated which object was moved during retention. The results showed that scene recognition accuracy was better in the *Subject Move* condition than in the *Table Rotate* condition, even though the viewpoint shift magnitude (and therefore the final retinal image) was identical in both cases. This difference in scene recognition performance following viewpoint shifts caused by observer locomotion and scene rotation is referred to as the facilitative effect of locomotion. This dissertation is concerned with examining whether or not the facilitative effect of locomotion is robust across a wide range of viewpoint shifts, as well as investigating the mechanism underlying this effect.

Rationale for Current Experimental Design

Before describing the individual experiments that investigate the nature of the facilitative effect of locomotion, it is imperative to describe our general experimental paradigm – which is common to *all* experiments – and how it differs from past studies. Despite previous high-quality experimental designs, unintended factors (e.g. residual cues regarding the degree of scene rotation, etc.) may have muddled accurate interpretation of the results. Therefore, we will first re-examine many of the studies that have used Wang & Simons' (1999) scene recognition paradigm and, with the benefit of hindsight, perform a series of experiments in which these factors are fully accounted for. In particular, we address drawbacks in previous experiments with regard to the objects used to construct the spatial scenes, as well as the instructions provided to participants regarding the viewpoint shifts. We intend to demonstrate how these superfluous factors were controlled for in our design, thereby allowing us to employ a more sensitive test of participants' scene recognition ability when experiencing viewpoint shifts caused by locomotion and scene rotation.

In order to address the factors that we believe inadvertently affected participants' scene recognition ability in past studies, it is important to mention that the primary *spatial* property of a scene is the relative position of objects (i.e. the spatial layout). To study one's memory of a spatial layout based on positional information alone, researchers should test participants using a layout wherein the positions of the individual objects are randomized. If the spatial arrangement of objects is not random, and instead possesses some intrinsic axis, spatial performance is enhanced along this axis even if it is misaligned with the intended learning direction (Mou & McNamara, 2002). In addition to a random arrangement of objects, in order to test for the effect of positional information alone, objects in the scene should have the same identity, and the shape of the objects should contain no information about their orientation – that is, the objects should look identical from any viewpoint given a particular horizontal plane. Examples of this type of object include cylinders or cones. Spatial layouts containing only positional information (i.e. identical objects positioned randomly) offer a powerful way to test for the effect of viewpoint shifts on spatial scene recognition. Nevertheless, typical real-world scenes contain other sources of information that can also aid scene recognition (e.g. different identities of objects). Indeed, most previous studies that have used the paradigm of Wang and Simons (1999) contain at least one of these extra sources of information. We argue that these experiments do not efficiently isolate the contribution of positional information alone on scene recognition.

The first factor that provides participants with additional information to aid scene recognition is the identity of the objects. Object relations can be based solely on relative spatial position, or they could be based on spatial position in conjunction with unique identities. It is conceivable that when objects in a scene possess different identities, both their position and identity will influence spatial processing (Wang, Wang, Wade, & Sun, in preparation). In a series of experiments by Wang et al. (in prep), participants were presented with an array of objects positioned on a circular, rotatable table that either remained stationary or was rotated. Identical cylindrical objects or different cylindrical objects were used. The number of objects presented was also varied from four to seven. For each trial, following learning, one of the objects was moved to a new position and participants were required to identify which object had moved. Results showed that for identical objects, participants' reaction time and error rate were similar regardless of the number of objects presented, and performance decreased following scene rotation. However, for different objects, participants' performance decreased as the number of objects increased, but was less sensitive to scene rotation. This trend was even more pronounced if the objects' identities were made to be more salient (to the extent that each one could be easily named due to color, material, surface pattern, and shape difference), but the trend disappeared if a verbal suppression task was performed simultaneously. This suggests that if the scene is comprised of identical objects, participants tend to take advantage of the global properties of the visual scene, and the spatial representation is viewpoint-dependent. However, if the scene is composed of objects with different identities, participants tend to focus on local spatial properties and the spatial representation is relatively viewpoint-invariant. It is therefore conceivable that when unique objects are used, as in most related studies (e.g. Burgess, Spires, & Palelogou, 2004; Mou, Zhang, & McNamara, 2009; Simons & Wang, 1998; Wang & Simons, 1998), participants may use verbal labels of the objects for recognition (see Finlay, Motes, & Kozhevnikov, 2007), as opposed to the scene's global spatial relations. Importantly, using a verbal encoding strategy to determine the ordinal information among objects does not necessitate the formation of spatial representations (i.e. encoding may be strictly verbal). Thus, scenes that possess objects with unique identities may be processed fundamentally different from those wherein the objects are alike.

Scenes that are comprised of objects with unique identities present another issue aside from the interaction between spatial position and identity. Specifically, using asymmetrically shaped objects (e.g. scissors) (e.g. Burgess et al., 2004; Mou, Zhang, & McNamara, 2009; Simons & Wang, 1998; Wang & Simons, 1998) introduces additional information into the scene since these objects possess salient and inherent orientation cues which can serve as indicators of the viewpoint shift of the entire scene. For example, when the scene is rotated, the degree to which the scissors have changed orientation gives a cue as to the magnitude of change of the entire scene. When a visual indicator of this sort informs participants about the magnitude of the viewpoint shift, performance following scene rotation can actually increase to match that of locomotion (Mou, Zhang, & McNamara, 2009). Therefore, scene recognition accuracy may have been inflated in past studies wherein the spatial array consisted of unique objects.

The second set of factors that potentially affected scene recognition in past studies is the instructions that participants received regarding the magnitude and direction of the viewpoint shift. Specifically, in most past studies that utilized the Wang and Simons (1999) paradigm (e.g. Burgess et al., 2004, Mou, Zhang, & McNamara, 2009; Simons & Wang, 1998) participants were instructed about whether a viewpoint shift would occur. Some studies (e.g. Greenauer & Waller, 2008; Mou & McNamara, 2002) have shown that participants can learn a spatial scene from a nonegocentric viewpoint (i.e. a viewpoint misaligned with the learning direction) when explicitly instructed to do so by the experimenters. These instructions have been shown to improve recognition performance at the instructed angle. By extension, there is another instructional effect that has been overlooked in the literature which regards the impact of implicit instructions on scene recognition. Participants in past studies usually experienced only one repeated viewpoint shift magnitude throughout the entire experiment (e.g. Burgess et al., 2004; Mou, Zhang, & McNamara, 2009; Simons & Wang, 1998; Wang & Simons, 1999). Prior to learning the spatial scene, participants were also explicitly instructed as to whether or not there would be a viewpoint shift (i.e. whether they would move or the table would rotate). As a result, participants in these experiments may have been able to predict the viewpoint shift prior to learning, and thereby encode the scene from that angle. We contend that repeated exposure to the same novel viewing angle serves to implicitly instruct participants of the testing angle, thereby allowing them to adopt this nonegocentric viewpoint during learning. This would also manifest as inflated scene recognition performance when experiencing a viewpoint shift.

In summary, using unique objects and providing participants with instructions regarding the magnitude of the viewpoint shift may have unintentionally inflated scene recognition performance in past studies. Nevertheless, most past studies that have used the Wang and Simons (1999) paradigm have successfully demonstrated the facilitative effect of locomotion (e.g. Burgess et al., 2004; Mou, Zhang, & McNamara, 2009; Simons & Wang, 1998; Wang & Simons, 1999). Therefore, it does not seem likely that these visual and instructional cues can fully account for the facilitative effect of locomotion; that is, there is no reason to believe that these cues selectively increased performance for locomotion but not scene rotation. Then again, locomotion may involve an updating process that is automatic and internally driven (see Farrell & Robertson, 1998), in which case it is possible that this updating process interacts with these external sources of information (i.e. visual cues and instructions), consequently leading to an exaggerated facilitative effect of locomotion. Since all past studies have provided participants with knowledge of the viewpoint shift in one form or another, the pure benefit of locomotion-based spatial updating has yet to be demonstrated.

General Details of Current Experimental Design

Although the general consensus in the literature is that locomotion facilitates scene recognition at novel angles, past studies prevent us from knowing the *true effect* of novel-view scene recognition following locomotion and scene rotation due to numerous visual and instructional factors that enable participants to use strategies that confound processing of object spatial relations alone. In the current design, care was taken to ensure that object-to-object spatial relations were the only source of information available to participants. First, the objects used to construct the spatial scene were devoid of unique identities, and possessed no inherent orientation cues. The current study used randomly arranged spatial arrays of identical, symmetrical Styrofoam cups. Furthermore, we did not introduce any additional cues that could possibly indicate the magnitude of the viewpoint shift. Also, to rule out the possibility that participants used visual cues in the environment to assist in scene recognition (e.g. Burgess et al., 2004), we enclosed the testing space in a large symmetrical 10-sided room and turned down the lights during experimentation.

In addition to controlling for the abovementioned visual factors, we avoided providing participants with any implicit or explicit instructions regarding the magnitude or direction of the viewpoint shift. To minimize the likelihood that participants adopt a nonegocentric learning direction via implicit instructions, we used multiple novel testing angles and shifted the viewpoint in both the clockwise and counter-clockwise direction. By presenting multiple levels of viewpoint shift in a random order, it would be far too difficult for participants to predict both the magnitude and direction of the viewpoint shift on any given trial. We introduced six different angular viewpoint shifts: 50°, 80°, 110°, 130°, 160°, and 180°. Not all of these magnitudes were used in every experiment, but a subset of at least four of them was selected for each experiment. All experiments included the small viewpoint shift of 50°, which was chosen since it is similar to that used in previous research. The remainder of our viewpoint shifts (80°, 110°, 130°, 160°, and 180°) were chosen so that we could examine the nature of the facilitative effect of locomotion across a wide range of viewpoint shifts.

Having outlined our general experimental design - and why we believe it is more highly controlled than the designs of past studies - we now present six experiments that investigate the nature of the facilitative effect of locomotion. In Chapter One, we submit two experiments: Experiment 1a is concerned with determining whether or not the facilitative effect of locomotion is robust across a wide range of viewpoint shifts. Experiment 1b tests the hypothesis that visual cues in the surrounding environment improve scene recognition performance, and that those cues can exacerbate the facilitative effect of locomotion. In Chapter Two, we delve into the mechanism underlying the facilitative effect of locomotion. Specifically, Experiment 2a explores whether or not the facilitative effect of locomotion is attributable to actively controlling the viewpoint shift. Experiment 2b then investigates what specific component of active control may be responsible for conferring a scene recognition advantage. Finally, in Chapter Three we inquire as to whether or not body-based cues (i.e. proprioceptive, vestibular, etc.) available during locomotion also contribute to the facilitative effect of locomotion. In particular, Experiment 3a aims to determine whether these body-based cues improve scene recognition to a degree that exceeds actively controlling the viewpoint shift alone. Finally, Experiment 3b investigates whether remaining oriented within the environment can account for the facilitative effect of locomotion.

Chapter One

This chapter is concerned with revealing common performance patterns in scene recognition using our adjusted paradigm. We re-evaluate key behavioural findings reported in the literature, while also building upon previous studies by including a wide range of viewpoint shifts, thereby making our results more inclusive and generalizable.

Experiment 1a

The purpose of Experiment 1a is to determine whether the facilitative effect of locomotion (i.e. [locomotion performance] > [scene rotation performance]) reported in the literature is robust across a wide range of viewpoint shifts. Most past studies that have demonstrated the facilitative effect of locomotion using the Wang and Simons (1999) paradigm have only investigated the effect at small viewpoint shift magnitudes (e.g. 49° in Burgess et al., 2004; 49° in Mou, Zhang, & McNamara, 2009; 47° in Simons & Wang, 1998; 50° in Vidal, Lehmann, & Bulthoff, 2009; 40° in Wang & Simons, 1999). It therefore remains unclear if this facilitative effect exists at relatively larger viewpoint shifts. In Experiment 1a, we are interested in whether or not this facilitative effect can be extended to a wider range of viewpoint shifts, including both small and large shifts. This is of interest because recent research by Mou, Zhang, and McNamara (2009) has suggested that the facilitative effect is attenuated at larger viewpoint shifts (98°). However, in their study, the comparison of different viewpoint shift magnitudes was performed across experiments and across participants. The within-subjects nature of our design dispels any systematic error that results from comparing different viewpoint shifts across experiments, thus allowing us to test this effect more efficiently. Unlike Mou, Zhang, and McNamara (2009), we predict that performance will be superior following observer locomotion compared to scene rotation across a range of viewpoint shifts.

As a result of our experimental manipulations (implementing multiple viewpoint shift magnitudes), we are also able to reveal a few secondary aspects of novel-view scene recognition. First, we are able to examine whether or not scene recognition is viewpoint-dependent or viewpoint-invariant – that is, if there is a cost to undergoing a viewpoint shift. In line with most of the scene recognition literature, we predict that scene recognition performance following both locomotion and scene rotation will exhibit viewpoint-dependence. Support for this prediction will manifest as superior performance when no viewpoint shift is experienced compared to any magnitude of locomotion (i.e. [no viewpoint shift performance] > [locomotion performance]) or scene rotation (i.e. [no viewpoint shift performance] > [scene rotation performance]). Furthermore, our design allows us to determine how recognition performance changes across magnitudes of scene rotation. Past research suggests that object recognition (e.g. Srinivas, 1995; Tarr & Pinker, 1989) and scene recognition (Diwadkar & McNamara, 1997; Christou & Bulthoff, 1999) exhibit angular dependency. For example, Diwadkar and McNamara (1997) and Finlay, Motes, and Kozhevnikov (2007) have demonstrated a linear decline in recognition performance as the magnitude of scene rotation increases. We also predict that accuracy should decline linearly as the magnitude of scene rotation increases. Finally, our design allows us to determine how recognition performance changes across magnitudes of locomotion. Past studies have shown that, as the magnitude of observer *rotation* increases, performance decreases in judgment-of-relative-direction (JRD) tasks (e.g. Farrell & Robertson, 1998). Also, Mou, Zhang, and McNamara (2009) have recently shown that, as the magnitude of observer locomotion increases from 49° to 98°, scene recognition performance decreases. To our knowledge, only one group of researchers have systematically manipulated the magnitude of the viewpoint shift due to locomotion, and they demonstrated a linear decline in scene recognition performance as the magnitude of locomotion increases (Finlay, Motes, & Kozhevnikov, 2007; Motes, Finlay, & Kozhevnikov, 2006). However, for both scene rotation and observer locomotion, participants in the above studies potentially had knowledge of the magnitude of the viewpoint shift by virtue of the objects used and the instructions provided. By implementing our new design, we provide a more sensitive test for scene recognition following locomotion. We predict that scene recognition performance will decreases as the magnitude of observer locomotion increases.

Method

Participants

Seventeen undergraduate students (8 males and 9 females, 17-42 years of age [$M = 20$, $SD = 5.62$]) from McMaster University participated in return for course credit. All participants reported normal or corrected-to-normal vision, and none had previous experience with spatial learning paradigms like the one presented here.

Materials, Apparatus, and Design

The testing area was enclosed in a large 10-sided room (approximately 5.18 m across, and 3 m high). This room was made of opaque black cloth that covered all sides of the room and the ceiling. Furthermore, the lights were turned down such that the external environment was completely blocked out. These manipulations were so effective that participants could not distinguish any corners or edges of the room. The experimental display consisted of five identical Styrofoam cups (approx. 250 mL volume) placed in random configurations on a white, circular table (1.2 m diameter; 0.75 m off the ground) that was freely rotatable in either direction. Around the table (on the floor) were black tape markings at equal intervals of 10°.

MATLAB 7.0 was used to generate 58 (four practice and 54 test) irregular spatial configurations wherein only two objects could be aligned with each other during each trial. The computer program randomly selected the cup to be moved, and dictated the direction of movement. Movement of the objects was always of the same magnitude (approximately 15 cm). In order to ensure accurate and timely control by the experimenters, a projector was attached to the ceiling directly above the table. This projector outlined the configurations and the alterations made to the layouts (Figure 1). A hole was cut in the centre of the ceiling to permit use of the projector. In order to control the shape of the outline made by the projector on the table, a funnel was placed around the lens of the projector so that the image projected onto the table was circular. The beam of light from the projector enabled participants to see the spatial arrangement of objects on the table, but nothing else.

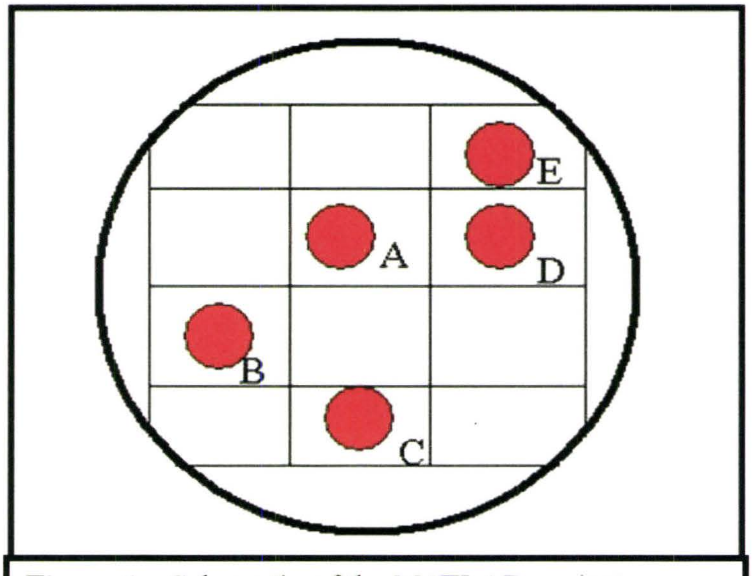

Figure 1 – Schematic of the MATLAB projector layout as it appears from a topographical view above the table. The red circles represent the position of the cups. The grid and circles are only seen by the experimenter for accurate placement of the cups.

Participants wore a blindfold prior to each trial and during phases of the experiment wherein the spatial scene was meant to be occluded. In order to control for auditory localization cues, participants listened to white noise throughout the experiment. The experimenter listened to the computer instructions through cordless headphones. The experimenter communicated with the participant by tapping them on the shoulder when they were supposed to lift or replace the blindfold. This manipulation removed any sort of auditory cues that may have informed the participant of their position or orientation inside the room.

Procedure

Learning Phase. Participants stood at the learning position (0°) with the blindfold on. Upon hearing the commands from the computer, the experimenter tapped the participant on the shoulder, at which point they removed the blindfold and viewed the layout of cups for five seconds (Figure 2). After five seconds of learning, the experimenter tapped the participant on the shoulder again, thus signalling them to replace the blindfold.

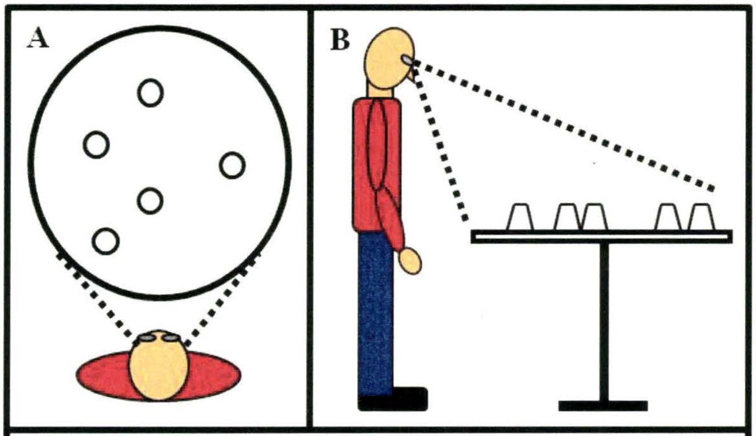

Figure 2 – Schematic of the learning phase. Participants view the scene for 5 seconds. (A) Top-down view; (B) Side View

Retention Phase. The retention phase involved the change to the spatial layout (i.e. cup relocation), and the viewpoint shift of the participant. First, the experimenter moved one of the cups to a previously unoccupied position on the table (Figure 3).

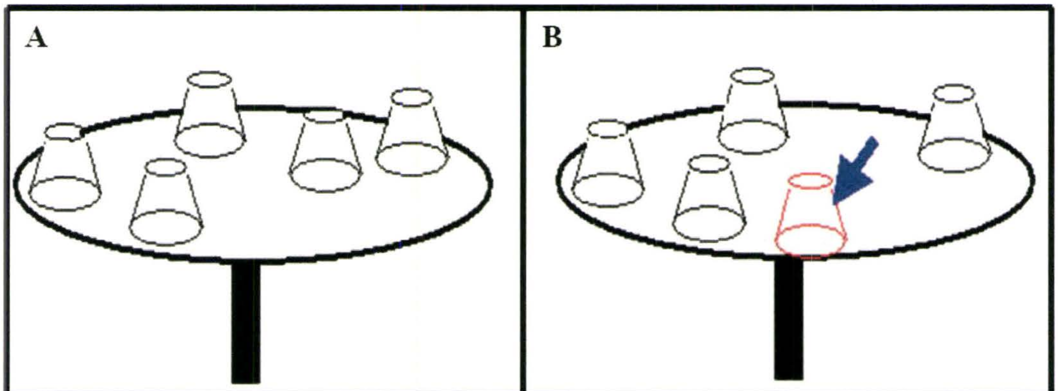

Figure 3 - (A) Five identical cups are positioned in an asymmetrical pattern and are viewed by the participant during learning. (B) One of the cups is moved to a new position (indicated by the arrow) by the experimenter during the retention phase.

