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ABSTRACT

THE INTERACTION OF TRANSIENT AND ENDURING SPATIAL REPRESENTATIONS: USING VISUAL CUES TO MAINTAIN PERCEPTUAL ENGAGEMENT

by Eric P. Hodgson

Four experiments are reported that investigate the role of visual cues in keeping people perceptually engaged in their environments in a classic spatial updating task. These experiments replicated Wang and Spelke's (2000, Exps. 4 & 5) finding that a continually available visual gradient was sufficient to allow people to maintain baseline levels of performance after an otherwise disorienting rotation. In contrast, people who could view the gradient during testing phases but not during the rotation responded slower and showed decreased levels of pointing precision after rotation despite having accurate perceptual information about their final heading. This paradigm was extended to show that continuously-available perceptual information was not necessary to keep participants perceptually engaged. Brief, intermittent glimpses of the environment (i.e., a visual fix) enabled people to maintain baseline levels of performance after rotation as long as the visual fixes were given every 75º; wider visual fix intervals were ineffective. Finally, it was demonstrated that a sufficiently rich visual cue that was visible during testing, but not during a disorienting rotation, could effectively re-engage people's perceptual awareness of unseen target's locations. Participants in this condition pointed as quickly and precisely as when they were able to perceive the visual cue throughout the entire rotation. The results of these experiments are discussed in the context of a two-systems framework of spatial cognition recently espoused by Burgess (2006) and others. Across experiments, trends in spatial updating performance were used to explore how transient and enduring spatial representations interact to enable flexible, robust performance in spatial tasks.

THE INTERACTION OF TRANSIENT AND ENDURING SPATIAL REPRESENTATIONS: USING VISUAL CUES TO MAINTAIN PERCEPTUAL ENGAGEMENT

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DEDICATION

This dissertation is dedicated to my loving wife Pamela, who helped support me both emotionally and financially throughout my five-year journey through graduate school. Thank you for being there to encourage me and keep me on task.

This dissertation is also dedicated to our newly born son, Nolan, who has added great joy to my life and provided some needed distractions from the monotony of analyzing data and writing research reports.

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THE INTERACTION OF TRANSIENT AND ENDURING SPATIAL REPRESENTATIONS:
USING VISUAL CUES TO MAINTAIN PERCEPTUAL ENGAGEMENT

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Spatial representations of one's environment serve multiple purposes in daily life, such as walking across a room without running into obstacles, reaching for a pen without looking up from reading, giving directions to a colleague, or trying to remember where you parked in a sizable lot. Most theories that explain human spatial representation recognize that the representation of spatial information is likely governed by two separate subsystems (e.g., Avraamides & Kelly, 2008; Burgess, 2006; Creem & Proffitt, 1998; Easton & Sholl, 1995; Menzel, Brandt, Gumbert, Komischke, & Kunze, 2000; Mou, McNamara, Rump, & Xiao, 2006; Mou, McNamara, Valiquette, & Rump 2004; Sargent, Dopkins, Philbeck, & Modarres, 2008; Waller & Hodgson, 2006; Wang & Spelke, 2000). Theorists often disagree on the precise nature of these two systems (e.g., whether each utilizes an egocentric or allocentric reference system) and which system is the primary basis of most day-to-day spatial tasks. However, most theorists agree that one system relies primarily on perceptual information and transient representations while the other relies primarily on enduring spatial memory (Burgess, 2006; Creem & Proffitt, 1998; Mou et al., 2004; Mou et al., 2006; Waller & Hodgson, 2006; Wang & Spelke, 2000). In the above examples, one might consider interaction with the objects in a person's immediate environment or obstacle avoidance as being based on a transient, perceptual representation, while imagining distal environments to give directions or recovering spatial information from an episodic memory to be tasks that utilize enduring spatial knowledge.

The evidence to support multiple spatial systems – rather than a complex single system based on visual snapshots, a cognitive map, egocentric codes, or some other representation – comes from a wide variety of paradigms and spatial tasks. For example, Creem and Proffitt (1998) asked people to estimate the slope of a hill either while standing and looking at the incline, or at a later time when it was not perceptible. Two response modes were employed; a tilt-board that could be manually adjusted to match the hill's slope and a verbal estimate.

Participants in Creem and Proffitt's experiments could match the slope of the hill relatively accurately (without looking at the tilt-board) when the hill was perceptually available. However, verbal estimates of the slope were greatly overestimated, and tilt-board estimates made later (i.e., from memory) were also overestimated and more closely resembled the initial verbal reports. The authors interpreted this task dissociation as indicating people's reliance alternatively on an accurate perceptual-motor system or a coarse, higher-level cognitive system to make their responses. Verbal estimates and motoric responses made from memory fell into the latter category.

Similarly, Waller and Hodgson (2006) recently demonstrated that disorienting people could either inhibit their performance or improve it depending on the type of spatial task being completed. When participants were asked to complete a self-to-object pointing task (i.e., “Point to the door.”), their egocentric bearing estimates became significantly less precise after a disorienting rotation. Conversely, when participants were asked to complete an object-to-object pointing task (i.e., “Imagine you are at the desk, facing the shelf. Point to where the door would be.”), their judgments of relative direction became *more* precise after disorientation. The authors interpreted both effects as a disruption of a transient, perceptually-based spatial representation. In the first case, this disruption inhibited people's perceptual awareness of the environment around them, thus reducing the precision of self-to-object pointing estimates. In the second case, disorientation had the effect of removing a source of interference, and thus helped pointing accuracy. For example, it may be difficult to imagine a non-egocentric orientation, or, indeed, to make a correct rightward pointing estimate to an object that is physically to one's left. After disorientation – when one's current orientation and relationship to the targets is unknown – it should be equally easy to imagine any given orientation or to point in any direction. Thus, the most parsimonious explanation of the full data set was that disorientation induced participants to switch reliance from a relatively precise but transient perceptual system to a relatively coarse but enduring memory system.

Burgess (2006) has assembled an excellent review of this and other evidence supporting two distinct but parallel spatial systems (see also Avraamides & Kelly, 2008). His review draws from research on change detection in a spatial updating paradigm (e.g., Simons & Wang, 1998; Wang & Simons, 1999), pointing tendencies after disorientation (e.g., Waller & Hodgson, 2006; Wang & Spelke, 2000), alignment effects in memory (e.g., Rieser, 1989; Shelton & McNamara, 1997), and the use of geometric cues in reorientation (e.g., Cheng, 1986; Cheng & Newcombe, 2005; Hermer & Spelke, 1994; 1996). Burgess concludes that the most viable, unifying explanation of the extant spatial literature is a dual system framework in which egocentric and allocentric systems (or representations) work in parallel to supplement each other. This contrasts with previous approaches that argued for the primacy of egocentric representations (e.g., Wang & Spelke, 2000; 2002), allocentric representations (e.g., Easton & Sholl, 1995; Tolman, 1948), or intrinsic reference systems (e.g., Mou & McNamara, 2002). The present work adopts this approach with one exception. Rather than assuming the two systems to be necessarily based on egocentric and allocentric representations, the defining distinction here is assumed to be that one system is *transient* – based on fluctuating perceptual information integrated from several sensory modalities – and that the other system is *enduring* – based on memory codes and, in particular, long-term memory (see also Waller & Hodgson, 2006).

The reason for this discrepancy from Burgess' (2006) framework is that, in the authors opinion, the distinction between transient and enduring representations offers greater explanatory power. The terms 'egocentric' and 'allocentric' refer to the organizational structure of a given representation and are insufficient to explain the full spectrum of spatial representations. In fact, there is little evidence to support a type of representation fitting the traditional definition of 'allocentric;' that is, an all-centered representation that is equally well remembered or imagined from any perspective. Instead, the term 'allocentric' is too often used in an ambiguous way to describe a wide spectrum of non-egocentric representations. Such representations that are both non-egocentric and non-allocentric include those organized around intrinsic axes (e.g., Mou & McNamara, 2002; Mou, Zhao, & McNamara, 2007; Shelton & McNamara, 1997), hierarchical representations (e.g., Chown, Kaplan, Kortenkamp, 1995), and analog map-type representations (e.g., Tolman, 1948) that are often recalled with a preferred heading (e.g., Diwadkar & McNamara, 1997; Tversky, 1981).

The terms 'transient' and 'enduring' avoid this ambiguity and are agnostic as to the dominant reference frame of the representations they describe. Instead, they focus on the time-course, fragility, and function of the representation. Transient representations are those that are short-lived and fragile, but function to enable navigation on a moment-to-moment basis; Enduring representations are those that enable a more stable, long-term memory of spatial information. Transient spatial representations are most likely egocentric in nature, being based on egocentric viewpoints, egocentric vestibular cues, egocentric audition, and other egocentric perceptual input. However, it is certainly possible to have an enduring representation that is egocentric in nature, such as a visual snapshot (e.g., Cartwright & Collet, 1982; Diwadkar & McNamara, 1997) or even an imagined viewpoint (Greenauer & Waller, in press). Similarly, non-egocentric representations (e.g., a cognitive map) are more commonly enduring in nature, but one could conceive of a transient non-egocentric representation (e.g., a perceptual awareness of object-to-object relations). Transient non-egocentric representations are arguably less prevalent (or primary) than transient egocentric representations, but the more important point is that a transient non-egocentric representation serves a purpose that is different than an enduring non-egocentric representation. In this way, a transient non-egocentric representation is more similar to transient egocentric representations than it is to other enduring types of non-egocentric representations. Thus, characterizing various spatial representations as being transient on one hand or enduring on the other provides a more useful description of the two systems by dividing representations according to their functions rather by their organizational structure.

These transient and enduring systems and the processes that rely on each are known to exhibit different characteristics. For example, participants' task in the present experiments involves learning and keeping track of the locations of several target objects in the environment during movement, commonly referred to as *spatial updating*. Updating one's changing spatial relationship to the environment is a qualitatively different task depending on whether transient or enduring representations are used. Spatial updating that relies on a transient representation (i.e., o*nline updating*) would be expected to be carried out on a moment-to-moment basis during movement. Spatial updating that relies on an enduring representation (i.e., *offline updating*), by contrast, can be carried out in a post-hoc fashion after a period of movement is completed. These two different types of updating likely work in concert such that if perceptual information is degraded or unavailable – when walking in the dark, for example – online updating may become unreliable, but be supplemented by offline reconstruction based on an enduring spatial representations such as a cognitive map (e.g., Tolman, 1948) or a stored viewpoint (e.g., Diwadkar & McNamara, 1997).

In addition to the underlying source of information and the temporal difference in processing, online and offline updating are known to differ on several other dimensions. These differences can help illuminate more general, expected characteristics of tasks utilizing either the transient or enduring spatial system. First, online updating is generally more accurate and precise than offline updating (Amorim, Glasauer, Corpinot, & Berthoz, 1997; Waller & Hodgson, 2006), due to the relatively higher precision of perceptual information relative to memory. For example, a person throwing a dart is generally much more accurate and precise when visually guiding her shot than when throwing blindfolded at the remembered location of the bullseye.

Second, only online updating should degrade in the absence of full perceptual support (Farrell & Robertson, 1998) and be disruptable by disorientation or by other means (Mou, McNamara, Rump, & Xiao, 2006; Wang & Spelke, 2000; Waller & Hodgson, 2006). Because an enduring memory representation is not tied to the current perceptual state, it can easily survive a sudden loss of lighting or a state of disorientation – conditions under which the transient system should fail outright.

Third, online updating should exhibit characteristic limitations associated with other online processing tasks (Sholl & Fraone, 2004) such as proneness to interference (Lindberg & Gärling, 1981a) or limitations of capacity (Hodgson, 2008; Wang et al., 2006). It is simply not conceivable for an infinite amount of multi-modal perceptual inputs and high-precision spatial information to be processed in real time. Offline updating, in comparison, can retrieve an extremely large amount of information from a rich, enduring memorial representation, and thus would not exhibit characteristic limitations associated with online processing (e.g., Hodgson & Waller, 2006; Lindberg & Gärling, 1981b; Rieser & Rider, 1991). However, offline updating should be expected to exhibit distortions and biases typical of long-term memories (Haun, Allen, & Wedell, 2005; Huttenlocher, Hedges, & Duncan, 1991; Tversky, 1981).

If we accept that the transient and enduring systems are designed to work in concert, then it is functionally unnecessary to store highly-precise spatial information in an enduring memory. Instead, it is sufficient to remember an approximate bearing, distance, or location (or even merely a nearby landmark). When one travels approximately the right direction for approximately the right distance, there should be abundant perceptual cues and visible landmarks to guide one's actions with high precision. For example, in order to retrieve a child's favorite toy for him, it is enough to remember that it was left on the kitchen table, not that it was left 25.8 cm North and 37.2 cm East of the table's center.

Given the clear differences between these types of updating and, by extension, other spatial processes that rely alternatively on transient or enduring spatial representations, it will be important to determine precisely how these two systems interact with and each other (see Burgess [2006] for similar arguments). More specifically, under what circumstances do people typically rely on each type of spatial representation? How do the two systems supplement each other? What circumstances will tend to induce a person to switch from one system to the other? There is some preliminary evidence concerning these questions, described below, but much work remains to be done. The experiments contained in this dissertation will seek to explore the interactions between transient and enduring spatial systems in the context of a spatial updating task based on the influential series of studies by Wang and Spelke (2000; 2002).