Next, the viewpoint shift was achieved in one of three ways (see Figure 4 for examples): (1) *No viewpoint shift* (i.e. control condition): the participant remained stationary and the table was not rotated. (2) *Scene rotation*: the participant remained stationary, and the experimenter rotated the table by 50°, 80°, 110°, or 130°. Scene rotation could be in a clockwise or counter-clockwise direction on any given trial. (3) *Observer locomotion*: the participant walked to a novel viewing position around the table (i.e. 50°, 80°, 110°, or 130°), and the table was not rotated. Locomotion could be in a clockwise or counter-clockwise direction on any given trial. In this set of locomotion conditions, the participant sidestepped (guided by the experimenter) so that they always remained oriented with the display.

For a complete list of the experimental conditions, see Table 1.

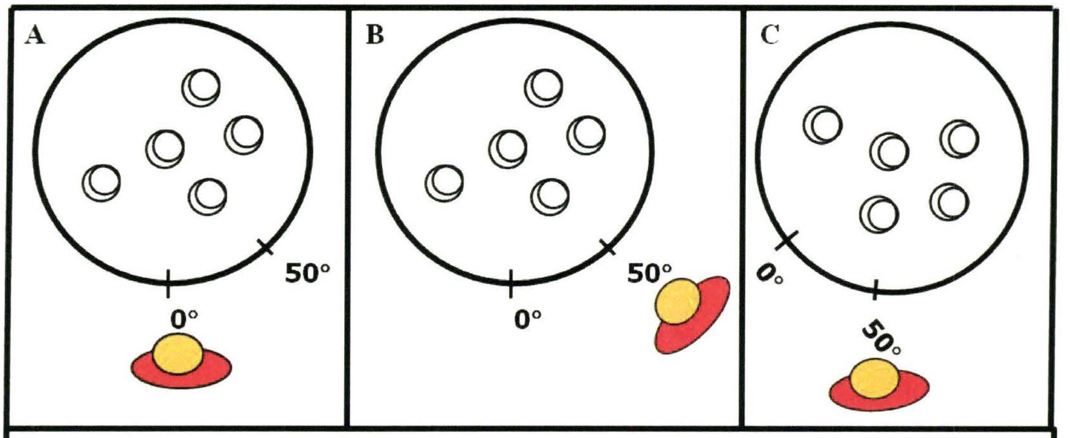

Figure 4 - (A) Control condition (no locomotion or scene rotation). (B) Observer Locomotion to 50°. (Note : locomotion could also be to 80°, 110°, or 130° on any given trial). (C) Scene Rotation of 50°. (Note: the scene could also be rotated by 80°, 110°, or 130° on any given trial).

Table 1: Summary of Conditions for Experiment 1a

Condition	Magnitude of Scene Rotation (°)	Magnitude of Locomotion (°)	Overall Viewpoint Shift (°)
1. Control	0	0	0
2. Scene Rotation of 50°	50	0	50
3. Observer Locomotion to 50°	0	50	50
4. Scene Rotation of 80°	80	0	80
5. Observer Locomotion to 80°	0	80	80
6. Scene Rotation of 110°	110	0	110
7. Observer Locomotion to 110°	0	110	110
8. Scene Rotation of 130°	130	0	130
9. Observer Locomotion to 130°	0	130	130

Prior to the experiment, participants were told that the table could rotate any magnitude on any given trial, but they were never instructed on a trial-by-trial basis as to the magnitude of locomotion or table rotation. All retention periods were 10 seconds in length. This retention time is longer than the seven-second period used by Simons and Wang (1998), but less than the 13-second period used by Burgess et al. (2004).

Test Phase. From the viewing position, the participant identified the cup that they believed was moved during the retention phase. Since the cups were exactly the same, we demarked them by projecting a different coloured circle next to each one. Circles were used since they provide no orientation cues. When making their response as to which cup moved, the participant indicated the color of the circle that corresponded to the cup that they believed had moved. Once their response was given, participants returned to the learning position (0°) to begin the next trial.

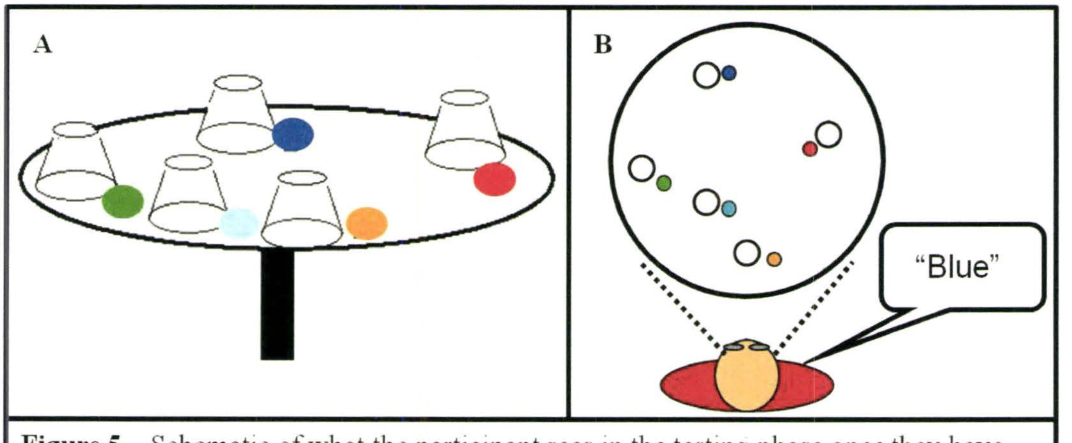

Figure 5 – Schematic of what the participant sees in the testing phase once they have removed the blindfold. Each of the cups is marked with a different coloured circle to differentiate them. (A) Straight-on view; (B) Topographic view. The participant indicated the cup that moved by indicating the colour next to the cup.

Design. Each participant experienced six control trials (no rotation or locomotion). They also experienced two viewpoint shift modes (scene rotation or locomotion) across four viewpoint shift magnitudes (50°, 80°, 110°, and 130°), each of which were experienced in two directions (clockwise and counter-clockwise), and all were repeated three times. In total, there were 54 trials (6 control + [2 modes x 4 magnitudes x 2 directions x 3 repetitions]). Trials were arranged into three blocks, with all conditions presented in a random order within each block.

Each of the 54 spatial configurations had an equal chance of being used for each of the conditions mentioned above. This eliminated any bias that may have arisen from some spatial configurations being inherently easier (or more difficult) than others when viewed from a particular angle.

Results

Scene recognition (i.e. change detection) performance was measured as the proportion of trials on which participants correctly identified the change to the scene. We also measured reaction time for correct responses. An initial analyses including the sex of the participants as a between-subject factor did not reveal any differences. There was also no effect of direction of movement/rotation (i.e. clockwise versus counter-clockwise). Therefore the data was collapsed across these variables for all subsequent analyses.

Preliminary Analysis with Control Condition

An important component of this study was to determine whether participants exhibited viewpoint-dependence following locomotion and scene rotation. A series of planned paired samples t-tests revealed that participants were significantly more accurate in the control condition ($M = 0.835$, $SD = 0.084$) than in any of the viewpoint shift (i.e. locomotion or scene rotation) conditions (all p's < 0.001). Participants' reaction time was also quicker in the control condition ($M = 6.54$, $SD = 1.73$) compared to all viewpoint shift conditions. Significant differences in reaction time were detected between the control condition and all magnitudes of scene rotation, as well as between the control condition and locomotion to 130° (all p's < 0.05). Reaction times following observer locomotion to 50°, 80°, and 110° were statistically comparable to the control condition (all p's > 0.05). After this set of comparisons, we removed the control condition from further analyses and focused on the differences between locomotion and scene rotation across the different magnitudes of viewpoint shift.

Observer Locomotion versus Scene Rotation

A 2 (viewpoint shift mode: observer locomotion versus scene rotation) x 4 (magnitude of viewpoint shift: 50°, 80°, 110°, 130°) repeated measures analysis of variance (ANOVA) was conducted separately for the proportion of correct judgments and reaction time.

Accuracy

For proportion of correct judgments, there was a significant main effect of viewpoint shift mode, with participants performing more accurately following locomotion compared to scene rotation, $F(1, 16) = 20.22$, $MSE = 0.011$, $p < 0.001$. There was also a significant main effect of magnitude of viewpoint shift, with performance gradually declining as the magnitude of viewpoint shift increased, $F(3, 48) = 9.01$, $MSE = 0.011$, $p < 0.001$. The interaction between mode and magnitude of viewpoint shift was not significant, $F(3, 48) = 0.308$, $MSE = 0.008$, $p = 0.819$.

We also performed a linear trend analysis to evaluate the hypothesis that the accuracy scores decrease linearly as the magnitude of viewpoint shift increases for both scene rotation and locomotion. There was a significant linear decline in change detection accuracy as the magnitude of scene rotation increased, $t(16) = -5.81$, $p < 0.001$, one-tailed. There was also a significant linear decline in accuracy as the magnitude of observer locomotion increased, $t(16) = -2.97$, $p = 0.004$, one-tailed. Each of these results is plotted in Figure 6A.

Reaction Time

For reaction time of *correct* judgments, there was a significant main effect of viewpoint shift mode, with participants responding more quickly following locomotion than scene rotation, $F(1, 16) = 22.25$, $MSE = 3.53$, $p < 0.001$. There was also a significant main effect of magnitude of viewpoint shift, $F(3, 48) =$

3.28, $MSE = 3.00$, $p = 0.029$. The interaction between mode and magnitude of viewpoint shift was not significant, $F(3, 48) = 0.170$, $MSE = 2.49$, $p = 0.916$.

We also performed a linear trend analysis to evaluate the hypothesis that reaction time increases as the magnitude of viewpoint shift increases for both scene rotation and locomotion. There was a significant linear increase in reaction time as the magnitude of observer locomotion increased, $t(16) = 2.15$, $p = 0.024$, one-tailed, but not as the magnitude of scene rotation increased, $t(16) = 0.904$, $p = 0.190$, one-tailed. These results are plotted in Figure 6B.

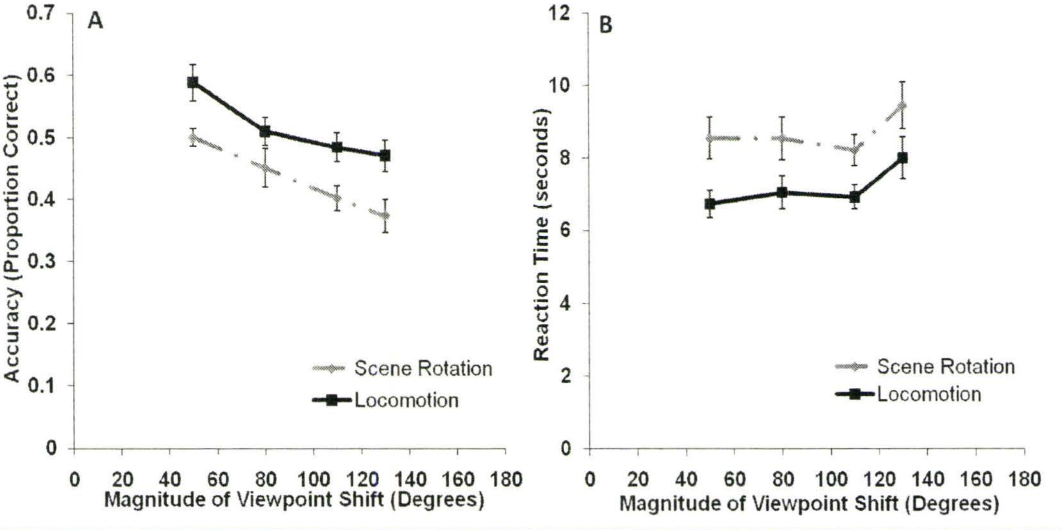

Figure 6: Scene recognition performance as a function of magnitude and mode of viewpoint shift in Experiment 1a. The external environment was removed. Solid line – observer locomotion; hashed line – scene rotation. (A) Scene recognition accuracy; (B) Reaction time on correct trials. Error bars represent between-subjects ± 1 standard error of the means (*SEMs*) computed from data points in each condition submitted to the analysis of variance.

Discussion

Experiment 1a aimed to determine four key aspects of scene recognition using our adapted paradigm which controlled for numerous factors that have been shown to affect scene recognition performance. First, scene recognition was both more accurate and faster in the Control condition (i.e. no viewpoint shift) than in all conditions of observer locomotion and scene rotation. This finding suggests that there is a cost to undergoing a viewpoint shift whether it is caused by locomotion or scene rotation – that is, scene recognition is viewpoint-dependent. In addition, there was a significant linear decline in accuracy as the magnitude of scene rotation increased (see Diwadkar & McNamara, 1997; Finlay, Motes & Kozhevnikov, 2007 for similar results) and as the magnitude of observer locomotion increased (Farrell & Robertson, 1998; Mou Zhang, & McNamara, 2009). This finding indicates that scene recognition ability becomes progressively more difficult as the magnitude of viewpoint shift increases.

Most importantly, the results showed that scene recognition was more accurate and quicker following observer locomotion than it was following scene rotation for all tested viewpoint shifts. This suggests that the facilitative effect of locomotion is robust across small and large viewpoint shifts. The robust benefit of locomotion (particularly at large magnitudes) found here is in contrast to what was found by Mou, Zhang, and McNamara (2009). Even though Mou, Zhang, and McNamara (2009) showed a clear benefit of locomotion when the viewpoint shift was 49° (Locomotion = 72.5%, Scene Rotation = 51.25%), they failed to this benefit when the viewpoint shift reached 98° (Locomotion =53.75%, Scene Rotation = 55.83%). It is important to note that their lack of a facilitative effect of locomotion is not simply due to the decline in locomotion performance across magnitudes, but due to a failure to show a decrease in performance as scene rotation increased. As previously described, the objects used by Mou, Zhang, and McNamara (2009) possessed features that allow for local processing because each object has a unique identity and asymmetrical shape. Given that both object recognition and scene recognition tend to exhibit angular dependency – and since Mou, Zhang, & McNamara (2009) failed to show this effect - participants in their study may have employed a different strategy than the participants in our study.

Importantly, a recent study by Finlay, Motes, and Kozhevnikov (2007) failed to show any facilitative effect of locomotion, regardless of the magnitude of viewpoint shift. This included a small viewpoint shift (36°), for which most previous studies show a benefit of locomotion (e.g. Burgess et al., 2004; Mou, Zhang, & McNamara, 2009; Simons & Wang, 1998; Wang & Simons, 1999). There are a couple of differences between Finlay, Motes, and Kozhevnikov's (2007) study and other studies that might explain these differences. One notable difference is that they used an LCD screen to display the scene, rather than using real objects. Their display was around 20 cm in diameter, which is much smaller than the scene dimensions in most other studies (about 120 cm in diameter). It is possible that a scene presented within a small region of a 2D screen might be processed differently from a real 3D scene where observers can clearly view the

3-dimensional relationships among objects (including cues such as shadow and occlusion).

The general conclusions regarding novel-view scene recognition reported here are similar to those of previous research. However, there are differences in the absolute values of the accuracy scores between our study and past studies that used Wang and Simons' (1999) paradigm. Although comparisons across studies are not ideal owing to multiple sources of variation, there are some interesting consequences if we make these comparisons. First, recognition performance following scene rotation of 50° in our study was worse than in previous studies that used comparable viewpoint shifts (e.g. Burgess et al., 2004; Simons & Wang, 1998; Wang & Simons, 1999). Likewise, recognition performance following observer locomotion of 50° was also considerably lower in our study compared to those same studies. Taken together, these findings support our contention that past studies which used a single repeated viewpoint shift tended to overestimate participants' scene recognition ability. Another explanation for the difference in performance between our study and past studies is that processing scenes comprised of unique objects is simply easier than processing scenes comprised of identical, symmetrical objects. If this is true, it supports our claim that using unique objects inflates scene recognition performance owing to an array of strategies that participants could use for spatial processing.

Furthermore, the cost of undergoing a viewpoint shift caused by scene rotation (i.e. [no viewpoint shift performance] - [scene rotation performance]) is greater in our study (about 33%) compared to previous studies (e.g. 20% in Wang & Simons, 1999; 25% in Burgess et al., 2004). Similarly, the cost of undergoing a viewpoint shift caused by locomotion (i.e. [no viewpoint shift performance] - [locomotion performance]) also appears to be greater in our study (24%) compared to previous studies (e.g. about 5% in Wang & Simons, 1999; about 13% in Burgess et al., 2004). Taken together, this suggests that the cost of a viewpoint shift on scene recognition is greater than previously reported in the literature for viewpoint shifts caused by both scene rotation and locomotion.

Finally, the facilitative effect of locomotion (i.e. [locomotion performance] - [scene rotation performance]) is smaller in our study (about 9%) compared to previous studies (e.g. 15% in Wang & Simons, 1999; about 13% in Burgess et al., 2004; 20% in Mou, Zhang, & McNamara, 2009). This result suggests that, while the facilitative effect of locomotion is clearly present, it might be smaller than previously reported in the literature. Recall that in previous studies both visual indicators (object identity, object shape) and instructional cues provided information about the magnitude of the viewpoint shift. In past studies, the spatial updating process may have interacted with these external factors, thereby leading to an exaggerated facilitative effect of locomotion.

It should be noted that these results do not preclude the possibility that individuals rely on the establishment and retrieval of spatial reference directions as proposed by Mou and his colleagues (Mou & McNamara, 2002; Mou, Liu, & McNamara, 2009; Mou, Xiao, & McNamara, 2008; Mou, Zhao, & McNamara, 2007). Under their model, participants identify a reference direction by which object relations are encoded during learning. Following a viewpoint shift, accurate retrieval of object spatial relations relies on precisely recovering the spatial reference direction. Mou and his colleagues (e.g. Mou, McNamara, Valiquette, & Rump, 2004; Mou et al., 2009; Mou, Zhao, & McNamara, 2007) propose that locomotion facilitates scene recognition because it provides additional information that permits recovery of the spatial reference direction more precisely than scene rotation. In that case, updating of self-to-object-array spatial relations during locomotion involves tracking the spatial reference direction. This, in turn, permits a more accurate comparison of object spatial relations. To extend this model, our results suggest that locomotion consistently provides additional information across a range of viewpoint shifts which enables participants to track the spatial reference direction more precisely than when they remain stationary and the scene rotates in front of them.

Experiment 1a showed a clear facilitative effect of locomotion at a range of viewpoint shifts when visual cues in the environment could not be used for scene recognition. It is now interesting to examine whether salient visual cues in the surrounding environment further assist in scene recognition by providing additional information that allows participants to determine the magnitude of the viewpoint shift. In contrast to Experiment 1a, which minimized visual cues from the external environment by darkening the testing space, in Experiment 1b we tested participants in a regular laboratory setting with the lights on. We can then determine how visual cues in the environment contribute to scene recognition when participants undergo viewpoint shifts caused by locomotion and scene rotation.

Experiment 1b

The purpose of Experiment 1b was to determine how visual cues in the environment affect participants' scene recognition ability using our adjusted version of Wang and Simons' (1999) paradigm. The influence of visual environmental cues on scene recognition is not totally clear. However, there are some findings in the literature that allow us to make predictions as to how visual cues may influence scene recognition. For example, consider a comparison between Simons and Wang's (1998) Experiment 1 (regular laboratory room with peripheral objects) and Experiment 2 (darkened room with objects coated in fluorescent paint). In both environments there was a clear facilitative effect of observer locomotion relative to scene rotation. However, an examination of the results shows that performance following locomotion was lower in the environment without external visual cues compared to the environment with those cues. One explanation for this effect is that participants might have used environmental cues to determine their position change after locomotion. This would allow participants to re-orient with the original learning direction and determine the magnitude of the viewpoint shift, thus facilitating the retrieval of object spatial relations. This re-orientation would manifest as improved recognition performance following locomotion in the environment with salient cues as compared to the environment without such cues. Moreover, Burgess et al. (2004) have shown that that scene recognition accuracy is superior when participants locomote to a new viewing position and an external visual cue (a fluorescent cue card) remains stationary compared to when the cue moves with the participant. This suggests that stable visual cues in the environment may augment scene recognition performance, potentially by promoting re-orientation and thus accurate recovery of object spatial relations. Collectively, the above findings imply that visual cues in the external environment may improve scene recognition ability, particularly following locomotion.