Wang and Spelke (2000) asked people to learn the locations of six objects and point to them without vision before and after a large rotation designed to induce disorientation. Wang and Spelke measured participants' knowledge of the relative configuration of the objects by having them manually point to each object. Conceptually, participants' *configuration error* assessed how well they could recreate the proper angular separation between objects regardless of the actual direction to each object. Thus, if a person pointed in exactly the wrong direction (180º absolute error) for every object, she would have zero configuration error because the relative configuration was preserved. Alternatively, missing each objects by 180º on average, with some objects being missed by 120º or 150º and others by 210º or 240º, would yield a high configuration error score because there was substantial noise in the relative configuration. Essentially, this is a measure of the precision of the spatial representation, and different theories of spatial representation make different predictions about the precision of spatial memory after disorientation. As Wang and Spelke correctly pointed out, cognitive mapping theories predict equivalent levels of configuration error before and after a disorienting rotation, because performance in each phase would be based on the same representation – an enduring memory representation that should not be impacted by a loss of knowledge of one's current facing direction. Conversely, egocentric theories predict an increase in configuration error after rotation because the knowledge of self-to-object vectors (a transient egocentric representation) has been disrupted. A strict interpretation of these theories from a single-system standpoint would predict that configuration error would degrade to chance performance (i.e., around 104º). This was clearly not the case as post-rotation configuration error in their experiments was generally less than 20º, but some degree of impairment was observed after rotation. Across an elegant series of six experiments, Wang and Spelke definitively demonstrated support for the egocentric updating theory and showed that people's pointing estimates reliably became more variable when disoriented. The authors used this finding to dismiss the notion of a cognitive map, and argued that their findings constituted evidence for the primacy of egocentric representations in spatial cognition.

Waller and Hodgson (2006) replicated Wang and Spelke's (2000) finding that disorientation induced a loss of pointing precision but re-interpreted the effect as an indication that people switch reliance from a precise transient representation to a relatively coarse, enduring representation spatial representations after being disoriented. To support this assertion, Waller and Hodgson demonstrated that when people were tested on knowledge for which an enduring representation would be expected to be used (i.e., visualizing and pointing to objects' locations in a familiar, over-learned environment like one's own bedroom), there was no increase in configuration error after disorientation. Furthermore, the magnitude of configuration error before and after rotation was equivalent to the disorientated performance of participants who pointed to recently learned objects in the physical testing room. Importantly for the present investigation, Waller and Hodgson also demonstrated that disorientation was not necessary to induce the switch from transient to enduring representations. Rather, there appeared to be a threshold of rotation beyond which this switch was apparent. The same type and magnitude of effect in pointing precision could be demonstrated with a rotation as small as 135º, but not with rotations of 0º, 45º, or 90º.

It is well known that people and animals navigating under reduced perceptual support (i.e., without vision) tend to accumulate error with increasing distance traveled (Benhamou, Suavé, & Bovet, 1990; Entienne & Jeffery, 2004; Entienne, Maurer, & Saucy, 1988; Loomis, Klatzky, Golledge, & Philbeck, 1999; Reiser, Ashmead, Talor, & Youngquist, 1990; Müller, & Wehner, 1988; Philbeck & O'Leary, 2005; Wehner & Srinivasan, 1981). Waller and Hodgson's findings suggest that when rotating blindly, enough error and uncertainty accumulates within less than half a revolution that pointing estimates based this uncertain perceptual information may be no more precise than those based on a coarse memory representation. At such a point it becomes more economical to place one's reliance on the more stable enduring system. For example, Müller, & Wehner (1988) have suggested that remarkable path integration ability of foraging desert ants may be less an accurate perceptual awareness of the true homeward vector and more a rough but functional approximation of the required distance and direction. An approximate homeward vector can return the insect to within visible range of familiar, remembered landmarks surrounding its nest while avoiding the perils of continually accumulating errors in the idiothetic sensory systems.

Given the assertion above that transient spatial knowledge is the primary means of moment-to-moment navigation and spatial updating, it is informative to consider how the transient system can be restored following some type of disruption. Two experiments in Wang and Spelke's (2000; Exps. 4 & 5) study spoke specifically to this issue and suggested that merely regaining knowledge of one's global orientation does not allow the transient system to re-engage and restore pointing precision. In one experiment, a light was placed on one side of the testing space and participants wore a translucent blindfold that allowed them to see diffused light without having vision of the room or of the to-be-remembered targets. The amount of light predictably fluctuated as people rotated toward and away from the light source, creating a continuous lightness gradient during learning, testing and, more importantly, during the otherwise disorienting rotation. In contrast to their basic disorientation effect, Wang and Spelke showed that participants with continual perceptual access to this light source did not show the increase in configuration error that would have indicated a disruption of their egocentric representation. A second experiment used the same lightness gradient during learning and testing, but extinguished the light source during rotation. Thus, having some diffuse vision of the light during the final testing phase allowed participants to sufficiently re-orient themselves to the room, but it was not available as continual perceptual input during movement. Participants in this experiment exhibited the standard increase in configuration error. An obvious limitation to the generalizations that can be made from this study is that the visual cue available for reorientation (a diffuse lightness gradient) was relatively abstract and imprecise. Part of the present research will return to this issue to investigate the effect of a more complex visual cue on reorientation.

Taken together, these two experiments from Wang and Spelke's (2000) study provide the basic paradigm for the proposed dissertation. It is intriguing that continual visual information – even diffuse, relatively abstract visual information – can prevent response precision from deteriorating after disorientation. Given that such visual information can prevent a switch to an enduring spatial representation, and given that previous research has indicated that the switch occurs between 90º and 135º of rotation (at least for a blindfolded updating task with six objects), it begs the question: How often is vision of the environment required to keep the transient system operating reliably? In other words, how often do people require a visual fix on the environment to maintain a precise perceptual awareness of their immediate environment? Temporary disruptions of vision such as during a saccade or the jarring of a foot strike while walking or running do not typically disrupt people's spatial knowledge or lead to disorientation; longer disruptions, such as walking in the dark or rotating while blindfolded, do disrupt people's spatial knowledge and can lead to errant estimates of position, heading, or distance (e.g., Loomis, et al., 1999; Philbeck & O'Leary, 2005; Waller & Hodgson, 2006). Thus, it seems logical to predict that if participants have access to visual information every Xº during a large rotation, then the transient system should remain engaged so long as Xº is less than the threshold for disruption.

An analogy can be made to an ancient mariner who sets his course and monitors how long and in what direction he is traveling, but is also at the mercy of cross currents, asymmetric drag across the hull, the prevailing direction of surface waves, and shifting winds that add uncertainty to his knowledge of the ship's position and bearing. Occasionally, the mariner will need to make a sighting of land or (more often) of known celestial bodies to get a visual fix of his position and bearing. These visual fixes do not need to be made continuously, but are necessary from time to time to correct for the error that builds up during the journey and plot a new heading. The rate of error build-up (noise in the body-based senses) as well as the frequency and quality of these sightings (frequency and quality of visual cues) contribute to the accuracy and efficiency of the overall journey. Along these lines, the following experiments are proposed to investigate (a) if intermittent visual fixes are sufficient to keep the transient system engaged, (b) how frequent these fixes must be to be useful, (c) if this threshold depends on the quality of the perceptual information, and (d) if sufficiently detailed visual information can bring the transient system back online once it has been disrupted. Investigating these questions will contribute to our knowledge of how people keep track of their environments during movement, but more importantly, it will also help advance the two-systems framework for spatial cognition by helping to better define the interaction between transient and enduring spatial representations, and investigating the conditions under which the people switch reliance from the one to the other.

General Methodology

All of the experiments in this dissertation will follow a similar methodology that is based on Wang and Spelke's (2000, Exp. 4 & 5) disorientation paradigm and the methods of the egocentric pointing tasks used by Hodgson and Waller (2006; see also Hodgson, 2008). Participants will be seated on a revolving stool in the center of six surrounding targets. After an opportunity to learn these targets, participants will be asked to point to each of the six objects (i.e., indicate the self-to-object direction) in each of three phases: an eyes-open practice phase, a blindfolded pre-rotation phase, and a blindfolded post-rotation phase. In between the pre-rotation and post-rotation phases, participants will be asked to rotate continuously for a period sufficiently long to induce disorientation (e.g., one minute). During this rotation, various types of visual stimuli (or none at all) ranging from an abstract visual gradient to a photo-realistic virtual environment will be presented to people via a head mounted display (HMD).

One concern in this paradigm is the issue of motion sickness (i.e., from rotating extensively) and the related phenomenon of simulator sickness (i.e., from viewing simulated visual stimuli in an HMD). Previous estimates of the base rate of simulator sickness has suggested that as many as 90% of all participants will experience at least minor symptoms akin to motion sickness (Harm, 2002; Lawson, Graeber, Mead, & Muth, 2002), with up to 30% of participants experiencing moderate to severe symptoms (e.g., DiZio & Lackner, 1997; Wilson, Nichold, & Ramsey, 1995). Despite the aged nature of some of these findings relative to modern simulation technology, there were several factors in the present experiments that were expected to contribute to the incidence of dizziness, nausea, stomach awareness, or other symptoms. Specifically, a prolonged rotation is sufficiently capable of inducing these symptoms and can be particularly troublesome if participants choose to rotate at excessive speeds. Also, the presentation of visual information in Experiments 2 and 3 was done in an intermittent fashion; participants viewed brief (400 ms) flashes of a virtual environment at predefined intervals, resulting in a somewhat stroboscopic display that may have been disconcerting. Furthermore, participants were informed during the consent process that they might experience simulator sickness, and if so, that they should inform the experimenter and would be free (and indeed, encouraged) to discontinue their participation without losing compensation. These instructions could arguably be expected to increase the self-reported incidence of simulator sickness, both because it primed people to be aware of their symptoms and – on a more facetious note – because it provided participants with an avenue to obtain free compensation and an early exit from an experiment that may otherwise last up to an hour.

Despite all of these factors, the incidence of simulator sickness was surprisingly low. In Experiments 1 and 4, no participant reported experiencing any symptoms. In Experiments 2 and 3, which featured stroboscopic views of the simulated environment, only two (6.45%) and seven (6.48%) participants reported experiencing even minor symptoms. Most of these voluntarily chose to continue their participation. It should be noted that no formal analysis of symptomology was conducted (e.g., pre- and post-experimental questionnaires), and that these figures rely instead on self-report. It may have been that a larger percentage of participants fell victim to mild symptoms of simulator sickness and failed to report it. However, it seems equally likely that simulation technology has advanced to the point where these side effects are reasonably low even under the highly adverse conditions of the present experiments.

Data collection and analyses. Performance in the present experiments will be assessed with several convergent measures. The primary means of analysis for each metric will be to construct 95% confidence intervals around either the mean value for a variable (e.g., heading error) or the mean increase from pre-rotation testing to post-rotation testing (e.g., latency). Means and confidence intervals are listed separately for each experiment, testing phase, and condition in Appendices A (variable error), B (pointing error), C (latency), D (signed distance error), and E (absolute distance error). All experiments included a within-participant manipulation and confidence intervals were constructed to exclude between-participant variation where appropriate (c.f., Cousineau, 2007; Loftus & Masson, 1994). In Experiments 1 and 4, paired-samples *t*-tests were conducted to explore differences between two experimental conditions. In Experiments 2 and 3, participants were given visual reminders of their orientation at increasingly-wide intervals across four conditions and trends across visual fix intervals were examined in the context of an ANOVA using the Greenhouse-Geisser correction (Greenhouse & Geisser, 1959) where appropriate. Planned contrasts were conducted to test for polynomial trends or the presence of step functions across visual fix intervals. Specifically, an error accumulation model (e.g., Loomis, et al., 1999; Philbeck & O'Leary, 2005; Rieser, et al. 1990) might predict that progressively wider intervals between visual fixes will produce progressively larger increases in errors or latencies (i.e., a linear trend). Alignment effect theories (e.g., Mou & McNamara, 2002; Rieser, 1989; Shepard & Metzler, 1972) might predict a quadratic trend in which progressively larger increases are seen with visual fixes separated by up to 180º, and then progressively smaller increases as the visual fixes approach 360º of separation (i.e., returning to 0º). Finally, the two-systems approach (Burgess, 2006; Waller & Hodgson, 2006) that provides the framework for the current investigation predicts that there will be a discrete switch point (i.e., a step function). All of these possibilities were examined for Experiments 2 and 3.

Primary Analyses. In keeping with the tradition of Wang and Spelke's elegent analyses, participant's mean *heading error* was assessed in each condition as a measure of participant's sense of orientation or disorientation. Heading errors were computed for each participant as the circular mean of all signed errors in a given condition (c.f., Batschelet, 1981). A mean heading error and 95% confidence interval was constructed for each condition by collapsing across participants. To the extent that people are well oriented, mean heading error should be approximately 0º with relatively small variability. When participants are disoriented, on the other hand, mean heading errors will be randomly distributed between ± 180º. In the present experiments, participants will be given various types of visual cues in all conditions that are expected to keep them relatively well oriented to the environment as a whole. Thus, heading error analyses will serve primarily as a manipulation check to verify the expectation that participant's were generally well oriented, with heading errors closely clustered around zero.

Additionally, mean *pointing error* was analyzed to provide a measure of the variability inherent in making multiple pointing estimates to each target in the same testing phase. Wang and Spelke (2000) argued that participants may become less precise in multiple estimates to the same target either because they are less certain of its location or because they are less certain of their overall heading and thus changed their estimate (even slightly) on a trial-by-trail basis. While the former explanation yields an effect that would parallel the increase in configuration error and demonstrate a disruption of (transient) egocentric knowledge, the latter explanation cannot differentiate between egocentric and cognitive mapping predictions. Because there was no way to differentiate the source of within-target pointing variability, Wang and Spelke (and subsequent investigations using their paradigm) used the observed increase in pointing error to factor out within-target variability from the overall increase in configuration error. The present experiments adhere to that tradition. Specifically, if an increase in pointing error is the sole cause of increased configuration error after rotation, then the expected increase in configuration error is equal to the increase in pointing error divided by the square root of the number of pointing estimates per target. These observed increases in pointing error were analyzed separately, and used to subtract the predicted increase in configuration error from the overall variability. To preview the results of the present experiments, however, the contribution of pointing error may better be characterized as a source of information, rather than noise to be accounted for. The magnitude of pointing error increases after rotation in the present experiments was not homogeneous across conditions, and fluctuated predictably in line with the hypothesized data pattern. This issue will be more fully addressed in the discussion.