The positive effect of visual cues on scene recognition has recently been demonstrated by Vidal, Lehmann, and Bulthoff (2009), who adopted a multisensory approach to scene recognition by using a virtual reality setup. In their study, participants were afforded different combinations of sensory modalities (i.e. vestibular, visual, and auditory) while experiencing viewpoint shifts in a typical scene recognition task. The results showed that vestibular cues available during simulated motion did not confer an accuracy advantage compared to scene rotation. However, in conjunction with salient visual cues in the environment, the cost of a viewpoint shift was greatly reduced and accuracy was shown to be superior following locomotion compared to scene rotation. This finding lends support to the notion that visual cues in the environment may not only improve scene recognition performance in general, but may actually exacerbate the facilitative effect of locomotion.

On the other hand, Mou, Zhang, and McNamara (2009) indirectly showed that scene recognition following locomotion is not substantially enhanced by the presence of a visual cue (i.e. chopstick) located within the experimental display which indicates the original learning direction. This suggests that local visual indicators of the learning direction may not improve scene recognition when the viewpoint shift is caused by locomotion.

With the exception of the study by Vidal et al. (2009), the abovementioned studies failed to show a significant influence of visual cues in the environment on scene recognition at small viewpoint shifts (e.g. 49° in Burgess et al., 2004; 49° in Mou, Zhang, & McNamara, 2009; and 47° in Simons & Wang, 1998). One explanation for the lack of significant results in the abovementioned studies is that when the viewpoint shift is small, spatial representations may be sufficiently updated through locomotion, and thus visual cues may not improve scene recognition beyond that which is achieved solely by motion. Nevertheless, these studies showed a trend towards a benefit of visual cues on scene recognition. Therefore, the benefit of visual cues in the environment may become apparent at larger viewpoint shifts, when more error has accumulated in the updating system and spatial representations are less reliable (e.g. Farrell & Robertson, 1998; Mou et al., 2009). As a result of this reduced reliability, participants may rely on other cues (such as visual information) to aid scene recognition.

Experiment 1b was conducted in a regular laboratory setting that had numerous peripheral objects (such as boxes, chairs, and computers). The lights were also turned up. At any point during the experiment wherein participants were not blindfolded, they could readily determine their position and orientation in the room. We predict that performance will follow the same basic trends as Experiment 1a. Specifically, we predict that recognition performance following both locomotion and scene rotation will exhibit viewpoint-dependence. Based on Experiment 1a, we expect recognition performance to decline as the magnitude of viewpoint shift increases for both scene rotation and locomotion. We also predict that performance following locomotion will be superior to that of scene rotation, thereby illustrating the facilitative effect of locomotion regardless of whether or not visual cues in the environment are present. However, compared to Experiment 1a - in which visual cues in the environment were relatively absent - we predict that recognition performance following locomotion will be enhanced, especially for large viewpoint shifts. Support for this finding would suggest that visual cues do indeed exacerbate the facilitative effect of locomotion (see Vidal et al., 2009).

Method

Participants

Thirty-four undergraduate students (13 males and 21 females, 17-24 years of age [M = 19, SD = 1.42]) from McMaster University participated in return for course credit. All subjects reported normal or corrected-to-normal vision, and none had previous experience with spatial learning paradigms like the one presented here.

Materials, Apparatus, and Design

The materials and apparatus were very similar to Experiment1a. However, since we were interested in testing for the effect of visual cues in the environment on scene recognition, the 10-sided enclosure from Experiment 1a was removed. Instead, the experiment took place in a regular laboratory space that had many peripheral objects. The lights were turned on, thereby making all environmental cues visible to the participants.

In addition to the asymmetry and salience of the environment, we removed the funnel from the lens of the projector. The result of this manipulation made the outline of the image projected onto the table rectangular. This provided participants with additional orientation/directional cues within the local display. The experimental display and set-up were otherwise the same as in Experiment 1a.

Procedure

Learning Phase. This was exactly the same as Experiment 1a.

Retention Phase. This was exactly the same as Experiment 1a.

Test Phase. This was similar to Experiment 1a, with the exception of the symbols used to demark the cups. Instead of using coloured circles which possess no orientation cues, we marked the cups with letters (A-E) in this experiment. These letters were oriented with the learning direction, thereby affording participants additional information that enabled them to re-orient towards the original learning direction. Following the viewpoint shift (or lack thereof), the participant identified the cup that they believed had moved during the retention phase by indicating the letter that corresponded to that cup. Once their response was given, participants returned to the learning position (0°) to begin the next trial.

Design. This was the same as Experiment 1a.

Results

Scene recognition (i.e. change detection) performance was measured as the proportion of trials on which participants correctly identified which cup had moved during retention. We also measured reaction time for correct responses. As in Experiment 1, an initial analyses including the sex of the participants as a between-subject factor did not reveal any differences. There was also no effect of direction of movement/rotation (i.e. clockwise versus counter-clockwise). Therefore the data was collapsed across these variables for all subsequent analyses.

Preliminary Analysis with Control Condition

As in Experiment 1, we examined whether or not novel-view scene recognition was viewpoint-dependent following observer locomotion and scene rotation. A series of planned paired samples t-tests revealed that participants were significantly more accurate in the control condition ($M = 0.81$, $SD = 0.11$) than in all scene rotation and locomotion conditions (all p's < 0.001). Participants' reaction time was also quicker in the control condition ($M = 6.13$, $SD = 2.15$) compared to any of the scene rotation or locomotion conditions (all p's < 0.05).

After this initial set of comparisons, we removed the control condition from further analyses and focused on the differences between locomotion and scene rotation across the different magnitudes of viewpoint shift.

Observer Locomotion versus Scene Rotation

A 2 (mode of viewpoint shift: observer locomotion versus scene rotation) x 4 (magnitude of viewpoint shift: 50°, 80°, 110°, 130°) repeated measures ANOVA was conducted separately for the proportion of correct judgments and reaction time.

Accuracy

For the proportion of correct judgments, there was a significant main effect of mode of viewpoint shift, with participants performing more accurately following locomotion compared to scene rotation, $F(1, 33) = 7.82$, $MSE = 0.043$, $p = 0.009$. There was also a significant main effect of magnitude of viewpoint shift, with performance gradually declining as the magnitude of viewpoint shift increased, $F(3, 99) = 3.53$, $MSE = 0.042$, $p = 0.018$. The interaction between mode and magnitude of viewpoint shift was not significant, $F(3, 99) = 0.194$, $MSE = 0.042$, $p = 0.900$.

We also performed a linear trend analysis to evaluate the hypothesis that the scores decrease linearly as the magnitude of viewpoint shift increases for both scene rotation and locomotion. There was a significant linear decline in change detection accuracy as the magnitude of scene rotation increased, $t(33) = -2.98$, $p = 0.002$, one-tailed. The linear decline in accuracy was marginally significant as the magnitude of observer locomotion increased, $t(33) = -1.69$, $p = 0.050$, one-tailed. Each of these results is plotted in Figure 7A.

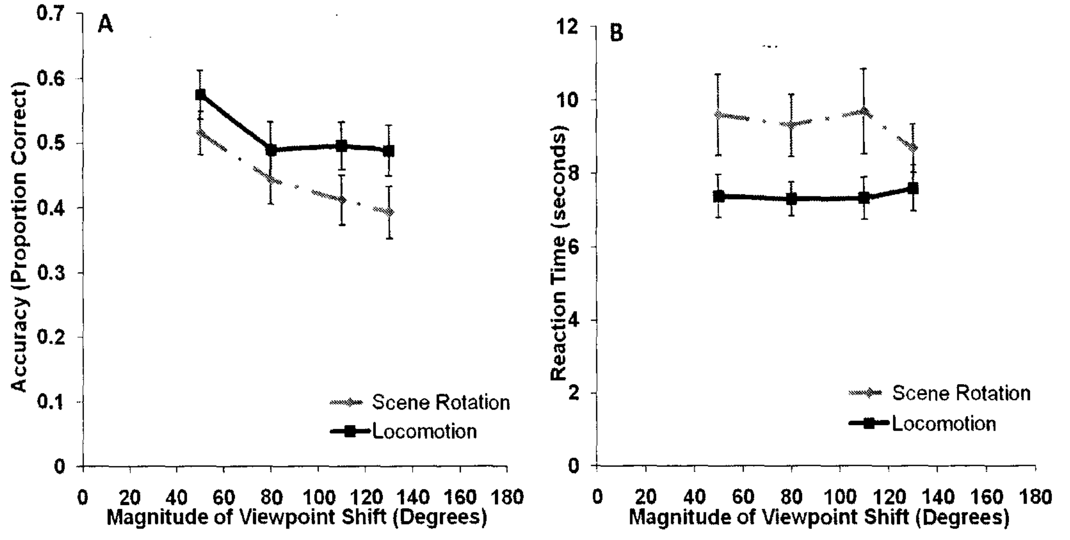

Figure 7: Scene recognition performance as a function of magnitude and mode of viewpoint shift in Experiment 1b. The external environment was visible. Solid line – observer locomotion; hashed line – scene rotation. (A) Scene recognition accuracy; (B) Reaction time on correct trials. Error bars represent between-subjects ± 1 standard error of the means (*SEMs*) computed from data points in each condition submitted to the analysis of variance.

Reaction Time

For reaction time of *correct* judgments, there was a significant main effect of mode of viewpoint shift, with participants responding quicker following locomotion than scene rotation, $F(1, 25) = 7.90$, $MSE = 15.46$, $p = 0.009$. There was no significant effect of magnitude of viewpoint shift, $F(3, 75) = 0.339$, $MSE = 9.38$, $p = 0.797$, and there was no significant interaction between mode and magnitude of viewpoint shift, $F(3, 75) = 1.24$, $MSE = 5.47$, $p = 0.301$.

We also performed a linear trend analysis to evaluate the hypothesis that reaction time increases as the magnitude of viewpoint shift increases for both scene rotation and locomotion. Reaction times did not increase linearly for either scene rotation, $t(26) = -1.095$, $p = 0.858$, or for observer locomotion, $t(29) = 0.332$, $p = 0.371$. These results are plotted in Figure 7B.

Between-Experiments Analysis

Finally, we conducted a subsequent analysis using Experiment (1a versus 1b) as a between-subjects factor after accounting for unequal variances between the two experiments. There was no effect of Experiment for change detection accuracy, $F(1, 47.3) = 0.037$, $MSE = 0.073$, $p = 0.849$, or for reaction time of correct responses, $F(1, 36.23) = 0.009$, $MSE = 59.124$, $p = 0.915$. None of the interactions including Experiment as a factor were significant (all p's > 0.05).

Discussion

The purpose of Experiment 1b was to examine the contribution of salient visual cues in the environment to scene recognition following viewpoint shifts caused by observer locomotion and scene rotation. First and foremost, the results of Experiment 1b are consistent with those of Experiment 1a in which those visual cues were lacking. In particular, scene recognition was superior when participants did not experience a viewpoint shift compared to any degree of observer locomotion or scene rotation. This finding again suggests that there is a cost to undergoing a viewpoint shift (i.e. scene recognition is viewpoint-dependent). Furthermore, performance following locomotion was more accurate and faster than that following scene rotation across all tested viewpoint shifts. This again suggests that the facilitative effect of locomotion is robust across small and large viewpoint shifts. Interestingly, the facilitative effect of locomotion (i.e. [locomotion performance] – [scene rotation performance]) appears to be greater at larger viewpoint shifts compared to smaller ones. This finding challenges the claim that the facilitative effect of locomotion is attenuated at relatively large viewpoint shift magnitudes (see Mou, Zhang, & McNamara, 2009).

Additionally, recognition performance declined linearly as the magnitude of scene rotation increased, which is consistent with the results of Experiment 1a. Furthermore, performance following locomotion also tended to decrease for larger viewpoint shifts, although this effect was only marginally significant. The difference in linear trends for locomotion between Experiments 1a and 1b is evaluated further below.

Neither accuracy nor reaction time differed statistically between Experiment 1a (lack of visual cues) and Experiment 1b (presence of visual cues). This lack of difference suggests that visual cues in the environment cannot account for the facilitative effect of locomotion in our design (see also Simons, Wang, & Roddenberry, 2002). Nevertheless, the difference in the strength of the linear trends for locomotion performance between Experiment 1a and Experiment 1b requires elaboration. In the absence of environmental landmarks or intrinsic axes, scene recognition following locomotion primarily depends on the reliability of updated spatial representations. Experiment 1a clearly demonstrates a significant linear decline in recognition performance as the magnitude of locomotion increases, thereby suggesting that error in the updating mechanism accumulates over longer walking distances (see also Farrell & Robertson, 1998; Mou, Zhang, & McNamara, 2009). On the other hand, in the presence of environmental cues (Experiment 1b), the decline in performance was not as substantial as when those cues were absent (Experiment 1a). One potential reason for this is that there was a much larger variance in performance across magnitudes of locomotion in Experiment 1b, which masked any prominent statistical effect. In fact, supplementary analysis showed that error variance was statistically greater in Experiment 1b as compared to Experiment 1a at every magnitude of locomotion. This suggests that the availability of visual cues in the environment has the effect of increasing variability in performance among participants. It is likely that some participants were able to take advantage of environmental cues in order to improve their recognition performance following locomotion, while other participants may have actually been hindered by the presence of those cues or not used them at all. It is interesting to note that performance following locomotion in Experiment 1b (regular laboratory space with visual cues) appeared to level off at larger viewpoint shifts. Therefore, it is possible that environmental cues help to improve performance for some participants by allowing them to overcome some of the natural error that exists in the updating mechanism. The degree to which some participants are helped or hindered by environmental cues (and the nature of that effect) is an area that requires further investigation.

To explain why Vidal et al. (2009) showed a benefit of visual cues when experiencing small viewpoint shifts, we must consider the nature of their "locomotion" condition. In their study, when participants underwent a viewpoint shift caused by physical movement around the scene, they sat in a chair and were passively rotated via movement of an underlying platform that simulated the vestibular system. By their own admission, the proprioceptive information gained from this manipulation was not optimal since participants did not actually walk to the new viewpoint. Therefore, it is possible that visual cues had a positive effect on scene recognition during these viewpoint shifts since the body-based cues gained during movement were not as rich as in previous designs (including the present study). Without inclusive body-based information (i.e. proprioceptive, vestibular, inertial, kinaesthetic, etc.) during movement, participants' spatial representations may not have been adequately updated, thereby enabling visual cues in the environment to have a notable effect.

In sum, the addition of visual cues to the environment did not improve scene recognition performance in our design, and the presence of these cues did not exacerbate the facilitative effect of observer locomotion. Therefore, it does not appear as though participants in Experiment 1b used environmental cues in order to gauge their change in position and thus re-orient with the original learning direction. This suggests that the facilitative effect of locomotion is mainly attributable to body-based cues that enable participants to update their self-to-object-array representations during locomotion (see Simons, Wang, &

Roddenberry, 2002). In fact, it has been shown that spatial representations rely on vestibular, proprioceptive, and kinesthetic cues (e.g. Berthoz, Israel, Francois, Grasso, & Tsuzuku, 1995; Israël, Bronstein, Kanayama, Faldon, & Gresty, 1996), while visual information alone is generally not sufficient for spatial updating (e.g. Klatzky, Loomis, Beall, Chance, & Gollege, 1998). The influence of body-based cues on updating spatial relations during locomotion is investigated further in Chapter Three.

Chapter Two

Chapter One established that the facilitative effect of locomotion is robust across a wide range of viewpoint shifts (Experiment 1a), and that this facilitative effect cannot simply be attributed to the presence of visual cues in the environment (Experiment 1b). Given this phenomenon, Chapter Two begins our investigation into the potential mechanism underlying the facilitative effect of locomotion. In particular, this chapter tests the hypothesis that active control over the viewpoint shift may partially account for the facilitative effect of locomotion, and that the specific benefit of active control may include an acquisition of knowledge regarding the magnitude and direction of the viewpoint shift.

Experiment 2a

The purpose of Experiment 2a is to uncover the mechanism responsible for the facilitative effect of locomotion. Most past studies that have demonstrated the facilitative effect of locomotion have attributed this effect to the presence of body-based cues (e.g. proprioceptive, vestibular, etc.) that promote updating of spatial relations, whereas those cues are not available during scene rotation since participants remain stationary (e.g. Rieser, 1989; Simons & Wang, 1998; Simons, Wang, & Rodenberry, 2002; Wang & Simons, 1999). While it is possible that body-based information gained during motion contributes to the facilitative effect of locomotion, there is an alternative explanation that can be posited. Recall that in the case of observer locomotion, participants actually walk to a new viewing position; thus they are actively controlling the viewpoint shift. On the other hand, in the case of scene rotation, the experimenters are responsible for rotating the display, and therefore participants passively experience the viewpoint shift. It is possible that the benefit of locomotion is actually a result of actively controlling the viewpoint shift, as opposed to distinct body-based cues that are afforded to participants during locomotion.

The benefit of active control on spatial processing has been demonstrated in previous studies, most of which employ paradigms that are fundamentally different from ours. For example, Harman, Humphrey, & Goodale (1999) investigated how active exploration of 3-dimensional objects influences later recognition of those objects. In their study, participants were presented with a series of geon-like objects on a screen, and were asked to examine and memorize the different objects. In one condition, participants were able to actively manipulate the rotation of the objects. In the other condition, participants passively viewed the same rotation profile as in the active condition, but had no control over the view of the objects. This means that participants in the passive condition saw the exact same views as participants in the active condition. Following this learning phase, participants were tested in an old-new recognition task in which they had to indicate for every test object whether they had seen it before. Results showed that participants recognized objects more quickly when they had actively learned them than when they had passively viewed them. Similar results have been demonstrated when much larger objects are manipulated, and when this manipulation occurs in virtual space (James, Humphrey, Villis, Corrie, Baddour, & Goodale, 2002).

Since active manipulation of object views facilitates later recognition, it is conceivable that active manipulation of entire scenes comprising numerous objects would also confer a recognition advantage. In fact, several studies have shown that participants who actively control their movements have better spatial knowledge than when they passively experience those movements (e.g. Christou & Bulthoff, 1999; Larish & Anderson, 1995; Peruch, Vercher, & Gauthier, 1995). In a study by Christou and Bulthoff (1999), participants explored a virtual environment and were instructed to remember the location of several markers. In Experiment 1, participants actively controlled their motion through the environment, whereas in Experiment 2 they were only able to view static snapshots of the environment. The views experienced in the active and passive condition were matched. Results showed that, compared to passively viewing the static snapshots, interactive learning facilitated recognition of novel-perspective views and of topographic floor plans. Larish and Anderson (1995) provide similar evidence for a benefit of active learning on orientation estimations. In their task, active observers controlled their motion through a 3-D scene, whereas passive observers viewed the display generated by the control of active observers. Following this learning period, there was a brief blackout. This blackout was immediately followed by a static image of the scene, which could either be in the correct orientation and position, or an incorrect orientation/position. The results demonstrated that active observers were more sensitive than passive observers in detecting a change in orientation. Taken together, the above findings speak to a scene recognition advantage when individuals actively learn the spatial properties of an environment compared to passively learning it.

Active *learning* of spatial environments is not the only means of improving spatial processing, however. For example, Yardley and Higgins (1998) have shown that participants are able to judge their orientation more accurately when they undergo an orientation shift that is caused by active rotation compared to passive rotation. These researchers posit an increase in sesorimotor feedback as the mechanism underlying the benefit of active control. Fery, Magnac, & Israel (2004) extend this notion to suggest that active control enables individuals to incorporate a copy of the motor plan into their spatial representations, which allows them to adjust their representations in the course of changing spatial relationships. In their study, participants sat in a large rotative robot and were told to learn the locations of five objects in the environment. Following this period, participants were blindfolded and underwent a series of rotations. Participants in the active condition controlled the rotation of the robot in accordance with instructions from the experimenters, whereas participants in the passive condition experienced the same combination of rotations without active control. After the rotations, participants in both conditions had to point to the objects while still blindfolded. The results showed that actively controlling the rotation series resulted in lower absolute pointing error compared to passively experiencing the same rotations. Overall, these studies suggest that actively controlling a viewpoint shift also facilitates spatial processing.

While the abovementioned studies have utilized experimental paradigms that are different from ours (and thereby test uniquely different aspects of spatial memory), there is one notable study that has used a paradigm similar to ours to test whether active control facilitates scene recognition. In a study by Wang and Simons (1999), participants briefly viewed a spatial arrangement of objects on a circular table in front of them. Following this learning phase, the scene was blocked and one of the objects was relocated to a new position on the table. Concurrent with this change, the table was rotated a given amount. In the active condition, participants remained stationary and rotated the scene themselves by grasping a handlebar attached to the table and pulling it towards themselves. They were also able to directly view the rotation of the handle, but not the scene itself. Alternatively, in the passive condition participants remained stationary and the experimenters rotated the table. Importantly, participants in the passive condition were also able to view the rotation of the handlebar. Note that there was no locomotion in either the active or passive condition, which factors out any body-based cues that may be available during locomotion. The participants then viewed the scene and indicated which object had been moved. Results showed that scene recognition accuracy was no better whether the viewpoint shift occurred actively or passively. These researchers concluded that active control over the viewpoint shift alone could not account for the facilitative of locomotion since there was no benefit of active control after controlling for the cues gained during locomotion. Instead, they suggested that the benefit of locomotion must be attributed to the presence of body-based cues that permit accurate updating of spatial representations.