Whereas heading error and pointing error were analyzed largely as controls, the primary means of analyzing participant's performance was through two redundant measures – the adjusted increase in *variable error* (akin to Wang & Spelke's [2000] configuration error) after rotation (c.f., Waller & Hodgson, 2006, Exp. 4), and the increase in response *latency* after rotation (c.f., Hodgson, 2008). The label 'configuration error' was not used here because it is somewhat misleading in the sense that a configuration is composed of both relative angular separation between objects and relative distances to the objects. A true 'configuration error' measure should reasonably measure both components. Because the measure used here reflects only angular estimates, the term 'variable error' was used instead (see also Waller & Hodgson, 2006). A separate analysis was conducted to measure participants' knowledge of object's distances, which is described in detail below.

For variable error and latency, a switch in reliance from transient, perceptual spatial knowledge to enduring, memorial spatial knowledge predicts an increase that is significantly greater than zero. Reconstruction of information from memory requires additional time (Amorim, et al. 1997; Hodgson, 2008), and it also relies on a representation that is coarser than perceptual information, which leads to decreased precision in pointing estimates (Hodgson & Waller, 2006) and can sometimes introduce gross errors in other spatial estimates (Amorim, et al. 1997; Tversky, 1981).

Variable error was calculated in the same manner as Waller and Hodgson (2006) and Wang and Spelke's (2000) configuration error. Specifically, a signed error was calculated separately for each pointing response and decomposed into circular sine and cosine components (c.f., Batschelet, 1981). These components were averaged across multiple pointing estimates per object to obtain a mean signed error for each target. The variability (standard deviation) of these estimates was calculated separately for each phase (pre- and post-rotation) in each experimental condition, and the signed difference between pre-rotation and post-rotation variability was calculated to produce a variable error increase score for each condition. Finally, the variable error increase was adjusted to account for any variability that arose from inconsistent pointing to the same object on multiple trials of the same phase. An unbiased estimate of the amount of overall pointing variability that can be accounted for by within-object pointing variability is the increase in within-target pointing variability (hereafter called *pointing error*) divided by the square root of the number of pointing estimates per object. Thus, the mean pointing error was calculated for each phase and each condition, and the signed difference between phases was found for each condition to obtain a pointing error increase. Each pointing error increase was divided by the square root of the number of pointing estimates per phase (i.e., 4 trials per target in the current experiments), and this quantity was subtracted from the mean increase in variable error to create a final, *mean adjusted increase in variable error* measure.

Response times were measured as the time span between pointing instructions being presented in the headset (e.g., "Point to the Duck") and participant's clicking the trigger-button on the pointing device to signal their response. As with variable error, the signed difference in latency from pre- to post-rotation was calculated separately for each participant, stimulus, and experimental condition. These increases were collapsed across stimuli and participants to obtain the *mean increase in latency* for each condition. To prevent extreme outliers, a conservative cut-off was applied that omitted trials in which the response was slower than 10 seconds (error data were retained). These trials generally represented abnormal circumstances, such as a participant stopping to ask a question or turn off a cell phone, or the HMD battery running out and needing to be replaced. Across the four experiments, this criterion respectively eliminated 0.34%, 0.48%, 1.13%, and 0.31% of all trials. This data filter did not alter the outcome of the experiments or their conclusions.

It should be noted that the magnitude of variable error effects are often smaller than originally reported by Wang and Spelke (2000) and have occasionally proven difficult to replicate. Specifically, Wang and Spelke originally reported increases in variable error (i.e., configuration error) ranging from 7° to 18°. In a series of four experiments that were designed to closely replicate Wang and Spelke's methods and procedures, Waller and Hodgson (2006) obtained effects of approximately 4º, 5º, 5º, and 6º. The magnitude of these effects were even smaller (3º to 5º) when adjusted to exclude the within-target pointing error across trials. In a similar line of research, Mou, et al. (2006) failed to find an increase in variable error when testing participants' knowledge of highly structured, nine-item arrays (Exps. 1 & 2), but obtained a non-significant 2º trend (Exp. 3) and a significant effect of 4º (Exp. 4) when testing participants on four-item arrays.

Finally, Holmes and Sholl (2005) conducted a series of seven experiments that closely replicated Wang and Spelke's methods, but failed to obtain any reliable increases in variable in any condition. In fact, there was a trend towards *decreased* variability after rotation in five of the seven experiments; this decrease was significant in two cases (approximately -6º and -9º). Holmes and Sholl attributed their failure to replicate Wang and Spelke's effects on participants' use of allocentric (i.e., enduring) spatial representations. Specifically, it was concluded that participants' transient, egocentric knowledge ("narrowly tuned codes") of objects' bearings had already been disrupted in the pre-rotation testing phase, leading to performance that was based on a relatively more coarse, enduring representation ("broadly-tuned codes"). For example, participants in Holmes and Sholl's experiments rotated blindfolded up to 180º between the eyes-open practice phase and the beginning of the pre-rotation testing phase. These relatively small rotations are commonly used in this paradigm to prevent people from merely repeating the same motor movements used in the practice phase, but as Waller and Hodgson (2006, Exps. 3 & 4) demonstrated, rotations as small as 135º are sufficient to disrupt people's transient knowledge of targets' bearings.

In concert, these lines of research converge both on the relative fragility and on the relatively small size of Wang and Spelke's (2000) effect as measured by variable error. To maximize the chance of detecting increases in variable error, the present experiments closely matched the methods of Wang and Spelke (2000) and Waller and Hodgson (2006) and employed relatively small rotations between practice and pre-rotation testing (approximately 40º) to avoid inadvertently disrupting participants' transient knowledge of the layout. Furthermore, the effect of variable error will be considered as only one converging measure. The same effects will be sought in participant's response latency. That is, the two-systems theory predicts that a switch from a transient to an enduring spatial representation should not only yield decrease precision, but slower responses as people engage in time-consuming, effortful retrieval processes. Recent research has indicated that increases in response latency after movement do occur under conditions that favor an enduring spatial representation (Amorim, et al., 1997; Hodgson, 2008; Hodgson & Waller, 2006).

In a spatial updating task, Amorim, et al. (1997) tested participants' knowledge of the bearing to a single target as well as its orientation after they had walked along a two-legged path. People who were asked to count out loud the number of steps taken while moving responded more slowly than people who were asked to report the status of the to-be-updated target while walking (i.e., “Which side is currently facing you?”). The authors concluded that this additional response time was due to people's need to reconstruct spatial information from memory in a post-hoc fashion when they had focused their attention elsewhere during movement.

Similarly, in a series of experiments designed to investigate the capacity limit of spatial updating, Hodgson and Waller (2006) asked participants to learn and point to various numbers of targets before and after rotations of 135º. With the exception of participants who were asked to update the location of a single target, there was a reliable increase in response latency after rotation. Again, the authors attributed this increased response time to offline reconstruction of spatial information from memory.

Extending this finding, Hodgson (2008) asked people to learn and update the positions of varying numbers of objects through a smaller, 45º rotation that would not be expected to disrupt people's transient spatial knowledge of the layout. Under these conditions, there was a reliable trend for participants to exhibit increases in post-rotation pointing latency only for layouts that contained six or more targets. Responses for smaller layouts were as efficient after rotation as before. Additionally, when rotation magnitude and the number of targets were jointly manipulated, latency increases were exhibited with increasingly smaller arrays as rotation magnitude was increased. These latency effects were interpreted as indicating a switch in reliance from transient to enduring spatial representations as the set size and / or rotation magnitude exceeded people's ability to update objects' locations online.

In the present line of experiments, the increase in latency after rotation will be used as a parallel measure to the increase in variable error after rotation. Based on Hodgson's (2008) findings, it is expected that latency effects will be relatively more robust than those of variable error, but the same data pattern is expected for each. As with other measures, the primary means of analysis for both measures will be to construct 95% confidence intervals around the mean post-rotation increase and compare to zero. A significant increase is assumed to provide an indicator that the transient system has been disrupted, inducing a switch to a slower, relatively coarse memory representation. If people's transient knowledge of the environment remains intact, they should be equally fast and precise after rotating as before. Note that this logic is slightly different than that of Wang and Spelke (2000; see also Holmes & Sholl, 2005; Mou, et al., 2006). Whereas they also argued that a zero increase indicated reliance on the same spatial representation before and after rotation, the representation implied by this data pattern was assumed to be an enduring, cognitive map type of representation. In contrast, the present investigation assumes that a zero increase is indicative of reliance on a transient, perceptual representation both before and after rotation. As indicated above, care was taken in the experimental design to prevent participants' transient knowledge of the environment from being disrupted by, for example, having participants rotate far less than 90º between practice and testing phases.

Supplementary analyses. In addition to the main analyses of latency and variable error, two exploratory analysis (signed and unsigned errors) were conducted in each experiment to examine participants estimates of the egocentric distance to each target. All previous investigations in this paradigm have measured knowledge of relative directions, and no data exists on the corresponding effect of rotation on participants' knowledge of relative distance. It may be that pointing estimates become more varied in pitch (distance error) as well as yaw (variable error) after participants are disoriented. The prediction for distance measures is similar in principle to those of the other dependent measures. That is, if participants' transient spatial knowledge of a target's location has been disrupted and subsequently reconstructed from a relatively coarser memory, it seems reasonable that participants would err in estimating both the target's distance and direction, as well as taking longer to respond. For example, an irregularly-spaced layout of objects at staggered distances that surrounds a participant in an approximate circle (see, e.g., Fig. 1.) may be remembered as an actual circle, with equidistant and equally spaced objects. Thus, relatively accurate pre-rotation distance estimates for each target degrade into estimates that are approximately accurate for the layout as a whole but less accurate on an object-by-object basis. Similarly, it may be that participants whose transient spatial knowledge has been disrupted by rotation may focus on the relatively more difficult task of determining an object's bearing, and respond with all pointing responses made at approximately the same, relatively level pitch angle. That is, instead of confidently responding, “It's right *there* (pointing to a particular spot),” people may be estimating, “I think it's *in that direction* (pointing to an approximate bearing).” In day-to-day life, this strategy would serve us sufficiently well, because we typically need to know the precise distances only to things that we are currently interacting with in the immediate, perceivable environment. To get to places that are not currently perceivable or to find something that we have forgotten, it is only necessary to look or travel in the approximate direction of the target; we are able to perceive the necessary distance information when it is near enough to be seen, so there is less need to store distance information with great precision.

In the present experiments, participants pointed to each target with an ergonomic hand-held pointing device that was shaped like a gun. Thus, the origin of each pointing response was the participant's hand rather than a known, fixed location such as the base of a tilt-board or the center of the stool on which the were seated (e.g., Hodgson & Waller, 2006; Holmes & Sholl, 2005; Sargent, et al., 2008). The gun was equipped with two infrared LED markers – one on the front and back – whose positions were each triangulated by four cameras (one in each corner of the room). The two LEDs were separated by approximately 36.5 cm and were aligned with the pitch axis of the gun. When participants depressed the trigger button on each trial, the positions of the two LEDs were calculated. Because participants were instructed to point *down* to each target's spot on the floor, the LED position highest off the floor was assumed to be the back of the gun. The pitch and heading were calculated for a ray that originated at the back (topmost) LED marker and passed through the front marker. The coordinates where this ray intersected the floor were also calculated, along with the distance of those coordinates from the center of the participant's stool. The signed distance from the stool (i.e., a radius) was used to calculate a *signed distance error* score by subtracting the estimated target distance from the actual stool-to-target distance (i.e., error = actual – estimate). Thus, negative values of distance error indicate an overestimation of distance.

To compute an *absolute distance error* score, a signed distance error was calculated for each trial, and collapsed across multiple pointing attempts per target for each testing phase and each participant. The absolute value of each target's distance error was then taken and used to calculate a mean distance error for each testing phase. Similar to the latency and variable error measures, distance error was analyzed by calculating a difference score from pre- to post-rotation and constructing a 95% confidence interval around the mean change. A significant increase in absolute distance error or a significant change in either direction for signed distance error will be taken as an indication that transient spatial knowledge of the relative distance to the target has been disrupted.

For both distance measures, the relatively few individual trials that had a signed error more extreme than ± 25 meters were excluded from analyses. This occurred when a participant pointed in a relatively level pitch and could yield abnormal and un-representative distance errors of up to several kilometers. Additionally, it should be noted that both of these distance metrics provide an assessment of relative distance that are independent of the direction estimate (e.g., if participants are disoriented) and they differ from a distance error score that measures the distance from an object's physical location to the coordinates of the estimated location.

It will be informative to generalize Wang and Spelke's (2000) disorientation effect to additional dependent measures such as latency and distance error. Pragmatically, this can provide researchers flexibility in how they measure people's performance as well as perhaps identifying a more robust dependent measure than variable error (configuration error). From a more theoretical perspective, the two-systems approach makes predictions about the underlying spatial representations being used under various circumstances and the nature of those representations. If people are truly relying on a coarse, enduring memory representation after their perceptual awareness of the environment has been disrupted, then the two-systems model predicts that not only will bearing estimates be more variable, but that distance estimates should suffer as well, and the process of reconstructing spatial information and responding should take more time. Thus, these different measures can hopefully provide converging evidence on the underlying processes of people's spatial updating performance in the present tasks in particular, and of people's spatial cognitive capabilities in general.

As a final note on data analyses, participants' gender was initially included as a factor in each test. It was not expected that gender differences would emerge in this particular task, but due to the occasional occurrence of gender effects in the spatial cognition literature (e.g., Kearns, Warren, Duchon, & Tarr, 2002; Montello, Lovelace, Golledge, & Self, 1999; Shepard & Metzler, 1971; Silverman, Choi, & Peters, 2007; Silverman & Eals, 1992; Vandenberg & Kuse, 1978; Voyer, Postma, Brake, & Imperato-McGinley, 2007; Voyer, Voyer, & Bryden, 1995), the effect of participants' gender was examined. Because no effects or meaningful interactions of gender attained statistical significance for any dependent measure, gender was dropped from the final analyses and will not be reported.

Experiment 1

While Wang and Spelke's (2000) study has inspired several subsequent research efforts (e.g., Holmes & Sholl, 2005; Mou, et al., 2006; Sargent, et al., 2008; Waller & Hodgson, 2006), none of this research was concerned with the findings of Wang and Spelke's Experiments 4 and 5, which examined the role of spatial information about the environment during and after disorientation. Because there are no extant replications of Wang and Spelke's findings in these experiments, a prerequisite to using this paradigm will be to replicate their findings. That is, a continuous visual cue is sufficient to maintain orientation and prevent an increase in configuration error, whereas a visual cue given as a reminder after the rotation is not sufficient to prevent the increase in configuration error despite providing information about the participant's orientation. In Experiment 1, these two conditions were combined and manipulated within participants. Each participant in Experiment 1 learned two different sets of six targets. During one of these sets (order counterbalanced), a directional light source was available during learning and testing but not during the rotation. During the other set the light source was available throughout learning, testing, and the rotation.

Given Wang and Spelke's findings, it was expected that participants' configuration error and latencies will increase after rotation only for the condition in which the lightness gradient is unavailable during rotation, leaving the participant perceptually disconnected from the environment and disrupting transient spatial knowledge of the environment.

Methods

Participants. Thirty undergraduate students (16 female) from Miami University participated in Experiment 1 in exchange for credit in an introductory Psychology course. Participants mean age was 19.4 (SD = 1.59). All data from one male participant were omitted because of technical difficulties. Pointing estimate data only for two female participants were removed from a single layout (one of each condition) due to a failure of the tracking equipment.

Materials. Experiment 1, and all of the subsequent experiments, were largely based on Wang and Spelke's (2000) materials and procedures, but did deviate in several important ways, as noted below. Like Wang and Spelke's experiments, participants in Experiment 1 learned the locations of six objects (e.g., glue, tape, disk, marker, calculator, notepad) arranged on the lab floor surrounding them. In order to combine Wang and Spelke's Experiments 4 and 5 into a single, within-participant design, each participant was asked to learn two sets of targets. Each set of objects was thematically different (i.e., office supplies, sports equipment) in an effort to prevent between-set interference. Also, to alleviate any influence of a specific object arrangement, the locations of targets within each set were pseudo-randomly selected for each participant from a set of 15 possible locations that were staggered around the room to create irregular arrays (see Fig. 1).

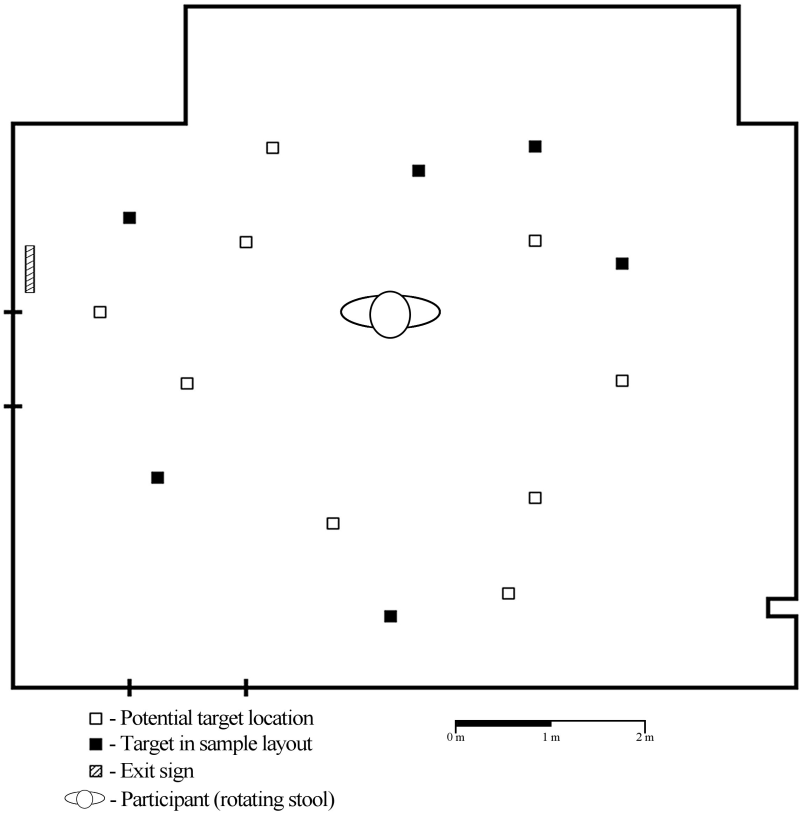

Figure 1: Schematic layout of the testing room. The 6 filled boxes indicate a sample layout of targets selected from the 15 possible locations.

Participants were tested while seated on a revolving stool in the center of the target array (see Fig. 2), and indicated the direction of each object by manually pointing to it. However, whereas Wang and Spelke's participants were tested within a small booth that occluded their view of the targets, no booth was used in the present experiments, (see also Holmes & Sholl, 2005; Waller & Hodgson, 2006).

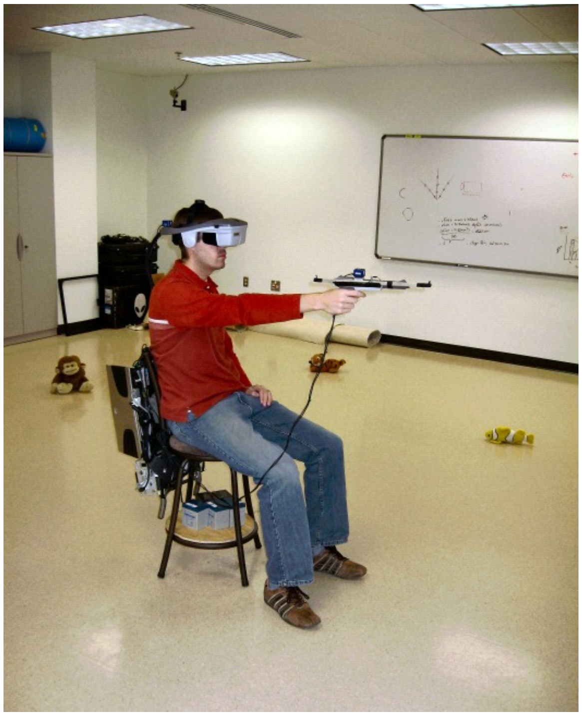

Figure 2: An example participant demonstrating the testing apparatus.

Rather than creating a lightness gradient via a translucent blindfold and single light source similar to that used by Wang and Spelke, participants in Experiment 1 viewed a 'redness' gradient inside of a head mounted display (HMD; that otherwise blocked participants view of the room (Virtual Research V8; dual VGA displays with 100% binocular overlap & 60º diagonal field of view). The facing direction of the HMD was tracked with an Intersense InertiaCube2, and the display presented participants with a view of the inside of a virtual cylinder that was textured with a red-to-black gradient. The reddest part of the gradient represented the direction of a red exit sign above the main lab entrance, and participants were made aware of this correspondence. Thus, when participants were physically oriented to face the exit sign, the view in the headset was very bright red in the center with increasingly darker shades of red towards the edge of the screen. Likewise, facing 90º to the right of the exit sign would display a medium shade of red with brighter shades toward the left edge of the screen and progressively darker shades toward the right. The view in the HMD was updated at 72 Hz, giving participants continuous – albeit abstract and non-specific – information about their facing direction. In line with Wang and Spelke's Experiments 4 and 5, respectively, this redness gradient was displayed either continually throughout the practice, pretest, rotation, and post-test, or it was displayed during the practice and testing phases but not during rotation. Text instructions were overlaid on the display to indicate which target should be pointed to and when to begin and end the rotation. White noise was played over stereo headphones built into the HMD to mask any ambient noise or directional auditory cues, such as noise from passersby in the hallway.

The simulation, white noise, presentation of instructions, and data collection were all controlled via a custom script written in the Python programming language (version 2.4 & 2.5; Python Software Foundation) and using the open source Panda3D game engine (version 1.3;

Panda3d.net) virtual reality toolkit and a custom research API written for the HIVE (for Huge Immersive Virtual Environment) research facility at Miami University (see Waller, Bachmann, Hodgson, & Beall, 2007). The script was run on a Thermite (Quantum3D, Inc.) portable computer that was mounted on an aluminum backpacking frame (see Fig. 3) and affixed to the back of the rotating stool (see Fig. 2). Also attached to the backpack were the HMD's video control unit and batteries to power the equipment. In this way, the entire VR rendering system rotated freely with the participant so that participants would not get tangled in the video cable that tethers the HMD to the rendering computer. This method of providing simulated visual information is arguably overly-sophisticated and unnecessary in Experiment 1, but provides a flexible framework for presenting more sophisticated visual information and for precisely controlling the timing and availability of perceptual cues as in Experiments 2 - 4.

Pointing estimates were made with a gun-shaped pointing device equipped with two active infrared LED markers – one at the front and rear – whose positions were tracked with a four-camera optical position tracking system (PPT x4; Worldviz LLC) and used to calculate a pointing direction and distance estimate for each trial. When participants pointed and depressed the trigger button, the experiment script recorded the heading between the two lights that corresponded to a negative pitch angle. That is, the heading from back to front that was pitched towards the floor was recorded, rather than the complementary heading from front to back that was pitched toward the ceiling. The experiment script also calculated the location in which participants' pointing estimate would intersect the floor and this location's distance from the participant to generate an egocentric distance estimate.

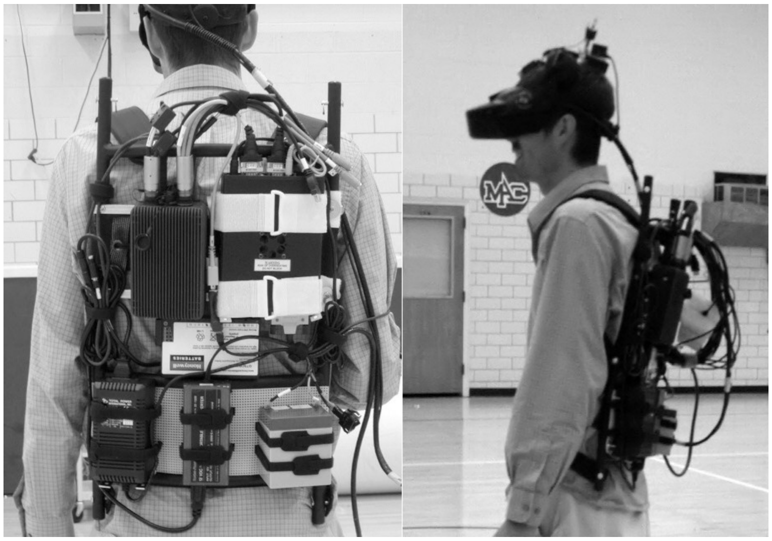

Figure 3: The backpack simulation system used in Exp. 1.

Procedures. Participants were greeted in the main lab room, given a brief description of the experiment, and introduced to the equipment before giving their informed consent. Included in this introduction was a chance for participants to view the redness gradient in the HMD and note its alignment with the exit sign. Participants were given a self-regulated study period, which generally lasted around one minute, to view the first layout and learn the location of each object. Participants were instructed that they would be asked to point to each object while blindfolded, then rotate for a full minute in whichever direction was comfortable, and finally point to each object again. Participants were also told that they would be given an eyes-open practice round with each layout, and were instructed to respond quickly and to aim accurately at the each object's spot on the floor – not just the correct direction.

At the beginning of each layout participants began in a random one of the four orientations defined by the center of each lab wall. Participants remained seated in this orientation throughout the practice phase, but were free to rotate their head and torso to comfortably point to objects that were not directly in front of them. In the practice phase, participants pointed to each object twice – once in each of two randomized blocks.

Following the practice phase, participants donned the HMD (effectively blindfolding them) and were asked to rotate a small amount (20º – 40º, direction counterbalanced) to prevent them from merely repeating the same motor movements. It has been shown previously (Hodgson, 2008; Waller & Hodgson, 2006) that a 45º rotation is not sufficient to disrupt the transient spatial system, so this small rotation should not adversely affect participants' perceptual awareness of the environment or their performance. Participants were then asked to point to each object four times – again once in each of four randomized blocks – to get a stable estimate of the represented self-to-object location of each object. This phase will be referred to as the *pre-rotation phase*. Whereas instructions for each trial were given verbally by the experimenter in the practice phase, trial instructions in the pre- and post-rotation phases were presented textually in the HMD (e.g., "Point to the Stapler").

Following the pre-rotation phase a message in the HMD prompted participants to begin rotating. After one minute, a second message informed participants that the rotation had been completed, and participants were given 25 – 30 seconds to recover from any dizziness or vestibular disturbances. Finally, participants were asked to complete a *post-rotation* phase from their new facing direction. This phase was identical to the pre-rotation phase. Each layout proceeded as described above.

Results

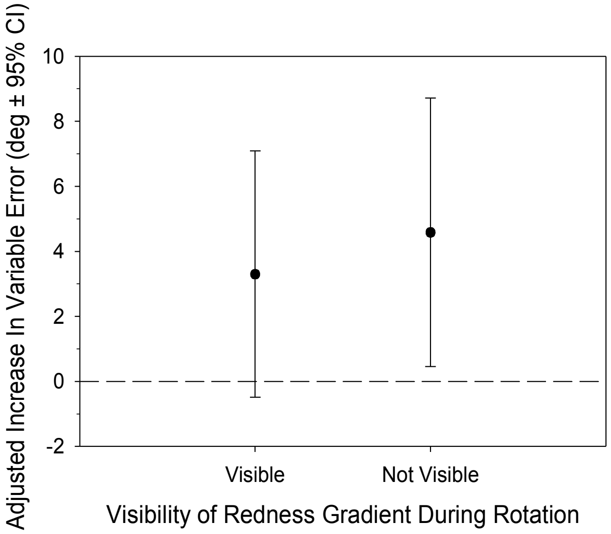

Figure 4: Adjusted variable error data for Exp. 1.