Despite the elegant design of Wang and Simons (1999), there is one glaring weakness in their study that needs to be addressed. Recall that in both the active and passive conditions participants were able to view the rotation of the handlebar. This handlebar directly informed participants about the magnitude and direction of the viewpoint shift in both conditions. It has been shown that when a salient visual indicator of the viewpoint shift is provided, recognition performance following scene rotation can actually be inflated to match that of locomotion (Mou, Zhang, & McNamara, 2009). Therefore, it is possible that the reason Wang and Simons (1999) failed to show a difference between active and passive rotation was that this strong visual cue masked any benefit of active control that existed. With that in mind, this experiment aims to re-evaluate the findings of Wang and Simons (1999) using our adjusted paradigm (as described in the General

Introduction). Specifically, we are interested in whether or not active control over the viewpoint shift can partially account for the facilitative effect of locomotion in the absence of any visual cues that indicate the magnitude or direction of the viewpoint shift.

In addition to examining whether active control over the viewpoint shift confers a scene recognition advantage, we again examine additional aspects of scene recognition, including the concept of viewpoint dependency, and how performance levels change as the magnitude of active and passive scene rotation increases. We predict that scene recognition performance will follow the same basic trends as in Chapter One. In particular, we expect scene recognition to be viewpoint-dependent, with performance following no viewpoint shift being more accurate and quicker than when the scene is rotated actively or passively. In line in Chapter One, we also expect scene recognition performance to decline as the magnitude of active and passive rotation increases. Finally, if there is a benefit of active control on scene recognition, performance should be superior when the viewpoint shift is actively controlled than when it is passively experienced.

Method

Participants

Sixteen undergraduate students (5 males and 11 females, 17-24 years of age [M = 19, SD = 1.41]) from McMaster University participated in return for course credit. All participants reported normal or corrected-to-normal vision, and none had previous experience with spatial learning paradigms like the one presented here.

Materials, Apparatus, and Design

This was the same as Experiment 1a, in which the testing area was enclosed in our large 10-sided room with the lights turned down. The experimental display again consisted of five identical Styrofoam cups placed in random configurations on a white, circular table that was freely rotatable in either direction.

In this experiment, MATLAB 7.0 was used to generate 124 (four practice and 120 test) irregular spatial configurations wherein only two objects could be aligned with each other during each trial. The trials were split across two days (60 trials on each day, with the four practice trials on the first day only), such that participants completed half of the trials one day and the other half exactly one week later. There was nothing systematically different about the methodology across the two days; we simply desired a larger number of trials per participant. The rest of the materials and apparatus were the same as Experiment 1a.

Procedure

Learning Phase. This was the same as Experiments 1a and 1b.

Retention Phase. The retention phase involved the change to the spatial layout (i.e. cup relocation), and the viewpoint shift. First, the experimenter moved one of the cups to a previously unoccupied position on the table. Next, the viewpoint shift was achieved in one of three ways: (1) *No viewpoint shift*: the participant remained stationary, and the table was not rotated. We employed two slightly different control conditions. The *passive*-control condition was the same as the control condition of Experiments 1a and 1b, in which participants remained completely stationary during retention and there was no scene rotation. Alternatively, for the *active*-control condition, participants reached out and grabbed the table, but did not rotate it any amount. This simply served to explicitly inform them that there was no viewpoint shift during the retention phase. In both cases (passive-control and active-control) there was no viewpoint shift. (2) *Active scene rotation*: the participant remained stationary and rotated the scene themselves by one of the chosen magnitudes (i.e. 50°, 80°, 130°, 160°, or 180°). Scene rotation could be in a clockwise or counter-clockwise direction on any given trial. For this set of conditions, the experimenter guided the participant's hand to the table, and the participant pulled it towards themselves (Figure 8A). The puling motion was always adductive, towards the median axis of the body. The number of table pulls required to achieve each magnitude of viewpoint shift was standardized across participants (see Table 2). (3) *Passive scene rotation*: the participant remained stationary and the experimenter rotated the table by 50°, 80°, 130°, 160°, or 180° (in either a clockwise or counter-clockwise direction on any given trial). Importantly, we attempted to match the motor effort and cognitive load of the passive rotation conditions with that of the active rotation conditions. To achieve this, whenever the table was rotated in the passive mode, participants performed synchronized arm motions that simulated their arm motions in the active condition. For example, if the magnitude of rotation was 50°, participants in the passive mode moved their arm above the table by the same amount (and in the same direction) as if they were rotating the scene actively (Figure 8B). However, we never instructed participants about what these arm motions meant in terms of actual scene rotation.

For a complete list of the experimental conditions, see Table 2.

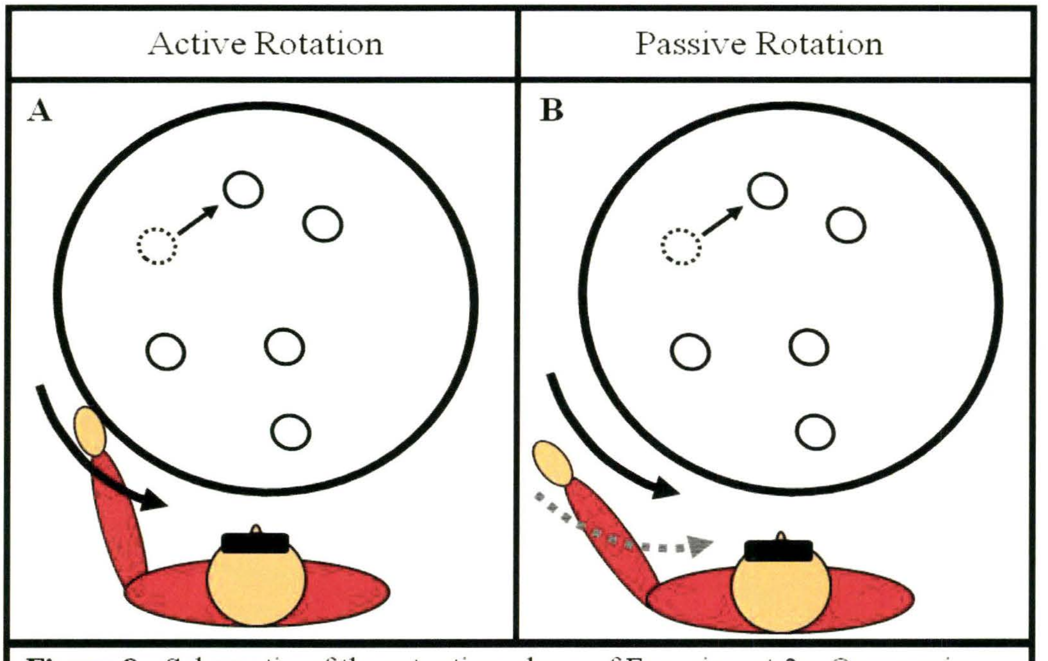

Figure 8 - Schematic of the retention phase of Experiment 2a. One cup is relocated, and the table is rotated. (A) Active rotation by the participant; (B) Passive rotation – the participant moves their arm(s) above the table to simulate the rotation of the active condition

As in Experiments 1a and 1b, participants were never instructed on a trial-by-trial basis as to the magnitude of active or passive rotation; however, in the active condition they obviously had information about the magnitude of rotation since they were actually causing the viewpoint shift. Unlike Experiments 1a and

1b, retention periods were 15 seconds in length to account for the added task demands on the experimenter and participants.

Table 2: Summary of Conditions for Experiment 2a

Condition	Magnitude of Rotation (°)	Magnitude of Locomotion (°)	Number of Table Pulls Required
1. Control-Active	0	0	0
2. Control-Passive	0	0	0
3. Active Rotation of 50°	50	0	1
4. Passive Rotation of 50°	50	0	1
5. Active Rotation of 80°	80	0	1 ½
6. Passive Rotation of 80°	80	0	1 ½
7. Active Rotation of 130°	130	0	2 ½
8. Passive Rotation of 130°	130	0	2 ½
9. Active Rotation of 160°	160	0	3
10. Passive Rotation of 160°	160	0	3
11. Active Rotation of 180°	180	0	3 ½
12. Passive Rotation of 180°	180	0	3 ½

Test Phase. Following the viewpoint shift (or lack thereof), the participant identified the cup that they believed was moved during the retention phase. The cups were demarked with coloured circles as described in Experiment 1a.

Design. Each participant experienced 10 passive-control and 10 active-control trials. They also experienced two viewpoint shift modes (active scene rotation and passive scene rotation) across five viewpoint shift magnitudes (50°, 80°, 130°, 160°, and 180°), each of which were experienced in two directions (clockwise and counter-clockwise), and all were repeated five times. In total, there were 120 trials (20 control + [2 modes x 5 magnitudes x 2 directions x 5 repetitions]). Trials were arranged into five blocks, with all conditions presented in a random order within each block. As mentioned above, trials were split across two days, with each testing session lasting approximately one hour.

Results

Scene recognition (i.e. change detection) performance was measured as the proportion of trials on which participants correctly identified which cup had moved during retention. We also measured reaction time for correct responses. An initial analyses including the sex of the participants as a between-subject factor did not reveal any differences. There was also no effect of direction of rotation (i.e. clockwise versus counter-clockwise). Therefore the data was collapsed across these variables for all subsequent analyses.

Preliminary Analysis with Control Conditions

We first examined whether or not there was a difference between the active-control condition (accuracy: $M = 0.84$, $SD = 0.17$; reaction time: $M = 5.35$, $SD = 1.02$) and the passive-control condition (accuracy: $M = 0.86$, $SD = 0.14$; reaction time: $M = 5.25$, $SD = 0.97$). As expected, there was no difference between these two conditions, either for proportion of correct judgments, $t(15) = -0.605$, $p = 0.554$, two-tailed, or for reaction time of correct responses, $t(15) = 0.841$, $p = 0.414$, two-tailed.

We then determined whether novel-view scene recognition was viewpoint dependent following active scene rotation and passive scene rotation. A series of planned paired samples t-tests revealed that performance was significantly more accurate (all p's < 0.001) and quicker (all p's < 0.05) in the control conditions than in any of their respective active or passive scene rotation conditions. After this initial set of comparisons, we removed both the active-control and passive-control conditions from further analyses and focused on the differences between active scene rotation and passive scene rotation across the different magnitudes of viewpoint shift.

Active versus Passive Scene Rotation

A 2 (mode of viewpoint shift: active scene rotation versus passive scene rotation) x 5 (magnitude of viewpoint shift: 50°, 80°, 130°, 160°, 180°) repeated measures ANOVA was conducted separately for the proportion of correct judgments and reaction time.

Accuracy

For the proportion of correct judgments, the main effect of mode of viewpoint shift approached significance, with participants performing more accurately following active scene rotation than passive scene rotation, $F(1, 15) = 3.615$, $MSE = 0.029$, $p = 0.077$. In addition, there was a significant main effect of magnitude of viewpoint shift, with performance gradually declining as the magnitude of viewpoint shift increased, $F(4, 60) = 8.54$, $MSE = 0.013$, $p < 0.001$. The interaction between mode and magnitude of viewpoint shift was not significant, $F(4, 60) = 1.381$, $MSE = 0.015$, $p = 0.251$.

An examination of the passive rotation data showed that scene recognition accuracy spiked at 180° to match that of active scene rotation. This spike in performance is typical in scene recognition studies (see discussion), and suggests a fundamental difference in spatial processing for angles at, or near, 180°. Thus, we removed 180° from the analysis to re-evaluate the difference between active and passive scene rotation. This analysis revealed a significant main effect of mode of viewpoint shift, with participants performing more accurately following active scene rotation compared to passive scene rotation, $F(1, 15) = 5.87$, $MSE = 0.029$, $p = 0.029$. There was still a significant main effect of magnitude of viewpoint shift, with performance gradually declining as the magnitude of viewpoint shift increased, $F(3, 45) = 11.13$, $MSE = 0.013$, $p < 0.001$, and the interaction between mode and magnitude of viewpoint shift was still not significant, $F(3, 45) = 0.143$, $MSE = 0.014$, $p = 0.934$.

We also performed a linear trend analysis to evaluate the hypothesis that the scores decrease linearly as the magnitude of viewpoint shift increases for both active and passive scene rotation. There was a significant linear decline in change detection accuracy as the magnitude of active scene rotation increased, $t(15) = -3.925$, $p < 0.001$, one-tailed. There was also a significant linear decline in accuracy as the magnitude of passive scene rotation increased, $t(15) = -3.48$, $p = 0.002$, one-tailed. Each of these results is plotted in Figure 9A.

Reaction Time

For reaction time of *correct* judgments, there was no difference between active and passive scene rotation, $F(1, 15) = 0.285$, $MSE = 1.641$, $p = 0.601$. Additionally, the main effect of magnitude of viewpoint shift approached significance, $F(4, 60) = 2.35$, $MSE = 1.39$, $p = 0.064$, but the interaction between mode and magnitude of viewpoint shift was not significant, $F(4, 60) = 0.941$, $MSE = 2.204$, $p = 0.446$.

We also performed a linear trend analysis to evaluate the hypothesis that reaction time increases as the magnitude of viewpoint shift increases for both active scene rotation and passive scene rotation. Reaction time increased linearly as the magnitude of active scene rotation increased, $t(15) = 3.044$, $p = 0.004$, one-tailed, and this linear trend approached significance for passive scene rotation also, $t(15) = 1.60$, $p = 0.066$. These results are plotted in Figure 9B.

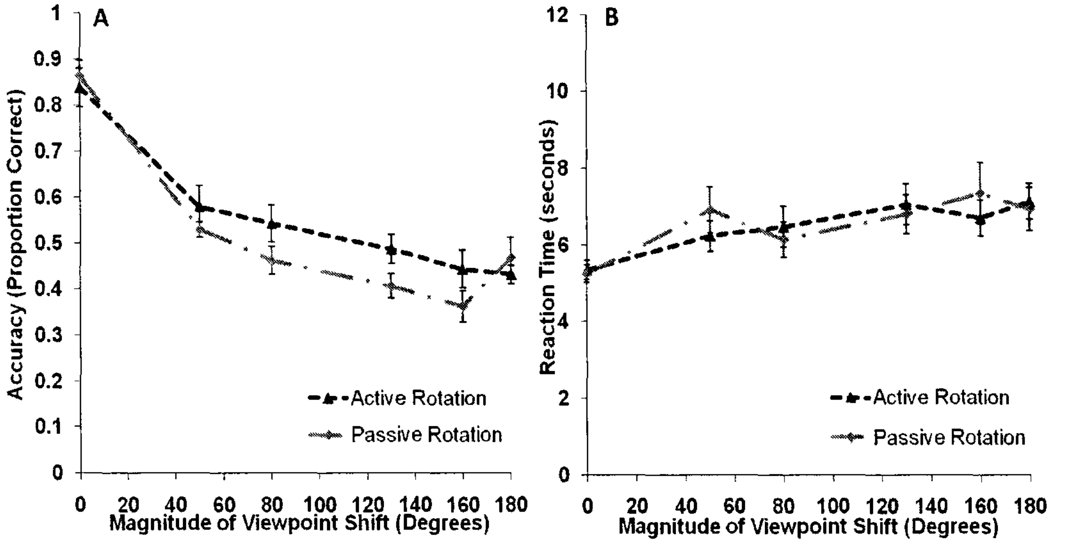

Figure 9 – Scene recognition performance as a function of magnitude and mode of viewpoint shift in Experiment 2a. The external environment was removed. Black line – active scene rotation; gray line – passive scene rotation. (A) Scene recognition accuracy; (B) Reaction time on correct trials. Error bars represent between-subjects ± 1 standard error of the means (*SEMs*) computed from data points in each condition submitted to the analysis of variance.

Discussion

This experiment examined whether the facilitative effect of locomotion could be attributed to active control over the viewpoint shift. First and foremost, however, we confirm our predictions regarding other aspects of scene recognition. In line with the results of Chapter One, this experiment showed that scene recognition is viewpoint-dependent, with performance being both more accurate and quicker when there was no viewpoint shift compared to any magnitude of active or passive scene rotation. Also, scene recognition accuracy declined, and reaction time increased, as the magnitude of viewpoint shift increased for both active and passive rotation. These results are consistent with past studies that demonstrate the angular-dependent nature of scene recognition (e.g. Diwadkar & McNamara, 1997; Finlay, Motes & Kozhevnikov, 2007). In general, this suggests that scene recognition becomes more difficult as the magnitude of viewpoint shift increases. The fact that both active and passive scene rotation exhibited the same trends in performance is important since it suggests that participants are employing the same basic strategy to recover object spatial relations for both modes. This is favourable since any potential difference between active and passive rotation is likely not attributable to a difference in strategy between the two conditions.

The most essential finding of this experiment is that recognition performance following active scene rotation was more accurate than that following passive scene rotation. This effect became more significant when we removed 180° - a magnitude known to result in a unique pattern of performance (Diwadkar & McNamara, 1997; Mou & McNamara, 2002; Shelton & McNamara, 2001) - from the analysis. This is consistent with the results of studies comparing active and passive movements through space, which tend to show that individuals who actively control their movements have greater spatial knowledge (e.g. Christou & Bulthoff, 1999; Larish & Anderson, 1995; Peruch et al., 1995). Furthermore, there was no difference in reaction times between active and passive rotation in our study. Taken together, these results suggest that actively controlling the viewpoint shift confers a scene recognition accuracy advantage compared to passively experiencing the shift, but this benefit cannot be attributed to a difference in processing times.

The ultimate goal of this experiment was to examine the mechanism underlying the facilitative effect of locomotion. Recall that there was no locomotion in either of the scene rotation conditions. This means that any body-based cues regularly available during movement had been controlled for in this experiment. This allowed us to determine whether active control alone (independent of additional body-based cues) can account for the facilitative effect of locomotion. Indeed, these results suggest that active control over the viewpoint shift - and not necessarily body-based cues specific to locomotion – may account for the facilitative effect of locomotion. However, it is possible that body-based cues gained during locomotion provide information beyond simply having active control over the viewpoint shift. This hypothesis is explicitly tested in Chapter Three.

To explain the active/passive difference in recognition accuracy, we consider a few hypotheses that have been proposed in the literature. The most prominent reason as to why active control facilitates subsequent recognition seems to be that direct manual control over the viewpoint shift provides efference copy and/or proprioceptive information that helps to integrate changing viewpoints, thus allowing participants to anticipate upcoming viewpoint shifts and relate them to previous shifts (Fery et al., 2004; Harman et al., 1999; James et al., 2002). When the viewpoint shift is actively controlled, efference copies of motor commands which are sent to the muscles may then be incorporated into the representation of that action (Wraga, Creem-Regehr, & Proffitt, 2004). Presumably, this would allow participants to keep track of changing spatial relationships and adjust their spatial representations more easily. Since these motor commands are only available during self-initiated movements, this may explain why participants who actively controlled the viewpoint shift were better able to recognize the scene than when they passively experienced the shift. Another explanation for the active/passive difference may be that individuals who actively control the viewpoint shift deploy more attentional resources than those who passively experience the shift (e.g. Fery et al., 2004; Harman et al., 1999; James et al., 2002). This hypothesis is consistent with the results of Yardley, Gardner, Lavie, and Gresty (1999), who demonstrated that individuals had difficulty monitoring their body orientation when they were simultaneously required to perform a mental arithmetic task. While our task does not require an estimation of body orientation, it does require that participants monitor the orientation of the scene (since it is constantly rotating various amounts). Therefore, it is possible that individuals allocate more attentional resources during active scene rotation, or strategically vary the degree of attention allotted during certain phases of the rotation (see Harman et al., 1999).

Returning to our examination of the facilitative effect of locomotion, actively controlling the viewpoint shift may account for this effect by providing participants with efference copies of motor commands, or by instigating more attentional resources during locomotion. However, there is another explanation as to why active manipulation of the viewpoint shift facilitates recognition. Rather than the process being solely implicit and relying on a bottom-up process, locomotion may also provide explicit information regarding the change in the relationship between the observer and the objects in their environment. That is, locomotion through the environment allows the observer to gain explicit knowledge about the magnitude of change between themselves and objects in the environment. For example, moving two steps in one direction is quantitatively different from moving nine steps in that same direction. Such knowledge regarding the change in one's position may afford individuals the ability to predict how spatial relationships are changing. It is therefore possible that movement allows individuals to establish a conscious understanding of the direction and magnitude by which their relationship with the environment has changed. This is the focus of Experiment 2b, which tests the hypothesis that gaining explicit knowledge about the magnitude and direction of the viewpoint shift can account for the benefit of active control.