After the potentially disorienting rotation, mean heading error remained at or very near 0º in both conditions, suggesting that the visual cue was effective in informing participants of their final facing direction. Post-rotation mean heading error was -2.25º ± 2.21 and -1.46º ± 3.43 when the redness gradient was visible and not visible, respectively, during the rotation.

The mean increase in variable error for each condition in Experiment 1 is plotted in Figure 4, adjusted to exclude the predicted increase in variability based on within-object pointing error. A complete listing of pre- and post-rotation means and confidence intervals are listed in Appendix A. When the red gradient was visible throughout the experiment, participants' unadjusted variability increased by 4.33º ± 3.79, which was not significantly different than the 1.03º increase predicted by the increase in pointing error. When the red gradient was not visible during rotation, participants' unadjusted variable error increased by 6.13º ± 4.13, which was significantly higher than the 1.55º increase predicted by the rise in pointing error. The pairwise difference between the two conditions was not significant, and was estimated at 1.27º ± 5.33.

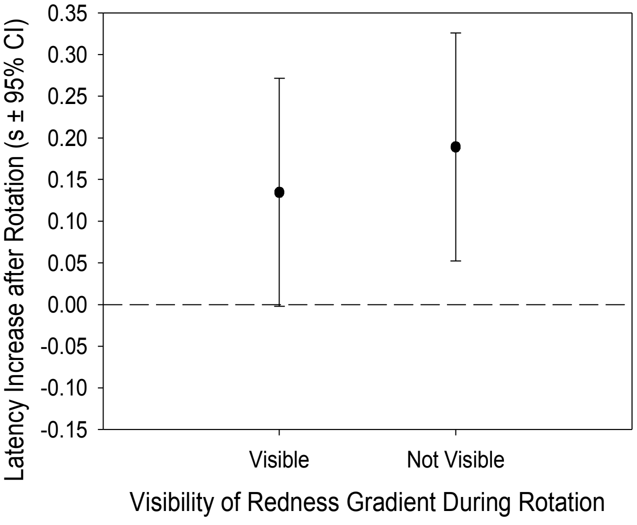

Figure 5: Latency data for Exp. 1

The mean increase in pointing error (within-item pointing variability) after rotation was significant both when the redness gradient was visible (3.20º ± 2.84) and when it was not visible (3.57º ± 3.10). The difference in pointing error increases between these two conditions was not significant, and was estimated at 0.23º ± 3.85. A complete listing of pre- and post-rotation means and confidence intervals are listed in Appendix B.

The mean increase in latency (in seconds) for each condition in Experiment 1 is plotted in Figure 5. A complete listing of pre- and post-rotation means are listed in Appendix C. When participants were able to see the redness gradient during the rotation, pointing responses did not become significantly slower after rotation (mean increase = 135 ms ± 137). Conversely, when the redness gradient was omitted during rotation, participants did exhibit a significant increase in latencies (189 ms ± 137). The difference between the two conditions was not significant, with a difference estimated at 55 ms ± 137.

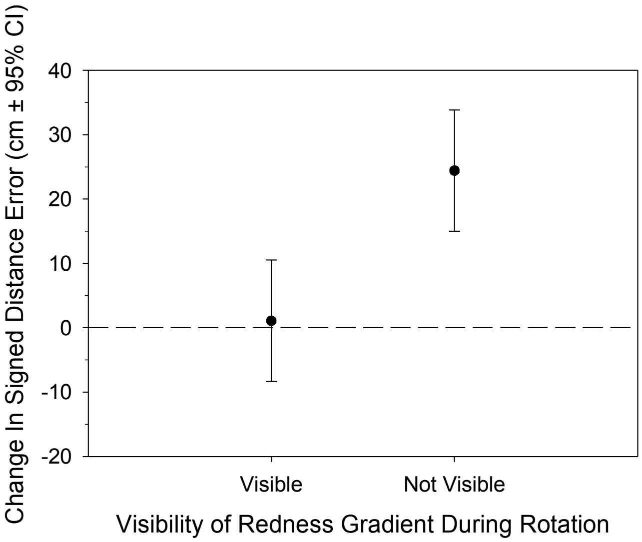

Figure 6: Signed distance error data for Exp. 1.

Post-rotation changes in signed distance error are plotted in Figure 6. A complete listing of pre- and post-rotation means and confidence intervals are listed in Appendix D. Data trends in signed distance error closely resembled those of latency and adjusted variable error. When participants could view the gradient during rotation, signed distance error did not change appreciably (1.10 cm ± 9.34). Conversely, signed distance error increased by 24.43 cm ± 9.43 when the gradient was removed, from -15.19 cm ± 13.27 to 7.89 cm from -15.19 cm ± 15.61. While this effect coincidentally was a result of participants becoming more accurate after disorientation, it nonetheless represented a reliable shift from pre-rotation distance estimates. The difference between these two conditions (24.19 cm ± 9.43) was significant.

This recurring data pattern was not exhibited in absolute distance error. When participants could view the redness gradient, absolute distance error increase significantly by 22.80 cm ± 7.98, from 80.09 cm to 100.67 cm. Similarly, absolute distance error increase by 26.91 cm ± 7.89 when participants rotated blindly, from 83.13 cm to 110.42 cm. The difference between these two conditions did not approach significance, and was estimated at 4.26 cm ±

7.98. A complete listing of pre- and post-rotation means and confidence intervals are listed in Appendix E.

Discussion

As expected, Experiment 1 replicated the variable error effects reported by Wang and Spelke (2000; Exp. 4 & 5). Having continual perceptual access to an abstract visual gradient was sufficient to prevent an increase in variable error that was greater than the increase predicted by changes in within-target pointing error. Conversely, removing the visual gradient during a prolonged period of movement (i.e., a disorienting rotation) yielded a reliable adjusted variable error increase of 4.59º. The unadjusted rise in variable error (6.13º) was also in line with the effect sizes reported by Waller & Hodgson (2006; 4º – 6º).

Wang and Spelke interpreted these effects as indicating that people's egocentric representations of self-to-object spatial relations had been successfully updated in the first case, but disrupted in the latter. Wang and Spelke also concluded that restoring perceptual access to the visual gradient after a blind, disorienting rotation was sufficient to reorient people to the environment as a whole, but did not restore the egocentric representations that had been disrupted. In the present two-systems framework these results are interpreted similarly, with the exception that once the transient (egocentric) representation is disrupted, an enduring representation takes over. Thus, rather than merely indicating a loss of self-to-object spatial knowledge, the effect is interpreted as a switch between systems; people relied on transient spatial knowledge prior to rotating blindly and then switched their reliance to an enduring spatial representation afterwards (see also Waller & Hodgson, 2006).

Importantly in Experiment 1, the same effect was obtained in variable error, latency, and one of the distance error measures. There were no significant increases when the visual gradient was present throughout the experiment, but participants' responses became 189 ms slower, 6.13º more variable, and their signed distance estimates shifted by 24.43 cm if the gradient was removed during rotation, despite people being well-oriented to the layout as a whole. These effects are predicted by a switch from a transient spatial representation to an enduring, memorial spatial representation that is less precise and requires additional processing time. These parallel findings add to a growing body of evidence that such a switch is taking place. Furthermore, the results of Experiment 1 also help to validate the use of latency increases and distance measures –

at least mean signed distance error – as an alternative metric to explore the sometimes elusive variable error effects.

There is some precedent of a person's memory of the global arrangement of objects may be distorted (e.g., Tversky, 1981), thus predicting the shift in signed distance error (i.e., overall bias). However, it is unclear why the measure of absolute distance error was not sensitive to the experimental manipulation. Absolute distance error, conceptually, is a measure of the average magnitude of each miss while signed distance error is a measure of average bias for the layout as a whole. The finding that both experimental conditions exhibited sizable, but equivalent increases in absolute distance errors (mean increase = 24.86 cm ± 7.98) suggests that the pitch component of pointing estimates became more variable after extensive rotation in both conditions. This is not necessarily an indication that some disruption of transient spatial knowledge took place that only affected absolute distance estimation, especially considering the discordance with other measures. It may be the case instead that some degree of fatigue in lifting the pointer during the final testing phase may have contributed to this increased variability; resting one's arm during the ensuing learning phase would then enable less variable performance during the pre-rotation phase of the second array. Because this is the first attempt to use any kind of distance estimates in this paradigm these findings and speculations should be considered tentative until further replication can be obtained.

A lesser, but still noteworthy contribution of Experiment 1 was to demonstrate that the simulated visual information presented in the HMD was as effective as the physical apparatus (i.e., a single light source and translucent blindfold) used by Wang and Spelke. The simulation techniques established in Experiment 1 provide great flexibility, ease-of-use, and control over the visual information available to participants and can be leveraged for future investigations.

More specifically, Experiment 1 employed a rather blunt all-or-none manipulation of visual information during movement. Participants rotated up to several thousand degrees with either constant vision of the gradient or vision only at the beginning and end. Experiment 2 employs a more fine-grained approach and investigates the idea that having intermittent visual reminders can serve to keep the transient system from being disrupted. To this end, Experiment 2 gives people intermittent visual glimpses of their environment either every 75°, 150°, 225°, or 300° during the entire course of the rotation. Experiment 3 takes this idea further by manipulating both how often people can glimpse their surroundings and the relative quality of the information that is available.

Experiment 2

Whereas Experiment 1 showed that people can remain perceptually engaged with the environment when provided with constant visual information, Experiment 2 investigated the ability to sustain transient spatial knowledge with intermittent visual fixes. This investigation is based in part on the finding of Waller and Hodgson (2006, Exp. 4), which suggested that participants could rotate up to 90° without disrupting the transient knowledge of their surroundings. In the current experiment participants were able to see brief glimpses of the environment while they rotated and the frequency of those glimpses were manipulated within participants so that during different rotations, people received a visual fix after every 75°, 150°, 225°, or 300° of rotation. It was hypothesized that getting a visual fix within 90° of movement (i.e., only the 75° condition) would allow the transient system to self-correct any error and uncertainty that had accumulated, preventing people from switching reliance to an enduring memory representation. One alternative hypothesis, of course, is that presenting people with intermittent flashes of the environment (i.e., a stroboscopic display) may be distracting or even disconcerting, causing disorientation and motion sickness.

Similar to Experiment 1, participants in Experiment 2 viewed simulated visual information rather than a physical visual cue. However, to maximize the ability for participants to get an accurate visual fix and correct any accumulated error, the visual information used in Experiment 2 was substantially more structured and concrete than the redness gradient used in Experiment 1. Specifically, participants viewed a photo-realistic virtual model of the lab room that was scaled and aligned to correspond with the physical room. Participants were able to see an accurate view of what they would otherwise be able to see if they were not blindfolded, with the exceptions that the field of view was somewhat limited in the HMD relative to natural vision, and the to-be-remembered objects were not visible.

Method

Participants. Thirty one undergraduate students (17 female) from Miami University participated in Experiment 2 in exchange for credit in their introductory Psychology course. Three participant (2 female) were removed for failing to follow directions (e.g., closing eyes while rotating). The mean age of participants was 19.3 yrs (SD = 1.94).

Materials and Procedures. Experiment 2 used the same materials and procedures as Experiment 1, with four exceptions. First, an upgraded backpack system was built and employed for Experiment 2 (and all subsequent Experiments). The new backpack system is shown in Figure 7 and employed more efficient batteries, a higher resolution HMD (nVis nVisor SX; SXGA displays, 60º diagonal FOV), and a more powerful rendering computer (Alienware Aurora M9700 laptop with dual nVidia GeForce Go 7900 GS graphics processors).

Figure 7: The upgraded backpack simulation system used in Exps. 2 - 4.

Second, instead of the simple lightness gradient of Experiment 1, Experiment 2 used a photo-realistic model of the actual room in which participants were tested. The model was constructed using Autodesk's Maya modeling software (version 8.5; Autodesk, Inc.) and it included furniture, detailed textures, lighting, and shadows (see Fig. 8).

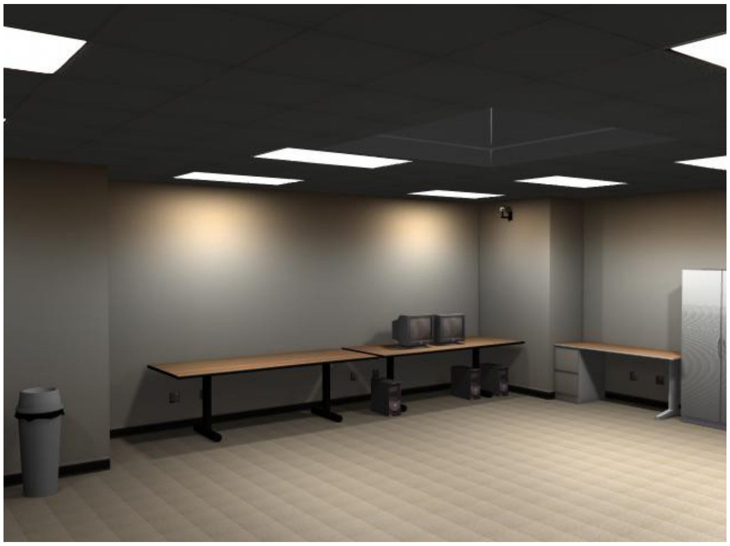

Figure 8: A screen shot of the virtual lab model used in Exps. 2 - 4.

Prior to the practice phase, participants were given an opportunity to put on the HMD and view the virtual lab room. During this period the alignment of the physical and virtual rooms were calibrated.

Participants were free to rotate 360º to familiarize themselves with the information available in the simulation and to note the 3D model's correspondence to the physical space. Throughout the experiment, the pitch of the viewpoint was dampened by a factor of one fourth so that participants could not look straight up or down. This attenuation was deemed necessary to keep the viewpoint relatively level because people sometimes droop their heads during periods where there is no visual information in the HMD, and thus could be presented with a brief view of the lab floor during a visual fix rather a useful view of the computer desk, for example. Dampening the pitch – rather than merely limiting its range – effectively kept the view centered on the most useful visual information (i.e., the walls and furniture) while still permitting some vertical movement of the head.

Third, the simulated visual information in Experiment 2 was only presented to participants in the initial familiarization phase and during the rotation. Unlike Experiment 1, participants could not see the simulated lab room during the pre- or post-rotation test phases. During these periods, participants viewed a blank grey background in the HMD. It was not expected that this period of perceptual (i.e., visual) detachment would disrupt participants' transient spatial knowledge. Participants in Waller and Hodgson's (2006) Experiment 4 were able to maintain baseline performance after several minutes of testing and a small rotation in the absence of any visual-spatial information; it was only those participants who rotated more 90º whose performance suffered (see also Hodgson, 2008).

Finally, participants in Experiment 2 were tested on four thematically distinct layouts, rather than two. Participants were tested on one set of objects with a visual fix interval of either 75º, 150º, 225º, or 300º. Both the order of the visual fix intervals and the assignment of object theme to fix interval was randomized, with the orders and combinations approximately counterbalanced across all participants. During the rotation, visual fixes were presented for a period of 400 ms , and were updated at a rate of 60 Hz during this period to display the current, accurate facing direction of the participant. It should be noted that a participant could hypothetically rotate fast enough to cover the interval between fixes in this 400 ms time span, triggering the subsequent visual fix and generating a continuous, uninterrupted stream of visual information. However, attaining this would require exceptional rotational velocities of 214.3 º/s, 428.6 º/s, 624.9 º/s, and 857.1 º/s in the four respective conditions. Alternative arrangements such as setting the visual fix intervals at a specific time interval or angular window were explored in pilot testing, but found to have similar shortcomings. For example, setting visual fixes to a specific angular window (e.g., 75º ± 2.5º) would always yield a period absent visual information regardless of rotational velocity, but participants who rotated very slowly could plausibly linger in the visual fix window and receive prolonged visual information while those who rotated quickly could pass through the visual fix window at a rate too fast to perceive adequately. Given the previous literature suggesting that amount of motion, rather than amount of time, is the crucial measure for updating performance (e.g., Elliott, 1987; Mittelstaedt & Mittelstaedt, 2001; Rieser, et al. 1990; Waller & Hodgson, 2006), it was deemed appropriate to space the fixes relative to the distance moved and independent of the amount of time elapsed. Likewise, it was deemed appropriate to give all participants a visual fix of the same temporal length to ensure that the visual fix was perceivable, but not prolonged.

Results

As in Experiment 1, participants remained well oriented after the large, potentially-disorienting rotation. Post-rotation mean heading error for the 75º, 150º, 225º, and 300º visual fix intervals were -3.23º ± 4.73, 4.12º ± 5.91, -4.06º ± 5.73, and 0.39º ± 4.57, respectively. In each case, the 95% confidence interval contained 0º.

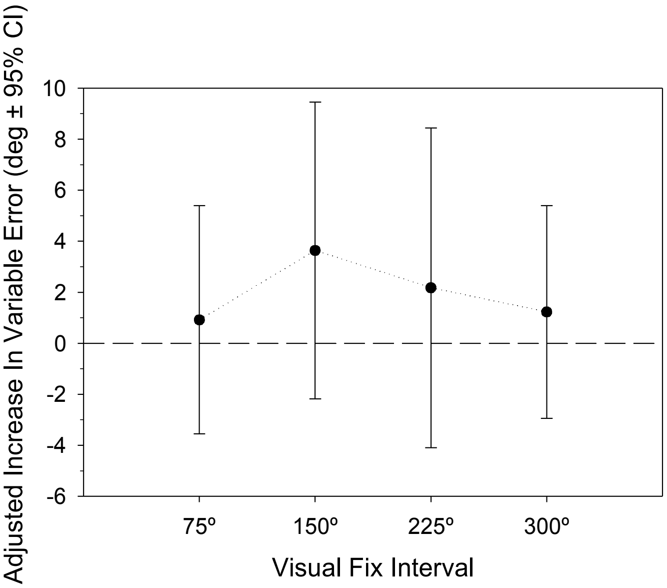

Figure 9: Adjusted variable error data for Exp. 2.

The mean increase in variable error for each visual fix interval in Experiment 2 is shown in Figure 9, adjusted to exclude any increase in within-object pointing variability. A complete listing of pre- and post-rotation means and confidence intervals are listed in Appendix A. In none of the conditions was the adjusted increase in variable error greater than zero. For the 75º condition, unadjusted variable error rose 2.01º ± 4.47, which included both zero and the 1.09º increase predicted by the rise in pointing error. Likewise, unadjusted variable error in the 150º condition rose 7.61º ± 5.82 and was not different than the 3.97º increase predicted by the rise in pointing error. In the 225° condition, unadjusted variable error rose 6.01° ± 6.27, which included both zero and the 3.83° increase predicted by the rise in pointing error. Finally, in the 300° condition, unadjusted variable error increased 3.02° ± 4.17, which includes both zero and the 1.79° increase predicted by the rise in pointing error. A repeated-measures ANOVA indicated that there were no significant differences amongst the different levels of visual fix intervals ($F < 1$). Planned comparisons testing for various step functions or polynomial trends were also conducted. There was a weak, non-significant quadratic trend to the data ($F(1, 27) = 2.57$, $p = 0.12$) due largely to the relatively larger increases for the 150° and 225° visual fix conditions, but no other contrast approached significance (all other Fs < 1.37, ps > 0.25).

Surprisingly, the increase in within-target pointing error after rotation was not homogeneous across conditions. This effect is not predicted by the hypothesis that pointing error is a source of random noise. The pointing error increase was non-significant at 75° visual fix intervals (2.19° ± 3.15), but was significant for the 150° (7.94° ± 5.44) and 225° (7.67° ± 4.78) visual fix intervals and was marginally significant for the 300° fix interval (3.59° ± 3.68, $p = 0.055$). Planned contrasts indicated that there was a significant quadratic trend to the pointing error increases ($F(1, 27) = 4.49$, $p < 0.05$). The step function comparing the 75° fix interval to wider fix intervals also approached significance ($F(1, 27) = 3.51$, $p = 0.072$). No other contrasts approached significance (Fs < 1.16, ps > 0.29). A complete listing of pre- and post-rotation means and confidence intervals are listed in Appendix B.

The mean increase in latency for each visual fix interval for Experiment 2 is presented in Figure 10. Participants' response times did not increase significantly when visual fixes were available every 75° (mean increase = 53 ms ± 138). Conversely, participants exhibited significantly non-zero increases in response time for conditions in which visual fixes were presented less frequently (mean

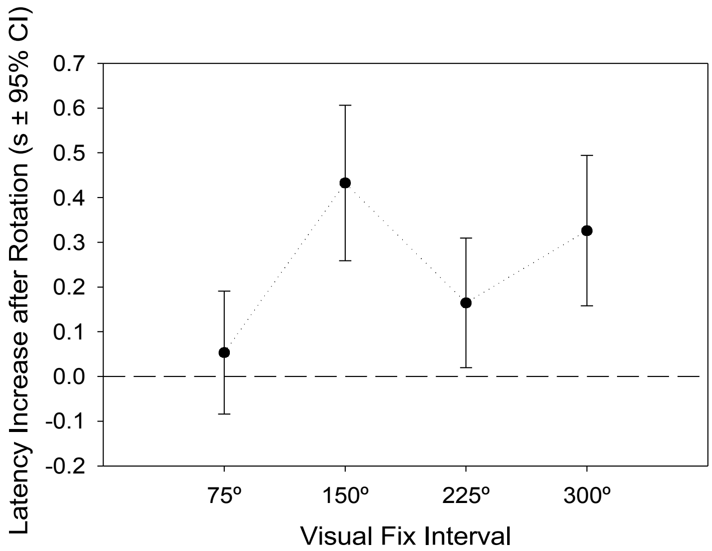

Figure 10: Latency data for Exp. 2.

increases of 433 ms ± 174, 165 ms ± 145, and 326 ms ± 168 for visual fix intervals 150°, 225°, and 300°, respectively). A repeated-measures ANOVA indicated a significant effect of visual fix interval (F(2, 65) = 3.64, $p > .05$). Planned contrasts indicated that this effect was driven by the difference between the 75° condition and the 150°, 225°, and 300° condition. This difference was estimated at 254 ms ± 183, and accounted for 76.13% of the variance of the main effect. No other contrasts approached significance (all $F < 1.00$).

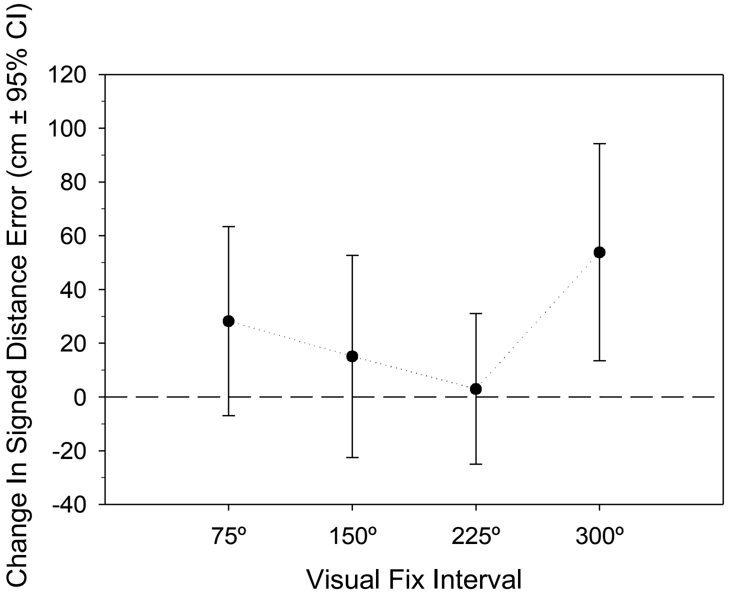

Figure 11: Signed distance error data for Exp. 2.

Changes in signed distance errors are shown in Figure 11. Means and confidence intervals for each phase and condition are listed in Appendix D. Signed distance errors were noticeably affected by the frequency of visual fixes, but not in the same manner as latencies. Specifically, there was no significant change in signed distance error when visual fixes were presented every 75°, 150°, or 225° (increases of 28.23 cm ± 35.19, 15.11 cm ± 37.64, and 2.99 cm ± 28.02, respectively). However, there was significant increase in signed distance error (53.84 cm ± 40.39) when participants were presented with visual fixes spaced 300° apart increased. Mean distance errors in this condition changed from -20.70 cm before rotation to 33.14 cm afterwards. A repeated-measures ANOVA testing the effect of visual fix interval on the mean change in signed distance error indicated that the main effect of fix interval was not significant ($F(4, 98) = 1.18, p = 0.319$). Despite the pattern of means, the planned comparison testing the 300° fix interval against all smaller intervals ($F(1, 27) = 2.14, p = 0.155$) was not significant. The only other contrast to approach significance was the quadratic trend ($F(1, 27) = 1.84, p = 0.186$; all other Fs < 1), but this effect was in the opposite direction as would be predicted to be meaningful and instead reflected relatively poor performance at the 75° and 300°.

Changes in absolute distance error exhibited a similar pattern. There were significant increase in absolute distance error when visual fixes were presented every 75º or 300º (38.83 cm ± 32.34 and 64.03 cm ± 38.46, respectively), but not for the two middle conditions (20.25 cm ± 33.88 and 11.30 cm ± 25.34, respectively). A repeated-measures ANOVA testing the effect of visual fix interval on the mean change in absolute distance error failed to detect a main effect of visual fix interval (F (3, 68) = 1.59, p = 0.206). As with signed distance error, only two planned comparison approached significance: the contrast testing the 300º fix interval against all smaller intervals (F (1, 27) = 2.635, p = 0.116) and the contrast testing for a quadratic trend (F (1, 27) = 2.90, p = 0.100; all other Fs < 1). Neither effect attained significance. A complete list of means and confidence intervals for each phase and condition is available in Appendix E.

Discussion

The results of Experiment 2 are somewhat mixed. Whereas the increases in variable error were not significant for any condition, the increases in latency exhibited a comparatively clear pattern in which participants were able to respond efficiently in the 75º condition, but required additional processing time for visual fix intervals of 150º or larger. This pattern, somewhat surprisingly, was apparent in within-target pointing error increases as well. In the exploratory measure of signed distance error, participants showed no significant changes in bias for visual fix intervals up to 225º, but did exhibit a large (relative to Exp. 1) and significant shift towards distance overestimation when visual fixes were spaced at 300º intervals. A similar pattern was apparent in absolute distance error, with a significant increase of 64.03 cm when visual fixes were spaced at 300º. However, there was also an unexpected (although smaller) increase of 38.83 cm for the most frequently presented visual fixes (i.e., 75º).