Experiment 2b

The aim of this experiment is to examine the nature of the benefit of active control on scene recognition. Recall that in Experiment 2a participants in both the active and passive condition moved their arms by the same amount and in the same direction during the viewpoint shift in order to control for the motor effort involved in the task. In the active condition, participants knew that the magnitude and direction of their arm movements explicitly indicated the magnitude and direction by which the scene would rotate (since they were actually causing the shift). On the other hand, in the passive condition participants were not explicitly informed about the basis of their arm movements, and thus probably did not make the link between what their arm movements meant with respect to the scene's rotation. Therefore, it is possible that active control simply provided participants with knowledge about the magnitude and direction of the viewpoint shift, as opposed to instigating some other cognitive process that is unique to active control. Here, we explore the possibility that actively controlling the viewpoint shift provides participants with explicit knowledge regarding the magnitude and direction of the viewpoint shift which, by extension, allows them to predict how the scene is changing. This would allow participants to consciously keep track of changing spatial relationships, thereby resulting in improved scene recognition ability.

This experiment replicated Experiment 2a with one major difference: in this experiment, we explicitly told participants prior to experimentation that, for *both* active and passive rotation, their arm movements would give them a direct cue as to the magnitude and direction of the viewpoint shift (i.e. how much, and in what direction, the scene is rotating). If active control over the viewpoint shift is simply providing participants with knowledge about the magnitude and direction of the shift, then scene recognition performance in the active and passive conditions should not differ in this experiment. Alternatively, if active control provides some residual benefit for scene recognition during viewpoint shifts, then we should still expect to see a benefit of active control.

Method

Participants

Sixteen undergraduate students (2 males and 13 females, 18-22 years of age [M = 19, SD = 1.54]) from McMaster University participated in return for course credit. All participants reported normal or corrected-to-normal vision, and none had previous experience with spatial learning paradigms like the one presented here.

Materials, Apparatus, and Design

This was exactly the same as Experiment 2a.

Procedure

Learning Phase. This was the same as all of our previous experiments.

Retention Phase. This was the same as Experiment 2a, with one major difference: all participants were given explicit instructions that the degree of their arm movements would inform them of the magnitude and direction of the viewpoint shift (i.e. scene rotation). Although this should already be apparent to participants in the active rotation mode (since they know the consequence of rotating the scene), it was made clear that their arm movements in *both* the active and passive mode would now give them a direct cue about the viewpoint shift. In that sense, we matched the knowledge participants received during retention regarding the direction and approximate magnitude of the viewpoint shift for both the active and passive mode.

Test Phase. This was exactly the same as Experiment 2a

Design. This was exactly the same as Experiment 2a.

Results

Scene recognition (i.e. change detection) performance was measured as the proportion of trials on which participants correctly identified which cup had moved during retention. We also measured reaction time for correct responses. An initial analyses including the sex of the participants as a between-subject factor did not reveal any differences. There was also no effect of direction of rotation (i.e. clockwise versus counter-clockwise). Therefore the data was collapsed across these variables for all subsequent analyses.

Preliminary Analysis with Control Conditions

We first examined whether or not there was a difference between the active-control condition (accuracy: $M = 0.86$, $SD = 0.12$; reaction time: $M = 5.31$, $SD = 1.10$) and the passive-control condition (accuracy: $M = 0.84$, $SD = 0.11$; reaction time: $M = 5.32$, $SD = 1.40$). As expected, there was no difference between these two conditions, either for proportion of correct judgments, $t(15) = 0.571$, $p = 0.577$, two-tailed, or for reaction time of correct responses, $t(15) = -0.371$, $p = 0.716$, two-tailed.

We then determined whether novel-view scene recognition was viewpoint dependent following active scene rotation and passive scene rotation. A series of planned paired samples t-tests revealed that performance was significantly more accurate (all p's < 0.001) and quicker (all p's < 0.01) in the control conditions than in any of their respective active or passive rotation conditions. After this initial set of comparisons, we removed both the active-control and passive-control conditions from further analyses and focused on the differences between active scene rotation and passive scene rotation across the different magnitudes of viewpoint shift.

Active versus Passive Scene Rotation (with Instructions)

A 2 (mode of viewpoint shift: active scene rotation versus passive scene rotation) x 5 (magnitude of viewpoint shift: 50°, 80°, 130°, 160°, 180°) repeated measures ANOVA was conducted separately for the proportion of correct judgments and reaction time.

Accuracy

For the proportion of correct judgments, there was no effect of mode of viewpoint shift, with participants performing equally accurate following active scene rotation and passive scene rotation, $F(1, 15) = 0.689$, $MSE = 0.037$, $p = 0.419$. There was also no significant main effect of magnitude of viewpoint shift, $F(4, 60) = 1.60$, $MSE = 0.021$, $p = 0.187$, or interaction between mode and magnitude of viewpoint shift, $F(4, 60) = 0.687$, $MSE = 0.014$, $p = 0.604$.

We then performed a linear trend analysis to evaluate the hypothesis that the scores decrease linearly as the magnitude of viewpoint shift increases for both active and passive scene rotation. There was a significant linear decline in change detection accuracy as the magnitude of active scene rotation increased, $t(15) = -1.825$, $p = 0.044$, one-tailed. There was also a significant linear decline in accuracy as the magnitude of passive scene rotation increased, $t(15) = -2.02$, $p = 0.031$, one-tailed. Each of these results is plotted in Figure 10A.

Reaction Time

For reaction time of *correct* judgments, there was no difference between active and passive scene rotation, $F(1, 14) = 1.66$, $MSE = 1.85$, $p = 0.218$. Additionally, there was a significant main effect of magnitude of viewpoint shift, $F(4, 56) = 3.59$, $MSE = 2.619$, $p = 0.011$, but the interaction between mode and magnitude of viewpoint shift was not significant, $F(4, 56) = 0.542$, $MSE = 2.126$, $p = 0.706$.

We also performed a linear trend analysis to evaluate the hypothesis that reaction time increases as the magnitude of viewpoint shift increases for both active scene rotation and passive scene rotation. Reaction time increased linearly as the magnitude of active scene rotation increased, $t(15) = 3.21, p = 0.003$, one-tailed. There was also a significant linear increase in reaction time as the magnitude of passive scene rotation increased, $t(14) = 3.33, p = 0.002$. These results are plotted in Figure 10B.

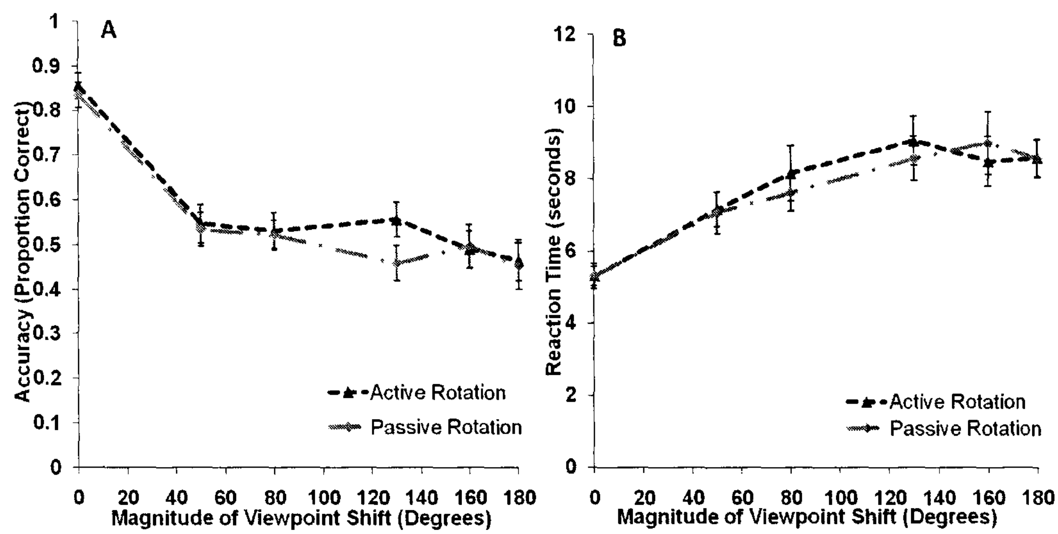

Figure 10 – Scene recognition performance as a function of magnitude and mode of viewpoint shift in Experiment 2b. The external environment was removed. Black line – active scene rotation; gray line – passive scene rotation. (A) Scene recognition accuracy; (B) Reaction time on correct trials. Error bars represent between-subjects ± 1 standard error of the means (*SEM*s) computed from data points in each condition submitted to the analysis of variance.

Discussion

This experiment sought to reveal whether the benefit of actively controlling a viewpoint shift is attributable to an acquisition of knowledge regarding the magnitude and direction of that shift. This was tested by directly comparing the effects of active and passive scene rotation on recognition ability when participants were given explicit instructions regarding the magnitude and direction of the viewpoint shift. We first corroborate the results of our previous experiments with respect to viewpoint-dependency and performance trends. Specifically, scene recognition was shown to be viewpoint-dependent, evidenced by superior recognition performance when no viewpoint shift was experienced compared to any amount of active or passive scene rotation. Also, scene recognition accuracy declined, and reaction time increased, as the magnitude of the viewpoint shift increased for both active and passive scene rotation. These trends parallel those of Experiment 2a. This is important since it suggests that our instructional manipulation likely did not alter the strategy participants employed in order to recover object spatial relations following scene rotation.

Despite the abovementioned similarities in scene recognition performance between this experiment and Experiment 2a, the most important result is the lack of difference between active and passive scene rotation demonstrated here. That is, when we provided participants with instructions regarding the magnitude and direction of the viewpoint shift for both the active and passive rotation, the performance advantage for active control was no longer apparent. This suggests that actively controlling the viewpoint shift actually affords participants knowledge about the magnitude and direction of the shift, such that directly providing that information washes out any difference between active and passive rotation.

An alternative explanation for the lack of difference between active and passive rotation is that - like the handlebar used by Wang & Simons (1999) - our instructions were so effective that they inflated recognition accuracy in both the active and passive condition to the point that there was no observable difference between them. Indeed, numerous studies have shown that providing instructions regarding the viewpoint shift can influence performance on spatial tasks (e.g. Greenauer & Waller, 2008; Mou & McNamara, 2002). This explanation seems implausible, however. If we examine the accuracy scores between Experiment 2a and 2b, it is apparent that active scene rotation performance is no different across experiments. This is expected since our instructions likely only reinforced what the participants already knew – that is, that the amount they rotate the table tells them how the scene is changing. Alternatively, it is clear that accuracy following passive scene rotation in Experiment 2b has increased to match that of active scene rotation. This result is also expected if we assume that participants are actually using the information we provided regarding the viewpoint shift (i.e. what their arm movements mean). Therefore, our instructions did not inflate recognition accuracy in general, they simply accounted for the difference between active and passive scene rotation.

In line with the prediction that participants are actually using their arm movements as an index of the magnitude of scene rotation, reaction times in this experiment are longer (about 2 seconds) than in Experiment 2a. This suggests that participants are taking additional time to consciously process what their arm movements mean in order to predict how the scene is changing. It is unclear, however, why reaction times following active scene rotation would also increase in this experiment. It is possible that participants in this experiment paid more attention in general, closely monitoring the relationship between their arm movements and how the scene changed both during the rotation, and once they removed the blindfold to view the scene.

The notion that active control over the viewpoint shift affords participants knowledge regarding the magnitude and direction of the shift can be interpreted in the context of literature which suggests that active control does not simply provide efference copies of motor commands. For example, Harman et al. (1999) have suggested that the benefit of active exploration of objects is that it enables participants to test predictions about how changes in viewpoint affect the appearance of the object (see also James, Humphrey, & Goodale, 2001). Under their model, participants who actively control viewpoint shifts can "hypothesize" about how an object will look from different views, and subsequently store trajectories that link the views to each other. These researchers concede that the same strategy can exist for passive rotations, but that the links produced by active control would be stored more effectively. In our design, active control over scene rotation would also allow participants to store information linking different views to one another, thus allowing them to predict how the scene is changing. Using their model as a framework, our results suggest that when participants can use their arm movements as an index of scene rotation, the link between views is stored equally well for both active and passive rotation, and does not necessarily require physical manipulation of the scene. Instead, explicitly knowing the magnitude and direction of the viewpoint shift is sufficient to link changing views to one another in order to anticipate how the scene will look following rotation.

To this point we have not yet speculated as to the actual mental process that is driving performance patterns in the case of scene rotations. While our results do not demonstrate the typical one-to-one linear relationship between viewpoint shift and reaction time that is seen in the object mental rotation literature (e.g. Shepard & Metzler, 1971; Shepard & Cooper, 1982), it is conceivable that participants in our study are exploiting a similar mental transformation strategy. Indeed, the angular-dependent linear decline in scene recognition performance shown here and in previous studies (Diwadkar & McNamara, 1997; Finlay, Motes, & Kozhevnikov, 2007) suggests that participants may use an analog of object mental rotation during instances of scene rotation. If we can accept that scene rotation relies on such a mental transformation process, another explanation for the benefit of active control is that it facilitates mental rotation of stored representations. The idea that motor processes and mental rotation are associated with one another has been suggested by numerous researchers. For example, Wolhschlager and Wolhschlager (1998) used a mental rotation task similar to that of Shepard and Metzler (1971) to show the relationship between manipulations of mental images and physical manipulations of actual stimuli. In typical mental rotation tasks, participants judge whether two objects rotated about some fixed axis are the same or different. Response times generally increase as a function of the angular difference between the two objects. Wolhschlager and Wolhschlager (1998) found that when participants physically rotated one object into alignment another, response times increased at approximately the same rate as during mental rotation. They also found that translational hand movements interfered with mental rotation if those hand movements occurred along an axis misaligned with that required for mental rotation. This suggests that motor rotation and mental rotation may rely on similar mental resources. The link between motor rotation and mental rotation has also been demonstrated by Wexler, Kosslyn, and Berthoz (1998). Using a typical Shepard-Metzler mental rotation task, they showed that when participants performed an unseen motor rotation of the hand that was in the same direction as mental rotation, response times were quicker than when the motor rotation occurred in the opposite direction of mental rotation. They also showed that the rate of motor rotation directly influenced the rate of mental rotation. In our task, arm movements were always along the same axis (and in the same direction) as scene rotation. Therefore, participants' arm movements likely did not interfere with their ability to mentally transform the scene. On the contrary, our results suggest that those arm movements, in conjunction with explicit knowledge about how they relate to the scene's rotation, actually facilitate mental rotation.

Returning to our investigation into the mechanism underlying the facilitative effect of locomotion, these results suggest that active control over the viewpoint shift may be one component of that effect. More specifically, actively controlling the viewpoint shift seems to provide participants with knowledge regarding the magnitude and direction of the shift. It is also possible that active control allows for efference copies of motor commands to be incorporated into individuals' representations. In terms of the facilitative effect of locomotion, this means that actively moving through the environment facilitates scene recognition since it provides individuals with knowledge regarding how far (and in what direction) they have moved. This knowledge, perhaps in conjunction with other factors (efference copy, increased attention, etc.), enables individuals to keep track of changing spatial relationships more easily when they locomote through the environment than when they remain stationary.

Despite the documented benefit of actively controlling a viewpoint shift on scene recognition, this may not be the only factor contributing to the facilitative effect of locomotion. Recall that in Chapter Two there was never any actual locomotion. Therefore, it is entirely possible that additional information acquired during locomotion facilitates scene recognition to a degree that exceeds simply having active control over the viewpoint shift. This is the focus of Chapter Three.

Chapter Three

This chapter further investigates the mechanism underlying the facilitative effect of locomotion. In particular, we explore the possibility that body-based cues acquired during locomotion improve scene recognition ability beyond that which is solely attainable with active control over the viewpoint shift. We also test the hypothesis that those body-based cues must be reliable and intact in order to improve scene recognition performance. Finally, we ask the question of whether or not the benefit of locomotion is attributable to an ability to remain oriented within one's environment during a viewpoint shift.

Experiment 3a

The idea that body-based cues available during locomotion improve spatial processing has been proposed by many researchers in the field of (visuo)spatial cognition/perception. In fact, some research suggests that body-based sources of information may be more important than visual information when it comes to spatial awareness. The overriding theory seems to be that body-based cues permit efficacious spatial updating during locomotion, which facilitates tracking of spatial relations. For example, Klatzky et al. (1998) used a triangle-completion task to examine how individuals update their position and heading direction when they are afforded different sources of spatial information. In their task, participants were exposed to a two-segment path with a turn between the segments. When experiencing the path, participants either physically walked along the path themselves, imagined walking from a verbal description, watched another individual walk, or received optic flow which simulated movement (with or without a physical turn between segments). In all cases participants were told to adopt the perspective of the person experiencing the path (either themselves or the individual they were watching). After they experienced the two-segment path, participants were required to turn to face the origin. Results showed that participants overturned by the angular magnitude between segments in the verbal description and watching conditions, whereas they were significantly more accurate in the walking condition. Simulated motion with optic flow was not sufficient to reduce overturning, yet optic flow with a physical turn between the paths mitigated the overturning bias. Researchers concluded that when proprioceptive cues are lacking, individuals fail to update an internal representation of heading that promotes accurate turning. These researchers also suggest that visual information in the absence of physical movement is not effective for spatial updating.

The importance of body-based information (i.e. proprioceptive, vestibular, etc.) on spatial updating has also been demonstrated by Chance, Gaunet, Beall, and Loomis (1998). In their task, participants travelled through virtual mazes and encountered target objects along the way. Movement through the maze occurred in one of three ways: In the *walk* condition, participants physically moved through the experimental room, with visual information being continuously updated through the head-mounted display based on the participants' position and orientation in the room. Participants in this condition controlled both rotational and translational movements. In the *visual turn* condition, participants stayed stationary and moved through the virtual environment using a joystick; thus only visual information was available in this condition. Finally, in the *real turn* condition, participants physically turned their bodies to create changes in orientation, yet translational movements were signalled by the computer-generated imagery. At the end of the maze, participants were required to indicate the direction to certain target objects. The primary result of this study was that participants' directional estimates were superior in the *walk* condition than in the *visual turn* condition. Also, estimates in the *walk* condition were better than in the *real turn* condition which, in turn, was better than the *visual turn* condition; however these results fell short of significance. Similar findings have been demonstrated in visual search tasks. For example, Pausch, Proffitt, and Williams (1997) found that participants were better able to keep track of items in their environment when the viewing direction was controlled by head turning than by a hand-held joystick. Collectively, these results suggest that proprioceptive and vestibular information acquired during physical movement are necessary in order to accurately update egocentric spatial relations.

Further evidence for the role of proprioceptive and vestibular information comes from studies examining individuals' ability to navigate without vision (i.e. path integration). Berthoz, Israel, Georges-Francois, Grasso, and Tsuzuku, (1995) were one of first groups of researchers to examine how movement is stored in memory. In their task, participants sat in a large rotatable/ translatable robot that they could manipulate by using a joystick. Participants were subjected to a passive linear displacement of various magnitudes. Following this movement, participants were signalled to reproduce the distance imposed by the robot without vision. The results showed that participants could accurately reproduce passive linear transport of a simple dynamic profile using only vestibular and somatosensory cues. In addition to accurately reproducing distance, participants were also able to reproduce entire velocity profiles (including durations). This suggests that, as opposed to a static representation of distance, the brain stores the dynamic properties of whole-body linear motion. Therefore, vestibular and somatosensory signals seem to allow real-time updating of individuals' position and orientation in space. Furthermore, it has been shown that distance estimations are not based on duration, peak velocity, or velocity profile, but rather are unique to stimulus distance (Israel, Grasso, Georges-Francois, Tsuzuku, & Berthoz, 1997). Even when velocity profiles are made impossible to reconstruct, distance is still accurately estimated (Grasso, Glasauer, Georges-Francois, Israel, 1999). These results suggest that the brain uses vestibular and somatosensory signals to build both static and dynamic representations of travelled paths. Finally, Brookes, Gresty, Nakamura, and Metcalfe (1993) have shown that healthy participants can accurately counter-rotate themselves back to an origin following random rotational displacements, yet patients with vestibular deficits are unsuccessful at this task.

The abovementioned studies support the hypothesis that body-based cues (proprioceptive, vestibular, somatosensory, etc.) available during movement are important for spatial updating. However, it is not clear whether body-based cues improve scene recognition to a degree that exceeds actively controlling the viewpoint shift alone. In this study, we examine whether locomotion facilitates scene recognition after controlling for the level of active control that participants are afforded over the viewpoint shift. This is accomplished by pairing locomotion conditions with a set of conditions in which participants actively rotate the scene (as in Chapter Two). Recall that actively controlling the viewpoint shift seems to provide participants with knowledge regarding the magnitude and direction of the shift (Experiment 2b). Therefore, to ensure that we have provided participants with matched active control in the locomotion and active scene rotation conditions, we have added a new feature to this experiment. Specifically, after undergoing a viewpoint shift of any kind, participants are required to verbally report (i.e. "predict") the magnitude and direction of the shift. This enables us to determine whether the knowledge participants have acquired – and hence the level of active control – is matched in the locomotion and active scene rotation conditions. We can then determine whether locomotion facilitates scene recognition ability beyond simply having active control.