As noted previously, the effect of a disrupting rotation on variable error across the extant literature is often small (2º - 6º) and occasionally difficult to replicate. Compounding this problem in Experiment 2 was a relatively higher level of variability than was seen in Experiment 1 (e.g., mean confidence interval widths for variable error = 3.96º and 5.18º in Exp. 1 and 2, respectively). It may be the case that Experiment 2 did not have enough power to detect an effect of variable error. Equally likely is the possibility that individual differences in the ability to make use of the visual fix information contributed to the lack of clarity in the effect of variable error. It can be noted that a similar problem affects signed distance error (mean confidence interval width = 35.31 cm and 9.43 cm in Exps. 1 & 2, respectively) as well as absolute distance error (mean confidence interval width = 32.51 cm and 7.89 cm in Exps. 1 & 2, respectively).

It is interesting though, that despite there being no reliable effect of visual fix interval on between-target variable error, the same was not true for within-target pointing error. Wang and Spelke's original paradigm tested participants on a single layout of targets, and correctly pointed out that there was no reasonable way to distinguish between pointing error increases that result from changes in target's represented direction and changes in participant's estimate of their global heading. Thus, they and others using their paradigm have largely treated pointing error as a source of noise to be accounted for (Mou, et al. 2006). In the present Experiment 2, however, participants completed multiple layouts in which post-rotation heading error was homogeneous across conditions both in terms of mean and variability. Thus, the hypothesis that larger pointing error increases were the result of more frequent fluctuations in participant's estimates of their heading seems untenable and cannot explain the observed fluctuations in pointing error. Experiment 2 suggests that participants may be more likely to change their estimate of a target's location from trial to trial when their transient knowledge has been disrupted by, for example, re-assessing their first estimate of an object's location based on later judgments of adjacent object's locations. Such a high-level cognitive strategy is accommodated by effortful processes that reconstruct information from memory. Additionally, the presence of such a strategy may be particularly noticeable in the present experiment because of the higher number of pointing estimates per target; participants had greater opportunity to change their pointing estimate – consciously or otherwise.

Regardless of its cause, the trend in pointing error increases across conditions suggested that participants struggled with fix intervals of 150º or larger. The one exception to this trend was the marginally non-significant increase in pointing error for the 300º fix interval condition. It may be the case that having a glimpse of the environment at an interval very close to 360º is a relatively useful cue as it can approximately demarcate one full rotation. This issue aside, the trend in pointing error was remarkably consistent with the pattern of latency increases.

Compared to the peculiarities of the error measures, the pattern of latencies was relatively straightforward and indicated a difference between visual fix intervals of less than 90º (i.e., the 75º condition) and those above. This was the predicted data pattern and is consistent with the findings of Waller and Hodgson (2006) that participants could maintain transient spatial knowledge of to-be-remembered objects through rotations up to 90º, but not through rotations of 135º or more.

During a blindfolded rotation, people would be expected to accumulate perceptual error and uncertainty in estimating precisely how far they had traveled and where the to-be-remembered objects were in relation to their current heading. For layouts during which participants were given visual reminders every 75º, this error and uncertainty could be corrected. When visual reminders were spaced further apart, participants' perceptual uncertainty may have already increased to the point of being deemed unreliable. In such a case, a visual fix could serve two potential roles. First, it is possible in these cases that a visual fix may not correspond with where participants' felt they were facing, and could thereby introduce a source of interference or prove distracting. Second, it is also possible that each of the visual fixes was useful, but that participants' could rotate only approximately 90º beyond the visual fix before the error once again accumulated beyond its reliable threshold, leading to a cycle of disruption and reorientation. Thus, at the termination of the rotation it would have been more than 90º beyond the last visual fix, leaving participants' transient spatial knowledge in a final state of disruption. The current experiment can not distinguish between these (or other) possible explanations, but it is clear that providing brief visual fixes every 75º benefited participants and kept them perceptually engaged with the environment whereas less frequent fixes did not. This benefit was apparent in response latency and within-target pointing error. It is unclear why the same effect was not replicated in between-target variable error or in distance errors.

One final point worth noting is that participants remained well oriented in all conditions, despite rotating in excess of 1800º (mean heading error for all conditions = -0.70º ± 5.23) with relatively little visual-perceptual support. Unlike Experiment 1, participants did not have access to some visual cue throughout testing that informed them of their final heading. Thus, it can be concluded that the visual fixes were useful in keeping participants oriented to the environment as a whole, even if their perceptual awareness of the relative configuration of objects was disrupted.

Experiment 3

Experiment 2 showed that intermittent visual information can be used to sustain transient spatial knowledge and keep people perceptually engaged with their environments. Experiment 3 was designed to further explore this effect by investigating what visual information is sufficient to enable this ability and how the quality of information interacts with the frequency of its presentation. For example, it seems likely upon introspection that a brief glimpse of the rather abstract and non-specific visual information presented in Experiment 1 (i.e., a redness gradient) would be unlikely to help people to reorient precisely. The visual gradient was useful for remaining oriented when it was constantly perceivable, but a brief glimpse would likely only give an approximate bearing that contained enough uncertainty in and of itself as to be relatively useless in correcting perceptual uncertainty. Even with such abstract visual information however, there may be some range of visual fix intervals small enough as to approximate continuous information, and thus be helpful. Additionally, it can be seen that the successfully used visual information in Experiment 2 was simultaneously more complex, more concrete, more detailed, and more relevant to the physical environment than the redness gradient of Experiment 1. Thus, there are several factors that could contribute – independently or in concert – to the usefulness of the visual fix. Experiment 3 investigates these issues by manipulating both the type of visual information being presented (between participants) and the frequency of the visual fixes (within participants).

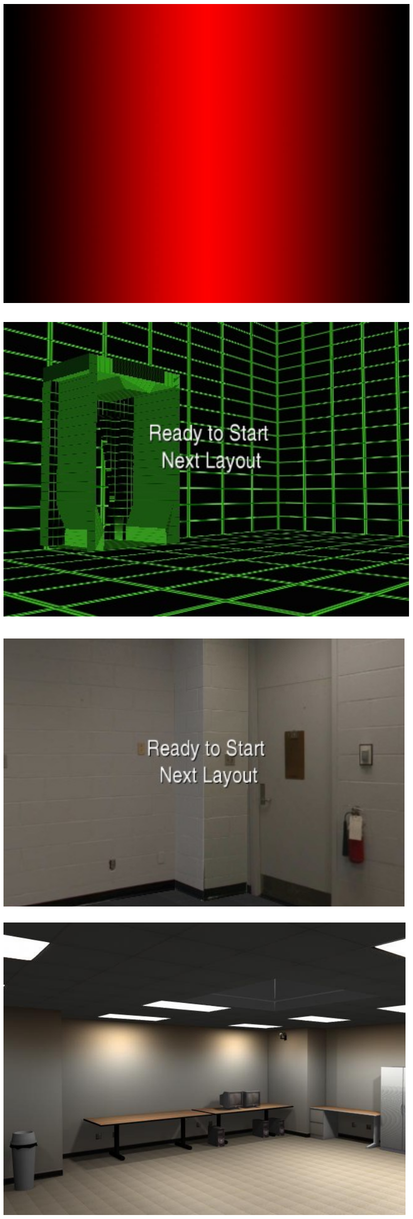

Figure 12: Screen shots of the four types of visual stimuli used in Exp. 3.

To this end, four different groups of participants were presented with either the redness gradient used in Experiment 1, a rectangular room rendered as a wireframe with a doorway on one side but no other details or textures, a photo-realistic virtual model of a different room (i.e., not the testing room), or the photo-realistic model of the lab room used in Experiment 2 (see Fig. 12). The wireframe room contained useful geometric features (e.g., “I'm facing the corner of the room.”) and a salient directional marker on one side to inform participants that they had made a full circuit. The photo-realistic other room also contained geometric cues, but also included many distinct features such as a fire extinguisher, doorway, and white-board that could be used as landmarks. The photo-realistic model of the actual testing room contained these geometric cues and abundant landmarks as well, but this information was arguably more relevant to the task at hand as the physical counterparts of the virtual landmarks were visible during learning and could be more easily used as associative cues (e.g., “The disk was next to the computer desk.”).

Because Experiment 2 suggested that visual fixes were effective when given every 75º but not for intervals of 150º or larger, 150º was used as the upper bound of visual fix intervals in Experiment 3. It seems likely that the virtual model of the actual environment represents a best case scenario, and that performance in the other three conditions (i.e., those with degraded and / or less useful visual information) should not exceed this threshold. Thus, participants completed four layouts of objects, and visual fixes were presented at intervals of 37.5º, 75º, 112.5º, or 150º (order randomized).

Experiment 3 is relatively exploratory in nature, and the predictions are naturally less solidified. However, it is generally predicted that better quality visual information will need to be viewed less frequently to be useful. In other words, it is predicted that performance will rely jointly on the visual fix interval and the quality of visual information, such that higher quality visual information will needed less frequently and lower quality visual information will need to be seen more often to prevent the transient updating system from being disrupted.

Methods

Participants. One hundred and eight undergraduate and graduate students (60 female) from Miami University participated in Experiment 3 either in exchange for credit in an introductory Psychology course or in exchange for $10. The mean age of participants was 19.8 (SD = 2.10). Data from one female participant was excluded because she was exhibiting a severe speed-accuracy trade-off; deliberating extensively on each trial. Indeed, the response time cutoff employed in the latency analyses (10 s) would have excluded nearly 60% of her data (mean RT = 16.17 s). Data from a single layout was excluded for four additional participants due either to technical difficulties (e.g., the laptop battery running out) or because a participant was experiencing simulator sickness and elected not to continue.

Materials and Procedures. Experiment 3 used the same materials and procedures as Experiment 2 with the following two exceptions. First, the visual fix intervals were restricted to a smaller range (37.5º, 75º, 112.5º, or 150º) to obtain a more fine-grained test of how frequently visual fixes are required and how this threshold changes with the quality of visual information. Second, additional virtual environments were created to provide varying levels of visual fix quality. Specifically, Experiment 3 used the cylinder textured with a redness gradient from Experiment 1 and the photo-realistic model of the lab room from Experiment 2, but also introduced two new environments. First, a rectangular-shaped wireframe room was used that portrayed the floor, walls, and ceiling as a coordinate grid with green lines. These grids provided basic textural information and distance cues (i.e., more distal grid units appeared smaller), and a participant could use the grids or the corners between them to inform her, for example, of her current orientation relative to the corners of the room or the center of a wall. Additionally, a wireframe doorway was rendered along one wall to provide a conceptual front to the model and inform the participant that they had completed a full revolution. The model was aligned with the actual lab room so that facing a corner of the wireframe room corresponded to facing a corner of the actual lab room. Likewise, the wall containing the wireframe door was aligned so that it corresponded to the wall containing the entrance to the physical lab. The final virtual environment was a photo-realistic model of a different lab room, and contained detailed textures, shadows, lighting, and furniture. It was similarly aligned to the physical lab space so that facing a corner in the virtual room corresponded to facing a corner of the physical space. There was also a virtual doorway in the direction of the physical lab entrance. The color, features, and building materials in this virtual room were sufficiently different from the actual lab room so as not to confuse participants into thinking that it was, for example, a slightly distorted recreation of the actual testing room.

Results

As in Experiments 1 and 2, participants remained well oriented after the potentially disorienting rotation. Mean heading errors after rotation for each condition are presented in Table 1. In all cases, heading errors were at or near zero. The only condition whose post-rotation 95% confidence interval failed (narrowly) to include 0º was the realistic actual room presented every 112.5º (mean heading error = 6.97º ± 6.32).

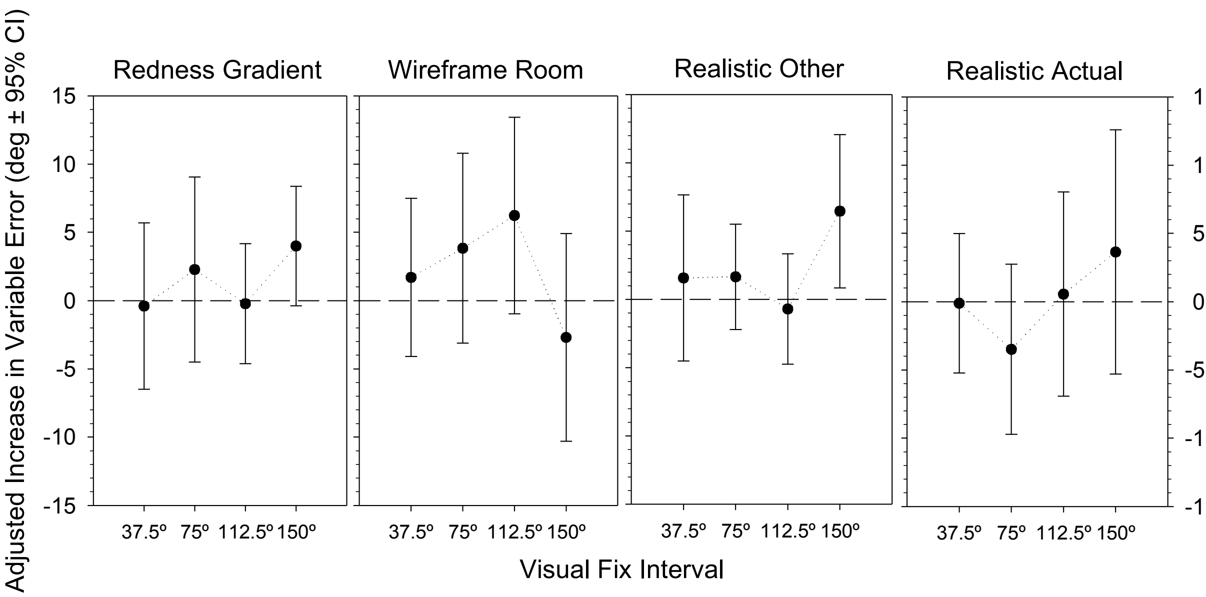

Figure 13: Adjusted variable error data for Exp. 3.