Finally, we have incorporated a new set of *disorientation* conditions in this experiment. In these conditions, we disrupt participants' body-based cues during the retention phase, thereby making them unusable for spatial updating. This is achieved by moving participants around the testing environment in a complex path which consists of a number of rotations and translations. To ensure that we have successfully disoriented participants, we again use our verbal report feature; disorientation is indexed by participants' inability to accurately report where they are in the room. This entire experiment was conducted in a regular laboratory setting with numerous peripheral objects. The results of Experiment 1b suggest that these visual cues do not improve scene recognition performance. Instead, the purpose of conducting this experiment in a regular laboratory setting is to allow participants to determine the magnitude and direction of the viewpoint shift following disorientation by using visual cues in the environment to see where they are in the room. We can then determine whether reliable body-based cues that enable spatial updating are necessary for improving scene recognition when experiencing a viewpoint shift. Alternatively, it could be the case that participants do not require body-based cues to improve scene recognition, and rather that they can simply use visual cues in the environment to re-orient with the learning direction, which itself is sufficient to accurately recover object spatial relations.

Method

Participants

Fourteen undergraduate students (5 males and 9 females, 18-23 years of age [$M = 20$, $SD = 1.33$]) from McMaster University participated in return for course credit or monetary compensation. All participants reported normal or corrected-to-normal vision, and none had previous experience with spatial learning paradigms like the one presented here.

Materials, Apparatus, and Design

The materials and apparatus were essentially the same as that of our previous experiments. However, as in Experiment 1b, this experiment took place in a regular laboratory room with numerous peripheral objects. At any point when participants were not blindfolded, they could readily determine their position in the room. The lights were also turned up.

MATLAB 7.0 was used to generate 88 (four practice and 84 test) irregular spatial configurations wherein only two objects could be aligned with each other during each trial. The trials were split across two days (42 trials on each day, with the four practice trials on the first day only), such that participants completed half of the trials one day and the other half exactly one week later.

Unlike all of our previous experiments, this experiment included a disorientation mode (see introduction for Experiment 3a). To facilitate disorientation, this experiment utilized a swivel chair made by Ergo-Industrial Seating Systems Inc., which could be rotated and translated easily throughout the testing space. This seat was raised 50cm from the ground for all participants. The rest of the materials and apparatus were similar to that of Experiment 1b.

Procedure

Learning Phase. This was the same as all of our previous experiments.

Retention Phase. As in all previous experiments, the retention phase involved the change to the spatial layout (i.e. cup relocation), and the viewpoint shift. First, the experimenter moved one of the cups to a previously unoccupied position on the table. In this experiment, the viewpoint shift was achieved in one of four ways: (1) *No viewpoint shift.* For this experiment we employed two different control conditions. The *standard*-control condition was the same as that in Experiments 1a and 1b, and similar to the passive-control condition of

Experiments 2a and 2b. In this condition, participants remained completely stationary during retention and there was no scene rotation, locomotion, or disorientation. Therefore, there was no viewpoint shift in the standard-control condition. In the second control condition - the *disorientation*-control condition - participants were disoriented (explained below) and brought back to the learning position. As with the standard-control condition, participants did not experience a viewpoint shift. Comparing the standard-control and the disorientation-control conditions allows us to determine if disorientation is generally disruptive to participants' scene recognition ability, perhaps by degrading their spatial representations. (2) *Active scene rotation*: the participant remained stationary and rotated the scene themselves by one of the chosen magnitudes (i.e. 50°, 80°, 110°, or 160°). Scene rotation could be in a clockwise or counter-clockwise direction on any given trial. This was comparable to the procedure for the active scene rotation condition of Experiments 2a and 2b. Again, the number of table pulls required to achieve each magnitude of viewpoint shift was standardized across participants. (3) *Observer locomotion*: the participant walked to a novel viewing position around the table (i.e. 50°, 80°, 110°, or 160°), and the table was not rotated. Locomotion could be in a clockwise or counter-clockwise direction on any given trial. In this set of locomotion conditions, the participant sidestepped (guided by the experimenter) so that they always remained oriented with the display. (4) *Disorientation*: in all disorientation conditions, the blindfolded participant sat in a swivel chair and was then translated and rotated in a predetermined path in order to disrupt the body-based information that is usually gained during locomotion. Following this disorientation, the participant was placed at one of the matched viewing positions (i.e. 50°, 80°, 110°, or 160° relative to learning), or brought back to the learning position of 0° (i.e. in the case of the disorientation-control condition described above). Movement could be in the clockwise or counter-clockwise direction on any given trial. When the participant removed the blindfold during testing, they could readily determine the magnitude of the viewpoint shift by using visual cues in the room to determine their starting position and ending position. The asymmetry of the experimental room produced no ambiguity about where they were (and thus how much they moved) once they removed the blindfold and viewed the scene. For all disorientation conditions, we developed a set of 3 standardized paths (which could take place in either the clockwise or counter-clockwise direction). The disorientation path for each trial was randomly selected so as to prevent participants from learning which path resulted in a particular viewpoint shift.

For a complete list of the experimental conditions, see Table 3.

As in all previous experiments, participants were told that the table could rotate any magnitude on any given trial, but they were never instructed on a trial-by-trial basis as to the magnitude of scene rotation, observer locomotion, or disorientation. As in Experiments 2a and 2b, all retention periods were 15 seconds in length.

Table 3: Summary of Conditions for Experiment 3a

Condition	Magnitude of Viewpoint Shift (°)		Disorientation?	Overall Viewpoint Shift (°)
	Observer	Scene		
1. Standard-Control	0	0	No	0
2. Disorientation-Control	0	0	Yes	0
3. Scene Rotation of 50°	0	50	No	50
4. Locomotion to 50°	50	0	No	50
5. Disorientation 50°	50	0	Yes	50
6. Scene Rotation of 80°	0	80	No	80
7. Locomotion to 80°	80	0	No	80
8. Disorientation 80°	80	0	Yes	80
9. Scene Rotation of 110°	0	110	No	110
10. Locomotion to 110°	110	0	No	110
11. Disorientation 110°	110	0	Yes	110
12. Scene Rotation of 160°	0	160	No	160
13. Locomotion to 160°	160	0	No	160
14. Disorientation 160°	160	0	Yes	160

One new aspect of this experiment is the inclusion of a verbal report feature at the end of the retention phase. Following the viewpoint shift (whether caused by scene rotation, locomotion, or disorientation), participants were required to verbally estimate the magnitude and direction of the shift. The verbal report data allowed us to determine whether we had matched participants' knowledge regarding the magnitude and direction of the viewpoint shift in the active scene rotation and observer locomotion conditions, in addition to whether or not we had sufficiently disoriented participants in the disorientation condition.

Testing phase. This was the same as Experiment 1b, in which letters were used to demark the cups. The orientation of the letters was aligned with the learning direction, which further facilitated knowledge of the viewpoint shift once the blindfold was removed. Participants indicated the letter that corresponded to the cup that they believed was moved during retention.

Design. Each participant experienced 6 standard-control and 6 disorientation-control trials. They also experienced three viewpoint shift modes (active scene rotation, observer locomotion, and disorientation) across four viewpoint shift magnitudes (50°, 80°, 110°, 160°), each of which were experienced in two directions (clockwise and counter-clockwise), and all were repeated three times. In total, there were 84 trials (12 control + [3 modes x 4 magnitudes x 2 directions x 3 repetitions]). Trials were arranged into three blocks, with all conditions presented in a random order within each block. As mentioned above, trials were split across two days, with each testing session lasting approximately one hour.

Results

Verbal Report Analysis

We were interested in determining two primary effects from the verbal report data. The first was to determine whether we had matched the degree of active control that participants were afforded - and by extension, matched participants' knowledge regarding the direction and magnitude of the viewpoint shifts - in the active scene rotation and observer locomotion conditions. Second, we aimed to determine whether we had sufficiently disrupted participants' body-based information during the disorientation conditions (indexed by participants' inability to accurately report where they were in the room following disorientation). We performed a 3 (mode of viewpoint shift: active scene rotation, observer locomotion, and disorientation) x 4 (magnitude of viewpoint shift: 50°, 80°, 110°, 160°) repeated measures ANOVA on the verbal report data. The omnibus test of mode of viewpoint shift was significant, $F(2,26) = 10.17$, $MSE = 1233.2$, $p = 0.001$, but there was no effect of magnitude of viewpoint shift, $F(3,39) = 0.504$, $MSE = 874.3$, $p = 0.682$, and the interaction between mode and magnitude of viewpoint shift was also not significant, $F(3,39) = 1.46$, $MSE = 1008.1$, $p = 0.205$.

Since there was a significant omnibus test for mode of viewpoint shift, we examined the pairwise differences between active scene rotation, observer locomotion, and disorientation. A direct comparison of active scene rotation and observer locomotion revealed that participants were equally good at predicting the magnitude and direction of the viewpoint shift in both modes, $t(13) = -0.959$, $p = 0.355$, two-tailed. Alternatively, participants in the disorientation mode were relatively less precise at predicting the magnitude and direction of the shift, and were significantly worse compared to active scene rotation, $t(13) = 3.04$, $p =$

0.009, two-tailed, and compared to observer locomotion, $t(13) = 4.17$, $p = 0.001$, two-tailed (see Figure 11).

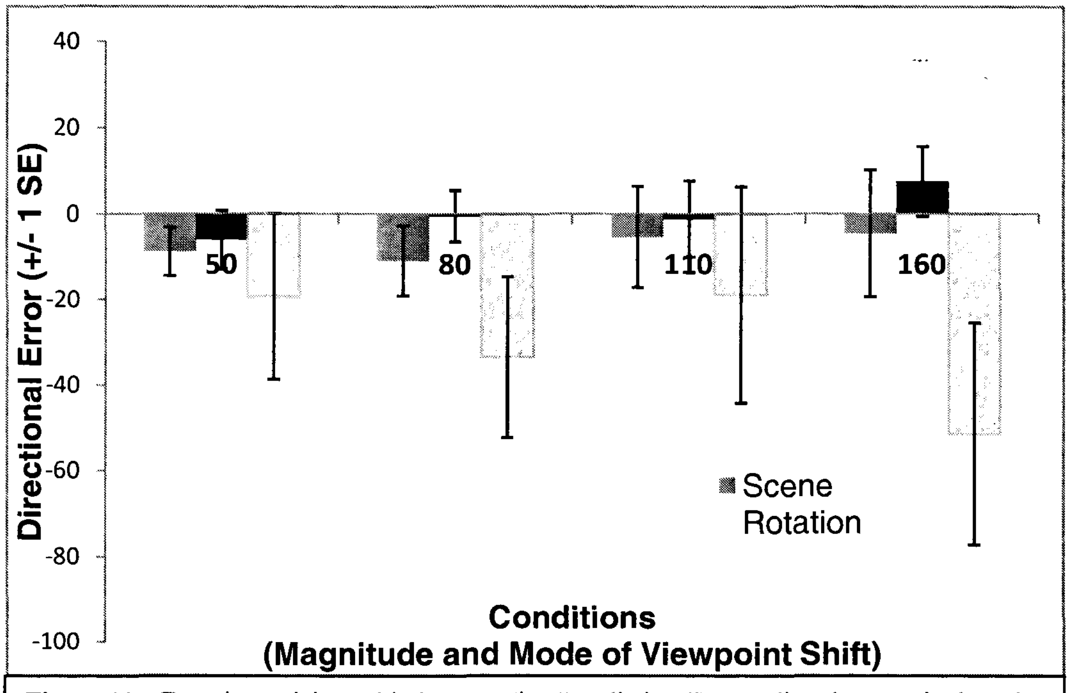

Figure 11 – Error in participants' judgments (i.e. "predictions") regarding the magnitude and direction of the viewpoint shift as a function of condition (i.e. mode and magnitude of viewpoint shift). Negative values represent underestimations of the viewpoint shift; positive values represent overestimations of the viewpoint shift. The x-axis represents zero error, or an exact prediction of the shift. Error bars represent between-subjects ± 1 standard error of the means (*SEM*s) computed from data points in each condition submitted to the analysis of variance.

Scene Recognition Analysis

We then examined participants' actual scene recognition performance, which was measured as the proportion of trials on which participants correctly identified which cup had moved during retention. We also measured reaction time for correct responses. An initial analyses including the sex of the participants as a between-subject factor did not reveal any differences. There was also no effect of direction of rotation (i.e. clockwise versus counter-clockwise). Therefore the data was collapsed across these variables for all subsequent analyses.

Preliminary Analysis with Control Conditions

We first examined whether or not there was a difference in performance between the standard-control condition (accuracy: $M = 0.77$, $SD = 0.23$; reaction time: $M = 6.40$, $SD = 1.49$) and the disorientation-control condition (accuracy: $M = 0.61$, $SD = 0.27$; reaction time: $M = 12.03$, $SD = 4.63$). Indeed, scene recognition was significantly better in the standard-control condition than the disorientation-control condition, both for proportion of correct judgments, $t(13) = 2.47$, $p = 0.028$, two-tailed, and for reaction time of correct responses, $t(13) = -5.76$, $p < 0.001$, two-tailed.

We then determined whether novel-view scene recognition was viewpoint dependent following active scene rotation, observer locomotion, and disorientation. A series of planned paired samples t-tests revealed that performance was significantly more accurate in the control condition ($M = 0.77$, $SD = 0.23$) than in any of the active scene rotation, observer locomotion, or disorientation conditions (all p's < 0.05). Participants' reaction time in the control condition ($M = 6.40$, $SD = 1.49$) was also quicker than in any of the scene rotation, locomotion, or disorientation conditions (all p's < 0.01). After this initial set of comparisons, we removed the control conditions from further analyses and focused on the differences between active scene rotation, observer locomotion, and disorientation across the different magnitudes of viewpoint shift.

Observer Locomotion vs. Active Scene Rotation vs. Disorientation

A 3 (mode of viewpoint shift: active scene rotation, observer locomotion, and disorientation) x 4 (magnitude of viewpoint shift: 50°, 80°, 110°, 160°) repeated measures ANOVA was conducted separately for the proportion of correct judgments and reaction time.

Accuracy

For the proportion of correct judgments, there was a significant main effect of mode of viewpoint shift, $F(2, 26) = 5.89$, $MSE = 0.042$, $p = 0.008$. The main effect of magnitude of viewpoint shift was not significant $F(3, 39) = 1.17$, $MSE = 0.044$, $p = 0.334$, nor was the interaction between mode and magnitude of viewpoint shift, $F(6, 78) = 0.580$, $MSE = 0.028$, $p = 0.745$.

Since there was a significant omnibus test for mode of viewpoint shift, we examined the pairwise differences between active scene rotation, observer locomotion, and disorientation. A direct comparison of active scene rotation and observer locomotion revealed that locomotion was significantly more accurate than active scene rotation across all tested viewpoint shifts, $t(13) = -4.35$, $p = 0.001$, two-tailed. On the other hand, scene recognition accuracy did not differ between active scene rotation and disorientation, $t(13) = -1.344$, $p = 0.202$, two-tailed, or between observer locomotion and disorientation, $t(13) = 1.77$, $p = 0.100$, two-tailed. However, an examination of the disorientation data revealed that scene recognition accuracy spiked at 160°. Since 160° is fairly close to 180° in our design, this spike in performance may signify a unique pattern of performance much like that which occurs at 180° (see Experiment 2a). For that reason, we removed 160° from the analysis to re-evaluate the differences between active scene rotation, observer locomotion, and disorientation. Again, observer locomotion resulted in significantly better scene recognition accuracy compared to active scene rotation, $t(13) = -3.42$, $p = 0.005$, two-tailed, and active scene rotation was no more accurate than disorientation, $t(13) = -0.519$, $p = 0.612$, two-tailed. However, by removing 160° from the analysis, observer locomotion resulted in superior scene recognition accuracy compared to disorientation, $t(13) = 2.311$, $p = 0.038$, two-tailed.

We then performed a linear trend analysis on the accuracy data to evaluate the hypothesis that the scores decrease linearly as the magnitude of viewpoint shift increases for active scene rotation, observer locomotion, and disorientation. There was a significant linear decline in change detection accuracy as the magnitude of active scene rotation increased, $t(13) = -3.35$, $p = 0.003$, one-tailed, and a marginally significant linear decline in accuracy as the magnitude of observer locomotion increased, $t(13) = -1.77$, $p = 0.050$, one-tailed. On the other hand, there was no linear decline in accuracy as the magnitude of disorientation increased, $t(13) = -0.080$, $p = 0.469$, one-tailed. Each of these results is plotted in Figure 12A.

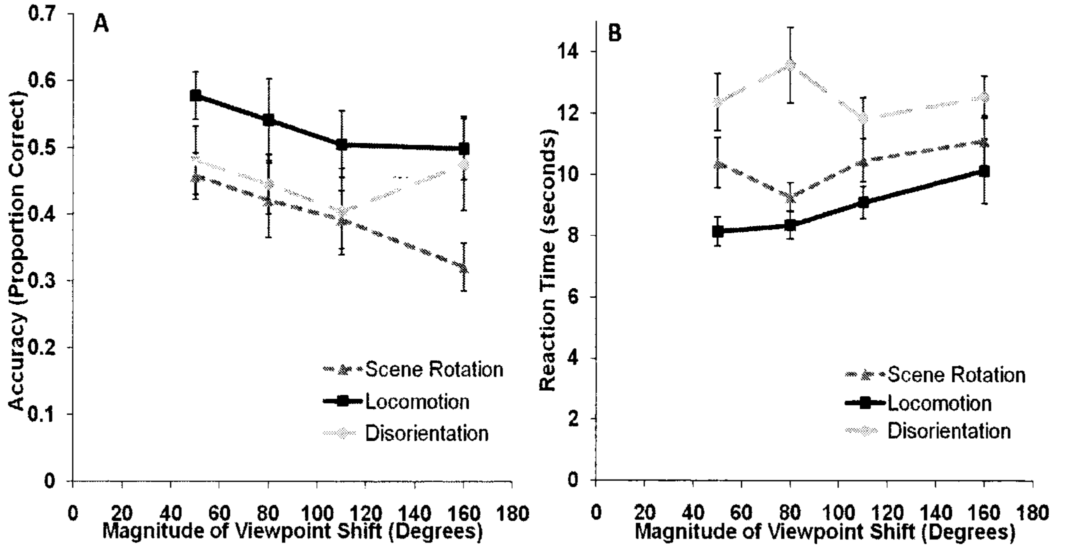

Figure 12 – Scene recognition performance as a function of magnitude and mode of viewpoint shift in Experiment 3a. The external environment was visible. Black line – observer locomotion; dark gray line – active scene rotation; light gray line - disorientation. (A) Scene recognition accuracy; (B) Reaction time on correct trials. Error bars represent between-subjects ± 1 standard error of the means (*SEM*s) computed from data points in each condition submitted to the analysis of variance.

Reaction Time

For reaction time of *correct* judgments, there was a significant main effect of mode of viewpoint shift, $F(2, 26) = 28.24$, $MSE = 6.67$, $p < 0.001$. Additionally, there was a nearly significant main effect of magnitude of viewpoint shift, $F(3, 39) = 2.73$, $MSE = 2.95$, $p = 0.057$, but the interaction between mode and magnitude of viewpoint shift was not significant, $F(6, 78) = 2.02$, $MSE = 4.65$, $p = 0.073$.

Since there was a significant omnibus test for mode of viewpoint shift, we examined the pairwise differences between active scene rotation, observer locomotion, and disorientation. A direct comparison of active scene rotation and observer locomotion revealed that locomotion was significantly quicker than active scene rotation across all tested viewpoint shifts, $t(13) = 3.071$, $p = 0.009$, two-tailed. Also, locomotion resulted in significantly quicker scene recognition compared to disorientation, $t(13) = -2.85$, $p < 0.001$. Active scene rotation was also significantly quicker than disorientation, $t(13) = -3.65$, $p = 0.003$.

We then performed a linear trend analysis to evaluate the hypothesis that reaction time increases as the magnitude of viewpoint shift increases for active scene rotation, observer locomotion, and disorientation. Reaction time increased linearly as the magnitude of active scene rotation increased, $t(13) = 1.78$, $p = 0.049$, one-tailed. There was also a significant linear increase in reaction time as the magnitude of observer locomotion increased, $t(13) = 1.96$, $p = 0.036$. There was no apparent increase in reaction time for disorientation, $t(13) = -0.362$, $p = 0.638$. These results are plotted in Figure 11B.

Discussion

We should first note that the results of this experiment are consistent with our previous findings with respect to viewpoint-dependency and performance trends. Specifically, scene recognition was more accurate and quicker when no viewpoint shift was experienced compared to any magnitude of locomotion, active scene rotation, or disorientation. This suggests that scene recognition is viewpoint-dependent. Also, scene recognition accuracy declined linearly, and reaction time increased linearly, as the magnitude of viewpoint shift increased for both locomotion and active scene rotation. This result parallels our previous contention that scene recognition difficulty increases as the magnitude of viewpoint shift increases.

The primary aim of this experiment was to determine whether body-based cues available during locomotion facilitate scene recognition by an amount that exceeds simply having active control over the viewpoint shift. First and foremost, we employed a novel verbal report feature which required participants to indicate the magnitude and direction of the viewpoint shift after undergoing any amount of locomotion, active scene rotation, or disorientation (but before viewing the scene). Analyses of these verbal reports showed that participants were equally proficient at estimating the magnitude and direction of the viewpoint shift in the locomotion and active scene rotation conditions. This suggests that the knowledge participants acquired regarding the viewpoint shift was approximately matched in the locomotion and active scene rotation conditions. Recall that active control over the viewpoint shift provides participants with knowledge regarding the magnitude and direction of the shift (see Experiment 2b). Therefore, since participants' knowledge about the shift was matched across the locomotion and active scene rotation conditions, we are confident that the degree of active control they had in each of those conditions was relatively equivalent. Given similar levels of active control over the viewpoint shift, we examined whether locomotion still conferred a scene recognition advantage compared to active scene rotation. Results showed that recognition performance following locomotion was both significantly more accurate and quicker than active scene rotation across a wide range of viewpoint shifts. This suggests that body-based cues acquired during locomotion facilitate scene recognition beyond actively controlling the viewpoint shift alone. Therefore, while active control over the viewpoint shift may be one component of the facilitative effect of locomotion (see Chapter Two), a second component of that effect seems to be receiving body-based cues that promote updating of spatial relations. On the other hand, the proprioceptive and somatosensory cues gained during active scene rotation do not appear to be as effective in promoting efficacious spatial updating.

The second function of this experiment was to confirm the importance of body-based cues for spatial updating by making those cues unreliable/unusable. We accomplished this by employing a set of disorientation conditions which were meant to disrupt the body-based cues that are usually available during locomotion. First, our verbal report data shows that participants were unable to accurately indicate where they were in the testing environment following disorientation. Participants were significantly less precise at predicting the magnitude and direction of the viewpoint shift following disorientation than in both the locomotion and active scene rotation conditions. Since participants were far less accurate at predicting the viewpoint shift following disorientation compared to locomotion (i.e. when those cues were intact), this suggests that we successfully disrupted participants' body-based cues in the disorientation conditions. Similarly, performance in the standard-control condition was significantly more accurate and faster than in the disorientation-control condition. This further strengthens the claim that we successfully disrupted participants' body-based cues during disorientation. However, this may also be indicative that the disorientation procedure was *too* arduous for participants and may have affected their ability to retain or accurately recall spatial relationships. This is accounted for in Experiment 3b.

An examination of participants' actual scene recognition performance revealed that recognition was both more accurate and faster following locomotion than it was following disorientation across our selected viewpoint shifts. When we removed 160° - an angle close to 180°, which is known to result in inflated recognition performance - from the analysis, the difference in scene recognition accuracy between locomotion and disorientation became even more substantial. In fact, scene recognition accuracy following disorientation was no better than that following active scene rotation. Another important result comes from the reaction time data. Reaction times following disorientation were significantly longer than both locomotion and active scene rotation. This result makes sense if we consider the nature of the disorientation conditions. Recall that during the locomotion and active scene rotation conditions participants were receiving information regarding the magnitude and direction of the viewpoint shift during the retention phase. On the other hand, in the disorientation conditions participants did not receive any information regarding the viewpoint shift during retention; they were simply being disoriented. The only time participants received any knowledge about the viewpoint shift in the disorientation conditions was after they removed the blindfold to view the scene. The high reaction times in the disorientation conditions suggest that participants may have been taking additional time to figure out where they were in the testing room - and hence the magnitude and direction of the viewpoint shift - once they removed the blindfold. Nevertheless, this "re-orienting" was not sufficient for improving scene recognition accuracy. Collectively, these results suggest that body-based cues available during locomotion do indeed facilitate scene recognition ability; and when those cues are unreliable/unusable, scene recognition suffers. Critically, re-orienting with the learning direction does not appear to alleviate the scene recognition deficit following disorientation. This highlights the importance of receiving online body-based information during viewpoint shifts. The latter abstraction is explored further in Experiment 3b.

The notion that body-based cues available during locomotion are important for facilitating scene recognition is consistent with the results of studies which have used paradigms similar to ours (e.g. Simons & Wang, 1998; Simons, Wang, & Roddenberry, 2002; Wang & Simons 1999). However, as far as we know, we are the first group of researchers to systematically show that locomotion facilitates scene recognition after controlling for the level of active control that participants have over the viewpoint shift. Most past studies have ignored the influence of active control on spatial performance due to findings that suggest active control alone does not confer any benefit (Wang & Simons, 1999). We have successfully shown that active control itself may improve scene recognition (Chapter Two), but that body-based cues gained during movement are particularly important to facilitate recognition performance. Similar findings have been reported by Wraga, Creem-Regehr, and Proffitt (2004). These researchers used an immersive virtual reality setup to compare updating performance during observer movement and scene movement conditions when optical information was continuously present. In their task, participants were required to search for objects (e.g. "Find the chicken") in a virtual room either by rotating themselves about the display, or by using a joystick to rotate the room. Results showed that participants responded faster and made fewer errors in the observer movement condition than in the scene rotation condition at all angles along a Cartesian axis (i.e. 0°, 180°, 90°, 270°). In line with the results of previous studies, this suggests that proprioceptive inputs, as well as vestibular inputs specifying angular body acceleration, are important for locating objects in the observer movement condition. Alternatively, haptic information elicited from joystick rotation during scene rotation was not as effective in allowing individuals to update the locations of objects. In a second experiment, Wraga et al. (2004) tested whether active control of observer movement resulted in superior spatial performance compared to passive movement. In the active condition, participants sat in a rotatable chair and searched the room by rotating the chair themselves. Participants in this condition were afforded proprioceptive inputs from the soles of the feet, the legs, and changes in pressure on the skin's surface, as well as vestibular inputs and efference copies of motor commands. In the passive condition, seated participants were rotated by the experimenters. Participants in this condition received vestibular inputs, as well as some proprioceptive inputs relating to changes in pressure on the skin's surface. No efference copies of motor commands were available in the passive condition. Results showed that passive rotation resulted in significantly slower updating performance compared to active rotation. However, error rates in the active and passive conditions were similar. These researchers concluded that the proprioceptive and vestibular inputs common to both active and passive movement play a more critical role in spatial updating than do efference copies of motor commands (which are only available in the active condition). The importance of body-based cues on spatial updating has also been demonstrated by Simons and Wang (1998, Experiment 3), who showed that scene recognition accuracy declines when proprioceptive and vestibular information are disrupted in a rigorous and unpredictable disorientation procedure. Despite the abovementioned findings, however, we present the first evidence that body-based cues available during locomotion improve spatial ability compared to scene rotation after equating levels of active control. Our results support the contention that proprioceptive and vestibular inputs may be more influential to spatial updating than efference copies of motor commands. In the context of our previous findings, while active control can improve scene recognition by virtue of the information it provides regarding the magnitude and direction of the viewpoint shift, body-based inputs from physical movement may be more important for spatial updating.

In summary, the results of this experiment suggest: (1) that body-based cues (i.e. proprioceptive, vestibular, somatosensory, etc.) acquired during locomotion facilitate scene recognition performance beyond that which is solely achieved with active control over the viewpoint shift (which may include efference copies of motor commands, knowledge about the viewpoint shift, increased attention, etc.); and (2) that those cues must be reliable and undisrupted, and that re-orienting with the learning direction following a viewpoint shift is not sufficient for improving scene recognition. However, the latter result contains a potential confound. It is unclear whether poor performance following disorientation is actually a result of disrupted body-based cues, or due to a lack of knowledge regarding the viewpoint shift. Recall that participants never received any information regarding the magnitude and direction of the viewpoint shift during the retention phase in the disorientation conditions. It could be the case that receiving information about the viewpoint shift during retention (i.e. online during a viewpoint shift) is critically important to the facilitative effect of locomotion. This is the focus of Experiment 3b.

Experiment 3b

The results of Experiment 3a suggest that body-based cues available during locomotion must be intact and reliable in order to confer a scene recognition advantage when experiencing a viewpoint shift. However, it is possible that the performance deficit in the disorientation conditions was not a result of disrupted body-based cues *per se*, but rather a consequence of not receiving any information regarding the magnitude and direction of the viewpoint shift during the retention phase. More specifically, while *re-orienting* with the learning direction following a viewpoint shift may not be sufficient to facilitate scene recognition (Experiment 3a), it is possible that *remaining oriented* via continuous online information about one's position and orientation could mitigate the performance deficit for disorientation. Alternatively, remaining oriented with the learning direction in the absence of reliable body-based cues may still be insufficient for updating spatial relations.

Evidence for the benefit of a continuous, online updating process comes from studies that examine the automatic, reflex-like nature of spatial updating during movement (e.g. Farrell & Robertson, 1998; Rieser, 1989). For example, Farrell and Robertson (1998) used a design similar to Rieser (1989) to explicitly examine the automaticity of spatial updating. In their task, participants learned the spatial locations of objects in a room. Participants were then blindfolded and underwent a viewpoint shift that was caused by either physical rotation (updating condition), imagined rotation (imagined condition), or physical rotation with instructions to ignore that rotation (ignoring condition). Participants were then required to point to surrounding objects. Results showed that there was a linear increase in pointing error as the angular deviation from learning increased for the updating condition. More importantly, in both the imagined and ignoring conditions there was a curvilinear increase in error as the angular deviation from learning increased. This suggests that individuals have difficulty ignoring their body cues when rotating, and thus that spatial updating is a relatively automatic process. Furthermore, Rieser (1989) has shown that response times for spatial updating are independent of the magnitude of self-rotation. Collectively, these results suggest that updating occurs in tandem with movement (see also Wraga et al., 2004). These findings underscore the importance of receiving online body-based information during locomotion.

Further support for the benefit of receiving continuous, online information during viewpoint shifts comes from studies examining the dissociation of egocentric and allocentric spatial representations. In a series of experiments by Wang and Spelke (2000), participants learned the locations of objects in a room and were subsequently required to point to them while blindfolded. Participants pointed to these unseen targets either after remaining oriented or after disorientation by self-rotation. Results showed that participants' pointing judgments were significantly impaired by disorientation. Importantly, disorientation itself did not seem to degrade participants' representations due to vestibular disturbance since the same performance impairments were present after an ample recovery period. The most interesting findings of Wang and Spelke (2000), however, come from their examination of the factors that reduced pointing errors (i.e. improved performance) during disorientation. Specifically, these researchers showed that pointing errors were attenuated when participants were provided with a directional cue (a light) that enabled them to continually remain oriented within the room during self-rotation. On the other hand, when the light was only available after the disorientation procedure, participants' pointing responses were still impaired despite an ability to re-orient with the light. Although there are obvious task differences between our design and that of Wang and Spelke (2000), the results of our Experiment 3a are fairly consistent with theirs. Like the results of Wang and Spelke (2000), our disorientation procedure also reduced participants' spatial performance (i.e. scene recognition ability). Likewise, re-orienting within the room upon removal of the blindfold did not improve scene recognition accuracy in our task, despite the fact that participants attempted such re-orientation. It follows that – like the participants of Wang and Spelke (2000) - participants in our experiment may benefit from receiving continuous orienting information during disorientation.

In this experiment, we replicated the locomotion and disorientation conditions from Experiment 3a with some important changes. First, we made the disorientation procedure less rigorous. Participants were still wheeled to a new position via a combination of rotations and translations, however this series of movements was more gentle. The idea behind this was to still disrupt participants' body-based cues, but not to overwhelm them with the complex motion experienced in Experiment 3a. Second, we attempted to provide participants with online knowledge about the viewpoint shift during the retention phase of the disorientation conditions. Whereas in Experiment 3a participants were wheeled all over the testing area and could not determine their position or orientation, in this experiment we restricted the direction of their movement to one side of the table. This gave participants knowledge about the direction of the viewpoint shift during the retention phase. Also, we enabled participants to remain oriented within the environment during retention. This was accomplished by mounting a fluorescent light above participants' heads at the learning position. To assure that this light was salient, the entire experiment was conducted in the dark 10-sided room used in our previous experiments. Participants also wore translucent goggles which prevented them from seeing the spatial scene, but allowed them to detect brightness gradients. When participants were wheeled around the room during disorientation, they could continually remain oriented with the learning position by virtue of the gradient provided by the fluorescent light. This allowed participants to know their orientation and approximate location within the testing room during the retention phase of the disorientation conditions. In that regard, we believe that we closely matched the information participants received regarding the viewpoint shift during the retention phase of locomotion and disorientation.

By providing participants with online information regarding their position and orientation during disorientation, we can determine whether the performance deficits following disorientation in Experiment 3a are attributable to disrupted body-based cues, or a lack of online knowledge regarding the magnitude and direction of participants' displacement in the room. If body-based cues available during locomotion are essential for updating spatial relations, we would still expect to see a scene recognition advantage following locomotion compared to disorientation (wherein those cues are disrupted despite an ability to remain oriented). Alternatively, if the facilitative effect of locomotion is simply attributable to an ability to remain oriented with the environment, we would not expect to see a performance difference between locomotion and disorientation conditions.

Method

Participants

Sixteen undergraduate students (4 males and 12 females, 18-23 years of age [$M = 20$, $SD = 1.40$]) from McMaster University participated in return for course credit or monetary compensation. All participants reported normal or corrected-to-normal vision, and none had previous experience with spatial learning paradigms like the one presented here.

Materials, Apparatus, and Design

The materials and apparatus were similar to that of our previous experiments. The experiment was conducted in the symmetrical 10-sided room with the lights turned down. We used the same Styrofoam cups as spatial stimuli. We also used the same swivel chair as in Experiment 3a for conditions in which participants were wheeled to a new viewpoint. Additionally, there were a couple of new features in this experiment. First, we mounted a fluorescent light tube (a Globe® 12" T5 Fluorescent Utility Light) on the ceiling of the 10-sided room, right above the learning position. Also, instead of wearing a blindfold during phases of the experiment where the scene was meant to be occluded, participants wore goggles with translucent lenses. These goggles prevented participants from seeing objects in the room (including the spatial scene) but allowed them to detect brightness gradients. As the participant moved throughout the room, the changing light gradient from the fluorescent light gave them information about their orientation and approximate location within the testing environment.

MATLAB 7.0 was used to generate 124 (four practice and 120 test) irregular spatial configurations wherein only two objects could be aligned with each other during each trial. The trials were split across two days (60 trials on each day, with the four practice trials on the first day only), such that participants completed half of the trials one day and the other half exactly one week later. Otherwise, the materials and apparatus were the same as that of Experiment 3a.

Procedure

Learning phase. This was the same as all of our previous experiments.

Retention Phase. First and foremost, as in all previous experiments, one cup was moved to a previously unoccupied position on the table. Next, there were three viewpoint shift modes: (1) *No viewpoint shift.* This mode included the same two control conditions as Experiment 3a – that is, the standard-control condition and the disorientation-control condition. (2) *Observer Locomotion*: this was the same as our previous locomotion conditions, with the exception of the magnitudes of viewpoint shift that were chosen (50°, 80°, 130°, 160°, and 180°). Locomotion could be in a clockwise or counter-clockwise direction on any given trial (3) *Disorientation*: even though this mode was meant to be an extension of the disorientation mode from Experiment 3a, it is not completely appropriate to call it "disorientation" anymore since participants can in fact remain oriented with the environment throughout this experiment. For simplicity and consistency, however, we will continue to call it disorientation. Similar to Experiment 3a, participants sat in the swivel chair and were translated and rotated in a predetermined path in order to disrupt the body-based cues that are typically acquired during locomotion. However, there are a few important differences between this mode and the disorientation mode of Experiment 3a. First, in this experiment we restricted the participants' direction of movement to one side of the table. This gave participants knowledge of the direction of the viewpoint shift. Second, we made the wheeling motion less rigorous than in Experiment 3a, thereby decreasing any anxiety and/or dizziness that may have arisen. Finally, instead of wearing a blindfold and thus being unable to gauge their position and orientation in the testing room, participants in this experiment were able to use the light gradient provided by the fluorescent light in order to remain oriented with the learning direction during movement. This manipulation gave participants knowledge about their orientation and approximate location in the room during the retention phase (i.e. online during the viewpoint shift).

Test Phase. Following the viewpoint shift (or lack thereof), the participant identified the cup that they believed was moved during retention. The cups were demarked with coloured circles as described in Experiment 1a.

Design. Each participant experienced 10 standard-control and 10 disorientation-control trials. They also experienced two viewpoint shift modes (observer locomotion and disorientation) across five viewpoint shift magnitudes (50°, 80°, 130°, 160°, and 180°), each of which were experienced in two directions (clockwise and counter-clockwise), and all were repeated five times. In total, there were 120 trials (20 control + [2 modes x 5 magnitudes x 2 directions x 5 repetitions]). Trials were arranged into five blocks, with all conditions presented in a random order within each block. As mentioned above, trials were split across two days, with each testing session lasting approximately one hour.

Results

Scene recognition (i.e. change detection) performance was measured as the proportion of trials on which participants correctly identified which cup had moved during retention. We also measured reaction time for correct responses. An initial analyses including the sex of the participants as a between-subject factor did not reveal any differences. There was also no effect of direction of rotation (i.e. clockwise versus counter-clockwise). Therefore the data was collapsed across these variables for all subsequent analyses.

Preliminary Analysis with Control Condition

We first determined whether novel-view scene recognition was viewpoint dependent following observer locomotion and disorientation. A series of planned paired samples t-tests revealed that accuracy in the control condition ($M = 0.84$, $SD = 0.13$) was significantly more accurate than in any of the observer locomotion or disorientation conditions (all p's < 0.01). Reaction time in the control condition ($M = 5.16$, $SD = 0.90$) was also quicker than in any of the observer locomotion or disorientation conditions (all p's < 0.05). After this initial set of comparisons, we removed the control condition from further analyses and focused on the differences between observer locomotion and disorientation across the different magnitudes of viewpoint shift.

Observer Locomotion vs. Disorientation

A 2 (mode of viewpoint shift: observer locomotion versus disorientation) x 5 (magnitude of viewpoint shift: 50°, 80°, 130°, 160°, 180°) repeated measures ANOVA was conducted separately for the proportion of correct judgments and reaction time.

Accuracy

For the proportion of correct judgments, there was a significant main effect of mode of viewpoint shift, with participants responding more accurately following locomotion than disorientation, $F(1, 15) = 21.0$, $MSE = 0.035$, $p < 0.001$. The main effect of magnitude of viewpoint shift neared significance, but did not reach it, $F(4, 60) = 2.14$, $MSE = 0.023$, $p = 0.087$. Also, the interaction between mode and magnitude of viewpoint shift was not significant, $F(4, 60) = 0.079$, $MSE = 0.039$, $p = 0.998$.

We then performed a linear trend analysis to evaluate the hypothesis that the scores decrease linearly as the magnitude of viewpoint shift increases for both observer locomotion and disorientation. There was a not a significant linear decline in change detection accuracy as the magnitude of observer locomotion increased, $t(15) = -1.04$, $p = 0.158$, one-tailed, or as the magnitude of viewpoint shift increased for disorientation, $t(15) = -0.758$, $p = 0.230$, one-tailed. Each of these results is plotted in Figure 13A.

Reaction Time

For reaction time of *correct* judgments, there was a significant main effect of mode of viewpoint shift, with participants responding quicker following observer locomotion than disorientation, $F(1, 12) = 7.91$, $MSE = 1.17$, $p = 0.016$. Additionally, the main effect of magnitude of viewpoint shift was very close to significance, $F(4, 48) = 2.52$, $MSE = 1.16$, $p = 0.053$. The interaction between mode and magnitude of viewpoint shift was not significant, $F(4, 48) = 0.656$, $MSE = 1.17$, $p = 0.625$.

We also performed a linear trend analysis to evaluate the hypothesis that reaction time increases as the magnitude of viewpoint shift increases for both observer locomotion and disorientation. Reaction time increased linearly as the magnitude of locomotion increased, $t(14) = 1.83$, $p = 0.044$, one-tailed. There was also a significant linear increase in reaction time as the magnitude of viewpoint shift increased following disorientation, $t(12) = 2.19$, $p = 0.024$. These results are plotted in Figure 13B.

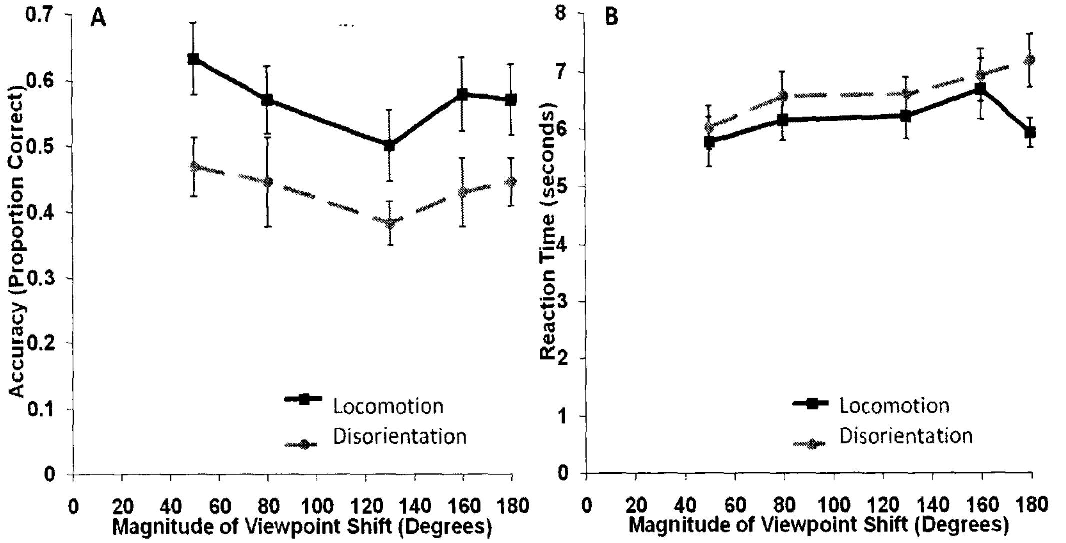

Figure 13 – Scene recognition performance as a function of magnitude and mode of viewpoint shift in Experiment 3b. The external environment was removed and a fluorescent light was mounted above the learning position. Black line – observer locomotion; gray line – disorientation. (A) Scene recognition accuracy; (B) Reaction time on correct trials. Error bars represent between-subjects ± 1 standard error of the means (*SEMs*) computed from data points in each condition submitted to the analysis of variance.

Discussion

This experiment extended the findings of Experiment 3a by resolving the ambiguity surrounding the performance deficits following disorientation. In particular, we examined whether poor scene recognition performance following disorientation was a result of disrupted body-based cues, or whether it was attributable to receiving insufficient online information regarding the viewpoint shift. We first substantiate our previous results which suggest that scene recognition is viewpoint-dependent. The results of this experiment also support our previous findings which show that scene recognition accuracy declines, and reaction time increase, as the magnitude of viewpoint shift increases. This supports the notion that scene recognition becomes progressively more difficult as the magnitude of viewpoint shift increases. Most importantly, however, the results show that scene recognition performance following locomotion was significantly more accurate and quicker than disorientation across our selected viewpoint shifts. Therefore, even when participants were afforded online knowledge regarding their orientation and approximate position in the environment, their scene recognition ability was still worse following disorientation compared to locomotion. Since participants' body-based cues were still unusable for spatial updating during the disorientation conditions, these results suggest that those cues must be reliable and intact during locomotion in order to facilitate scene recognition. These results also suggest that remaining oriented within one's environment during a viewpoint shift is not sufficient for improving scene recognition; and by extension, remaining oriented cannot account for the facilitative effect of locomotion. These results highlight the importance of having accessible body-based cues during locomotion in order to update spatial relations.

This experiment provides thorough support for the importance of body-based cues (i.e. proprioceptive, vestibular, somatosensory, etc.) on spatial updating during locomotion (see also Berthoz et al., 1995; Chance et al., 1999; Grasso et al.,1999; Israel et al., 1997; Klatzky et al., 1998; Simons & Wang, 1998;

Wang & Simons, 1999; Wraga et al., 2004). While this finding itself is not novel, we provide some of the first evidence demonstrating that there is something special about body-based cues beyond their impact on orientating that facilitates scene recognition. Our results challenge the idea that updating of spatial relations is simply a matter of remaining oriented with one's environment (e.g. Rieser, 1989), or remaining oriented with a particular reference direction (Mou, McNamara, Valiquette, & Rump, 2004). According to Mou et al. (2004), individuals establish an orientation-dependent spatial reference system which is comprised of a small number of dominant reference directions (usually two orthogonal axes). During locomotion, observers update their orientation with respect to the dominant spatial reference direction. Their model is as follows: individuals represent inter-object spatial relations with respect to a specific reference direction in the scene (Mou & McNamara, 2002; Mou Xiao, & McNamara, 2008). When the arrangement of objects is random (like that used in the current study), the dominant reference direction is the learning direction (Shelton & McNamara, 2001; Mou, Liu, & McNamara, 2009; Mou, Zhang, & McNamara, 2009). Mou et al. (2004) propose that individuals update their orientation during locomotion with respect to the same reference direction used to represent inter-object relations. In our experiment, this means individuals would update their orientation with respect to the learning direction. However, our results show that even when individuals are able to remain oriented with the learning direction by using a brightness gradient that informs them of their position and orientation, scene recognition is still inhibited by the absence of reliable body-based cues. In the framework of Mou et al. (2004), our results suggest that it is the presence of body-based cues themselves that is required for efficacious spatial updating, and not simply an ability to remain oriented with the dominant reference direction.

Keep in mind that, in addition to remaining oriented with the learning direction during the retention phase, participants in our study could also use the light to *re-orient* with the learning direction upon removal of the blindfold. Since the learning direction is the same as the dominant reference direction in our study, re-orienting is functionally equivalent to recovering the spatial reference direction (Mou et al., 2004). Mou, Zhang, and McNamara (2009) have recently proposed that locomotion facilitates scene recognition since it enables individuals to recover the spatial reference direction more precisely than scene rotation. In their study (which was similar to ours) participants learned a random spatial arrangement of objects on a circular table. Participants were then blindfolded and one of the objects was relocated. Concurrent with this change, participants either locomoted to a new viewing position, or they remained stationary and the scene was rotated. After this viewpoint shift, the experimenters placed a chopstick in the centre of the table which explicitly indicated the original learning direction (i.e. the reference direction). Participants then removed the blindfold and indicated which object had moved. The results showed that participants' scene recognition performance was equally accurate in the locomotion and scene rotation conditions when the chopstick was present. Basically, as long as individuals could recover the spatial reference direction (i.e. the learning direction), scene recognition performance was enhanced. Recall that in our study the fluorescent light tube was mounted at the learning position. Like the chopstick use by Mou, Zhang, and McNamara (2009), this provided participants with an explicit indication of the learning direction. Despite this information, participants' scene recognition ability was still impeded when they were unable to use body-based cues during disorientation. These results, in conjunction with those of Experiment 3a, suggest that simply recovering the reference direction (or re-orienting with the learning position) is not sufficient for improving scene recognition following a viewpoint shift (see also Greenauer & Waller, 2008). One explanation for this divergence of results is that our light may have been less salient than the chopstick used by Mou, Zhang, and McNamara (2009) since it was located outside the actual spatial scene. Nevertheless, it was plainly evident to the experimenters that participants were attempting to use the light to re-orient with the learning direction upon removal of the blindfold. Another possible explanation for the difference in results between our study and those of Mou, Zhang, & McNamara (2009) is that they used unique objects and a single viewpoint shift during experimentation. It is possible that these experimental manipulations differentially influence scene recognition in the presence of a cue indicating the learning direction (see General Introduction). Further research is needed to determine the conditions in which recovery of the spatial reference direction is sufficient for improving scene recognition ability.

General Discussion

The cognitive processes involved in the formation, maintenance, and retrieval of spatial representations are essential for everyday functioning. However, egocentric spatial representations are rarely static since individuals are constantly moving through their environment (i.e. locomotion), or objects in the environment are shifting in front of their eyes (e.g. scene rotation). Whenever an individual undergoes a viewpoint shift - a change in angular viewing perspective - the spatial relations between themselves and objects in the environment invariably changes. The ability to recognize whether a spatial scene is the same or different from a novel viewpoint is reduced when an individual locomotes around the scene and when the scene rotates in front of a stationary observer (e.g. Christou & Bulthoff, 1999; Diwadkar & McNamara, 1997; Burgess et al., 2004; Finlay et al., 2007; Mou, Zhang, & McNamara, 2009; Wang & Simons, 1999). However, the cost of undergoing a viewpoint shift is less for observer locomotion compared to scene rotation (e.g. Burgess et al., 2004; Mou, Zhang, & McNamara, 2009; Simons & Wang, 1999; Wang & Simons, 1999). This difference in scene recognition ability between viewpoint shifts caused by locomotion and scene rotation is called the facilitative effect of locomotion. This dissertation aimed to investigate the general characteristics associated the facilitative effect of locomotion, as well as the potential mechanism underlying its existence.

In Chapter One, we investigated whether the facilitative effect of locomotion is robust across a wide range of viewpoint shifts. In contrast to recent findings by Mou, Zhang, & McNamara (2009), the results of Experiment 1a suggest that the facilitative effect of locomotion is indeed robust across both small and large viewpoint shifts. The results also suggest that scene recognition is viewpoint-dependent, and that scene recognition becomes progressively more difficult as the magnitude of viewpoint shift increases. Next, in Experiment 1b we explored whether visual cues in the surrounding environment improve scene recognition ability, and if those cues exacerbate the facilitative effect of locomotion. Our results showed that visual cues in the environment do not improve scene recognition performance in general, although they may have the effect of increasing variability in participants' responses. Additionally, in contrast to the results of Lehman et al. (2009), our results suggest that visual cues do not exacerbate the scene recognition accuracy advantage for locomotion compared to scene rotation. In general, it does not appear as though visual cues in the environment contribute much to scene recognition in our paradigm.

Given that the facilitative effect of locomotion is real and robust, Chapter Two began our investigation into the mechanism underlying that effect. Specifically, we examined whether the facilitative effect of locomotion could be attributed to participants having active control over the viewpoint shift. In contrast to the results of Wang & Simons (1999), the results of Experiment 2a showed that actively controlling the viewpoint shift alone (i.e. in the absence of locomotion) confers a scene recognition advantage compared to passively experiencing the shift; and this advantage could not be attributed to a difference in processing times. Experiment 2b then investigated the nature of the benefit of active control. The results of Experiment 2b showed that when participants are provided with knowledge regarding the magnitude and direction of the viewpoint shift in both the active and passive conditions, the accuracy advantage for active control disappeared. This suggests that the benefit of active control may involve receiving knowledge regarding the magnitude of direction of the viewpoint shift. Collectively, the results of Chapter Two suggest that one component of the facilitative effect of locomotion may be actively controlling the viewpoint shift; and more specifically, acquiring knowledge regarding the magnitude and direction of one's movement.

Chapter Three then aimed to determine whether body-based cues available during locomotion facilitate scene recognition to a degree that exceeds actively controlling the viewpoint shift. The results of Experiment 3a showed that, after controlling for the level of active control that participants were afforded, scene recognition was still more accurate and faster following locomotion than active scene rotation. In addition, locomotion resulted in superior scene recognition performance compared to disorientation, in which participants' body-based cues were disrupted. Collectively, these results suggest that body-based cues available during locomotion are essential for updating spatial relations. Indeed, these cues may be more important than efference copies of motor commands which are available during active control (see Wraga et al., 2004). Finally, Experiment 3b explored a potential confound in Experiment 3a – that is, whether the performance deficit following disorientation was actually a result of disrupted body-based cues, or whether it was due to receiving inadequate online information regarding one's position and orientation within the environment. In contrast to the model of Mou et al. (2004), our results showed that - even when participants were able to remain oriented with the learning direction (i.e. online during the viewpoint shift) - scene recognition performance was still worse following disorientation compared to locomotion. These results suggest that remaining oriented with the learning direction is not sufficient to improve scene recognition, which further highlights the importance of body-based cues for spatial updating.

This thesis provides empirical evidence to explain the difference in scene recognition ability between viewpoint shifts caused by locomotion and those caused by scene rotation. We provide a unifying framework for understanding how different modes of viewpoint shift affect humans' capacity to recognize scenes from novel viewpoints, and what specific aspects of those modes are driving differences in recognition. However, these findings are not an exhaustive account of the mechanism underlying the differences between locomotion and scene rotation. For the remainder of this discussion, we address literature that further helps to explain the difference between viewpoint shifts caused by locomotion and scene rotation.

First, it is worth mentioning that the facilitative effect of locomotion reported here is not only robust across magnitudes of viewpoint shift, but it is also robust across changes in set size. That is, the facilitative effect of locomotion persists even when the scene is reduced to a single object; this is true for both imagined movement (Wraga, Creem, & Proffitt, 2000) and real locomotion (Simons, Wang, & Roddenberry, 2002) around a scene. Wraga et al. (2000) propose that the fundamental difference between observer locomotion and scene/object rotation is the manner in which corresponding reference frames are transformed in the brain. They suggest that, irrespective of whether the scene has one or many objects, the object-based (or scene-based) reference frame is adversely affected due to a deficit in transforming that coordinate system as a cohesive unit. On the other hand, the relative improvement in spatial ability in the case of locomotion suggests that representations in the egocentric (i.e. body-centred) reference frame are preserved by the unity of the human body. Simply stated, performance differences between scene/object rotation and self-movement critically depend on differences in transforming object-based and egocentric reference frames, the latter of which is achieved more efficaciously (Wraga et al., 2000).

As they are conceptualized, observer locomotion and scene rotation involve fundamentally different types of mental transformations. Hegarty and Waller (2004) have dichotomized locomotion and scene rotation in the following way: locomotion - which can be thought of as a form of perspective-taking - is interpreted as the ability to make egocentric spatial transformations, whereby an individual's egocentric reference frame changes with respect to the environment, yet object-based and environmental reference frames remain unchanged (see also Thurstone, 1950). On the other hand, scene rotation - which can be thought of as a form of spatial visualization – involves the ability to make object-based spatial transformations, wherein the positions of objects move with respect to an external reference frame, yet the egocentric frame remains unchanged. Indeed, a dissociation between egocentric and object-based mental transformations is supported by studies that show performance differences between locomotion and scene rotation (e.g. Burgess et al., 2004; Mou, Zhang, & McNamara, 2009; Simons & Wang, 1998; Wang & Simons, 1999). To further evaluate the distinction between egocentric and object-based mental transformations, Hegarty & Waller (2004) had participants complete numerous paper-and-pencil tasks that required either egocentric (i.e. perspective-taking) or object-based (i.e. spatial visualization) solutions. These researchers used a confirmatory factor analysis (CFA) to investigate whether performance patterns are best supported by a two-factor model that assumes distinctiveness, or a one-factor model that assumes the two mental processes load onto a single spatial factor. The results showed that, while highly correlated, egocentric and object-based spatial transformations are dissociable in both small and large-scale environments (for similar results see Kozhevnikov & Hegarty, 2001). Therefore, it appears as though viewpoints shifts caused by locomotion and scene rotation rely on different mental transformation processes. This is consistent with the results of the current study, which show clear performance differences between locomotion and scene rotation. To extend the findings of Hegarty and Waller (2004), our results suggest that active control over the viewpoint shift, in addition to body-based cues available during locomotion, may be responsible for the facilitation of egocentric mental transformations.

Further evidence for a dissociation between egocentric and object-based mental transformations comes from literature suggesting that these transformations rely on different neural structures (e.g. Kosslyn, DiGirolamo, Thompson, & Alpert, 2001; Zacks, Rypma, Gabrieli, Tversky, & Glover, 1999). For example, Zacks, Vettel, and Michelon (2003) used function magnetic resonance imaging (fMRI) to directly compare local brain activity during imagined object rotations and imagined observer rotations. In their task, participants viewed a picture of a square board with a coloured cube in each corner. Participants then imagined the board rotating a given amount (object-based change) or imagined themselves moving around the board (perspective change). In one experiment the participants were required to determine if a particular cube was on their left or right; and in a second experiment they had to indicate the colour of the cube immediately to their left or right. The results showed that object-based transformations led to a selective increase in blood oxygen level-dependent (BOLD) activity in the right parietal cortex and decreases in the left parietal cortex. On the other hand, egocentric perspective transformations led to greater BOLD activity in the left parietal-temporal-occipital (PTO) junction. Such a double-dissociation is suggestive of an updating mechanism that contains unique neural units which are differentially responsible for egocentric perspective taking and object-based transformations (Zacks et al., 2003).

A recent study by Wraga, Shephard, Church, Inati, and Kosslyn (2005) also used fMRI to investigate the neural mechanisms underlying imagined object rotations and imagined egocentric perspective changes. In their task, participants viewed abstract geometric objects (Shepard-Metzler-like objects) which were located within a sphere. A T-shape prompt then appeared at different locations outside the sphere. Participants in the object rotation condition had to imagine rotating the object so that one end was aligned with the prompt. On the other hand, in the perspective change condition, participants imagined themselves rotating to the prompt. Participants then made a yes/no judgment as to whether or not a textured portion of the object would be visible from the new viewpoint. Results showed that there was increased activation in the left pre-motor area extending to left primary motor (M1) cortex for object rotations, but not for perspective changes. Alternatively, increased activity was observed in the left supplementary motor area (SMA) for egocentric perspective changes. These results support the notion that object-based mental transformations and egocentric perspective changes are subserved by distinct neural structures.

While there is a paucity of neuroimaging studies dissociating object-based and egocentric mental transformations, a general rule of thumb seems to be that object-based transformations recruit neural substrates in the right posterior parietal, occipital, and superior temporal cortex, whereas egocentric perspective transformations are directed by activity in the left parietal-temporal-occipital (PTO) junction (Zacks et al., 2003; Zacks & Michelon, 2005) and/or the SMA (Wraga et al., 2005). Recall that egocentric mental transformations are induced during locomotion, whereas object-based mental transformations are instigated by scene rotation. The results of the present dissertation suggest that active control over the viewpoint shift and body-based cues (i.e. proprioceptive, vestibular, etc.) available during locomotion may be responsible for facilitating the transformation of egocentric representations. Interestingly, it turns out that the same brain regions associated with the transformation of egocentric representations (i.e. the PTO junction and the SMA) – which occur during locomotion – are also activated during instances of motion processing, active control, and input of body-based cues. For example, Zacks and Michelon (2005) suggest that activity in the superior temporal sulcus of the PTO likely overlaps with activity in the medial temporal complex. This area is believed to be homologous to the monkey medial temporal and medial superior temporal areas, which respond selectively to visual motion (see Huk, Dougherty, & Heeger, 2002). The PTO activation observed by Zacks et al. (2003) may also include an adjacent area in the posterior superior temporal sulcus, which has been shown to respond selectively to biological motion (Bonda, Petrides, Ostry, & Evans, 1996). These findings support the idea that discrete neural structures respond to egocentric perspective changes, and that neural firing in these structures may reflect general motion processing associated with movement of one's body (i.e. locomotion) (see Zacks et al., 2003). In addition, Mima et al. (1999) have shown that the SMA receives input from proprioceptors during active finger movements. Radovanovic et al. (2002) have reported similar findings. Using positron emission tomography (PET), the latter researchers showed that flexion-extension movements of the forearm resulted in increased regional cerebral blood flow (rCBF) in the SMA. Likewise, Weiller et al. (1996) have shown that there is increased rCBF in the SMA during active, but not passive, movements of the right elbow. The fact that cortical regions associated with egocentric mental transformations are also activated in response to motion processing, active control, and proprioceptive inputs further strengthens the present contention that active control and body-based cues are essential for updating egocentric spatial representations during locomotion.

In conjunction with the results of the present dissertation, the above reports on neural activity make it clear that egocentric mental transformations (via locomotion) and object-based mental transformations (via scene rotation) are characterized by different patterns of behavioural performance, different neural correlates, and different psychometric properties. It is important to note that the studies on neuronal activity mentioned above typically used tasks that are fundamentally different from ours. This is, in part, a result of restrictions in how fMRI and PET scans can be used. More systematic inquiries, possibly with more versatile imaging techniques, are needed in order to determine whether additional aspects of locomotion aside from active control and body-based cues improve spatial processing, and whether those aspects of locomotion share the same underlying neural structure.

In summary, the results of this dissertation suggest that the facilitative effect of locomotion may partially be attributed to active control over the viewpoint shift, as well as the availability of body-based cues which promote efficacious updating of egocentric spatial relations. On the other hand, it does not appear as though the facilitative effect of locomotion can be accounted for by visual cues in the surrounding environment, or simply by an ability to remain oriented within one's environment. Given the apparent advantage of active compared to passive scene rotation, this dissertation encourages future researchers who are investigating the facilitative effect of locomotion to account for the degree of active control that participants are afforded during viewpoint shifts. The results presented herein also promote the use of spatial scenes consisting of random arrangements of identical objects, which provide a more sensitive test of participants' scene recognition ability. Finally, given the discrepancies that exist within the literature regarding the role of body-based cues, active control, and visual cues in the environment, future research should strive to settle these ambiguities using more systematic, within-subjects experimental designs.

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