The mean increase in variable error for each visual fix interval and each type of visual information is shown in Figure 13, adjusted to remove any influence of within-object pointing variability. Means and confidence intervals for unadjusted variable error increase are listed in Table 1. Pre- and post-rotation means for each condition are listed in Appendix A. While there was a trend for participants to do well with visual fixes of 112.5° or less and show an increase in variable error when visual fixes were presented every 150°, this pattern was largely accounted for by increases in pointing error. The mean increases in variable error at the 150° fix interval were 9.81° ± 4.38, 1.42° ± 7.61, 8.88° ± 5.62, and 9.64° ± 8.95 for the red gradient, wireframe grid room, realistic other room, and realistic actual room, respectively; the associated predicted increases based on pointing error were 5.81°, 4.12°, 2.41°, and 6.01°. Only participants in the realistic other room showed a significantly higher increase in variable error than was predicted for that condition. A 4 (visual information type; between participants) X 4 (visual fix interval; within participants) mixed-model ANOVA indicated that there was no omnibus main effect of visual fix interval ($F < 1$) or of visual stimulus type ($F < 1$). Neither did the two factors interact ($F(9, 285) = 1.10, p = 0.361$). A simple effects analysis was conducted to examine the effect of visual fix interval separately for each visual stimulus type. In none of the visual stimuli conditions was the main effect of fix interval significant (all Fs < 1.29, ps > 0.285). Likewise, none of the planned comparisons attained significance (all Fs < 2.81, ps > 0.107).

Table 1.

Experiment 3 Error Data

Redness Gradient

Visual Fix Interval	*Post-Rotation Heading Error*	*Increase in Pointing Error*	*Increase in Variable Error*	*Change in Distance Error*
37.5°	-1.60° ± 4.48	-1.51° ± 2.61	-1.15° ± 6.10	-11.86 cm ± 18.27
75.0°	-2.14° ± 6.25	2.68° ± 4.33	3.62° ± 6.78	-6.53 cm ± 22.23
112.5°	-1.09° ± 3.07	5.75° ± 3.48*	2.65° ± 4.39	-9.94 cm ± 19.11
150.0°	7.92° ± 9.62	11.62° ± 6.25*	9.81° ± 4.38*	-2.23 cm ± 12.48

Wireframe Grid Room

Visual Fix Interval	*Post-Rotation Heading Error*	*Increase in Pointing Error*	*Increase in Variable Error*	*Increase in Distance Error*
37.5°	0.50° ± 3.68	4.00° ± 4.34	3.70° ± 5.80	35.48 cm ± 16.07*
75.0°	-5.42° ± 8.54	6.12° ± 5.56*	6.89° ± 6.96	57.10 cm ± 26.52*
112.5°	1.55° ± 8.00	8.45° ± 7.53*	10.46° ± 7.20*	50.94 cm ± 23.46*
150.0°	-0.13° ± 6.71	8.24° ± 6.61*	1.42° ± 7.61	32.30 cm ± 41.77

Realistic Other Room

Visual Fix Interval	*Post-Rotation Heading Error*	*Increase in Pointing Error*	*Increase in Variable Error*	*Increase in Distance Error*
37.5°	1.75° ± 6.30	6.79° ± 4.41*	4.97° ± 608	-2.42 cm ± 16.55
75.0°	-3.34° ± 3.44	3.03° ± 4.89	3.17° ± 3.86	-11.11 cm ± 15.74
112.5°	1.17° ± 3.93	3.11° ± 3.17	0.86° ± 4.04	-0.06 cm ± 10.34
150.0°	-6.01° ± 6.21	4.83° ± 4.54*	8.88° ± 5.62*	-2.18 cm ± 10.71

Realistic Actual Room

Visual Fix Interval	*Post-Rotation Heading Error*	*Increase in Pointing Error*	*Increase in Variable Error*	*Increase in Distance Error*
37.5°	2.60° ± 3.91	3.60° ± 4.30	1.69° ± 5.11	-8.39 cm ± 10.92
75.0°	-0.20° ± 3.18	4.02° ± 2.52*	-1.48° ± 6.24	-19.05 cm ± 9.75*
112.5°	6.97° ± 6.32*	4.98° ± 4.83*	3.05° ± 7.48	-10.51 cm ± 8.87*
150.0°	-0.53° ± 8.37	12.02° ± 4.97*	9.64° ± 8.95*	-10.48 cm ± 17.19

Note: Variable Error Scores are raw increases, not adjusted increases;
Distance error scores are the changes in signed distance error
* – Denotes significant at $p < 0.05$

As in Experiment 2, the increase in pointing error after rotation was not homogeneous across conditions. Pointing error increases (and 95% confidence intervals) for each fix interval and type of visual information are listed in Table 1, and a full listing of pre- and post-rotation means are available in Appendix B. A 4 (visual information type; between participants) X 4 (visual fix interval; within participants) mixed-model ANOVA indicated that there was a main effect of visual fix interval (F (3, 274) = 5.64, $p < 0.01$) and an interaction between fix interval and visual information type (F (9, 274) = 2.05, $p < 0.05$). The main effect of visual information type was not significant ($F < 1$). Simple effects analysis and planned contrasts were conducted at each level of visual information type to test for effects of visual fix interval. For the wireframe grid and the realistic other environment, there were no main effects (Fs < 1) or contrasts that approached significance (Fs < 1.92, ps > 0.17). Conversely, there were significant main effects of visual fix interval for both the redness gradient (F (2, 47) = 6.55, $p < .01$) and the realistic actual room (F (3, 67) = 4.02, $p < .05$). Planned comparisons indicated that the effect for participants viewing the redness gradient was best explained by the step function comparing the 37.5º to all wider fix intervals (F (1, 25) = 21.82, $p < 0.001$). Similarly, the effect for participants viewing the realistic actual environment was best explained by the step function comparing the 150º condition to all narrower fix intervals (F (1, 25) =8.51, $p < 0.01$).

Figure 14 shows the mean increase in latency after rotation for each visual fix interval in Experiment 3, plotted separately for each type of visual information. Means for pre- and post-

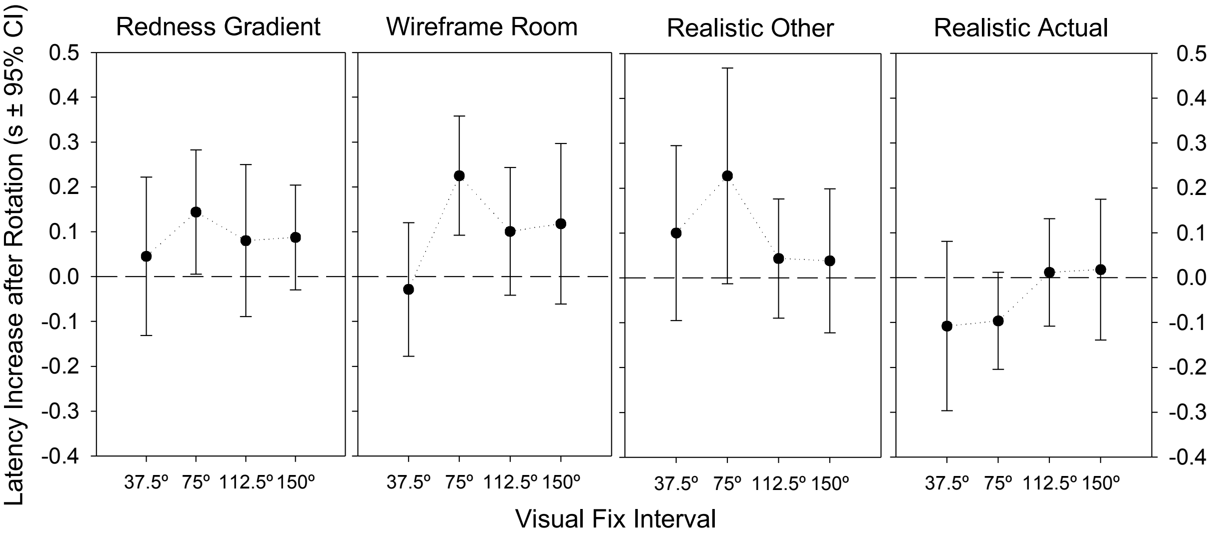

Figure 14: Latency data for Exp. 3.

rotation phases of each condition are listed in Appendix C. Unlike Experiment 2, no systematic pattern was apparent. Participants did not show a significant increase in post-rotation latency in any condition, save for two: the redness gradient at the 75º visual fix interval (mean increase = 144 ms ± 138) and the wireframe grid room also at the 75º visual fix interval (225 ms ± 133). A 4 (visual information; between participants) x 4 (visual fix interval; within participants) mixed-model ANOVA indicated no main effects or interaction (all *F*s < 1.15, *p*s > 0.33). Simple main effects analyses and planned contrasts across visual fix intervals were conducted separately for each type of visual information, but also yielded no significant effects. The only contrast to approach significance was that comparing the 37.5º visual fix interval to all wider visual fix intervals for the wireframe room ($F(1, 25) = 3.07$, $p = 0.092$).

The change in signed distance error is listed for each visual stimulus type and fix interval in Table 1 and plotted in Figure 15. As with other measures, the patterns of mean signed error across conditions did not lend themselves to a clear interpretation. A 4 (visual stimulus type; between participants) X 4 (visual fix interval; within participants) mixed-model ANOVA was conducted on the change in signed distance error for each condition. There was a main effect of visual stimulus type (F (3, 99) = 5.89, $p < 0.001$) that was characterized by relatively poor performance in the wire-frame VE compared to the other three conditions. The omnibus effect of visual fix interval was non-significant ($F < 1$) and the two factors did not interact ($F < 1$). A repeated-measures ANOVA was conducted separately for each type of visual stimulus to test for

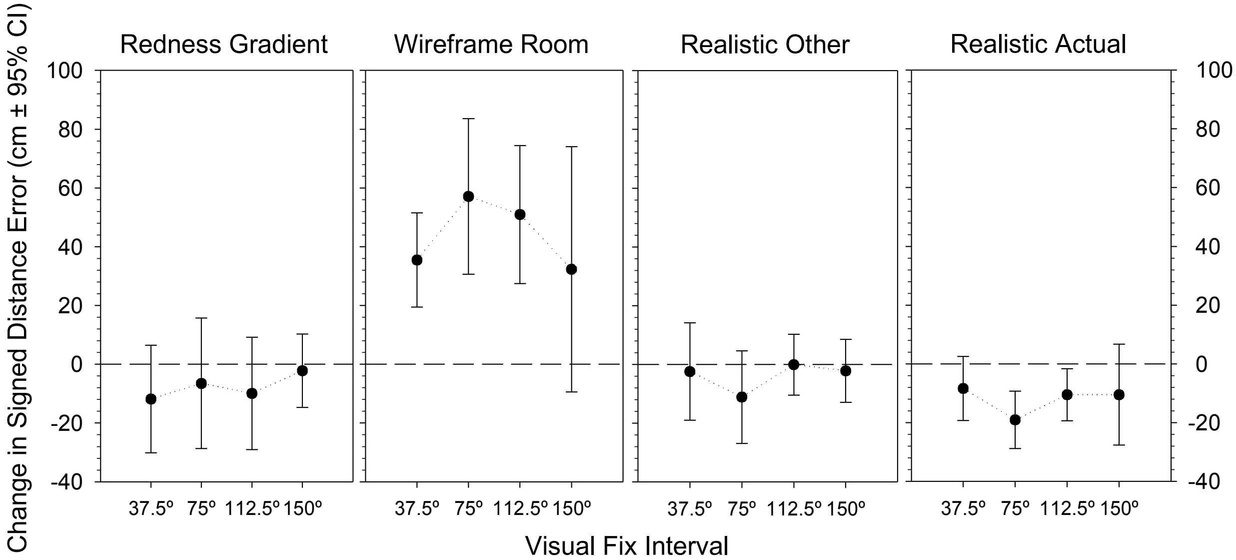

Figure 15: Signed distance error data for Exp. 3.

a simple effect of visual fix interval and to conduct planned comparisons. The main effect of visual fix interval was not significant in any condition (all *F*s < 1). Likewise, no planned comparison approached significance (all *F*s < 1.08, *p*s > 0.309).

Mean absolute distance errors and confidence intervals for each phase and condition of Experiment 3 are listed in Appendix E, along with the associated change after rotation. Generally, results were similar to those of signed distance error. A 4 (visual stimulus type; between participants) X 4 (visual fix interval; within participants) mixed-model ANOVA indicated that there was a main effect of visual stimulus type ($F(3, 99) = 5.19$, $p < 0.01$). Again, this was due to relatively poor performance in the wire-frame VE compared to the other three conditions. The omnibus effect of visual fix interval and stimulus type by fix interval interaction were not significant (*F*s < 1). A repeated-measures ANOVA was conducted separately for each type of visual stimulus to test for a simple effect of visual fix interval and to conduct planned comparisons. In none of the visual stimuli conditions did the main effect approach significance (all *F*s < 1.69, *p*s > 0.198. Likewise, no planned contrast attained significance (all *F*s < 2.36, *p*s > 0.137).

Discussion

It was predicted that having access to lower-quality visual fixes would be less useful, and thus would be required more often. In other words, people's transient spatial representations were expected to be more likely to remain in a state of disruption at smaller visual fix intervals when visual cue quality was poor. However, there was little evidence to support this hypothesis. The only data conforming to this prediction came from comparing the within-target pointing error from the richest and most impoverished visual cues. For participants viewing the redness gradient, pointing errors exhibited a step function after 37.5º. For participants viewing the realistic model of the actual testing room, pointing errors exhibited a step function after 112.5º. The middling levels of visual information, however, did not yield an intermediary step function after 75º to complete the predicted pattern. Thus, the results of Experiment 3 were largely inconclusive and suffered from relatively low agreement between dependent measures.

As with Experiment 2, there was relatively high noise in the variable error measure as compared to Experiment 1 (mean confidence interval width = 3.96º and 6.04º for Exp. 1 and 3, respectively). There was a numeric trend in three of the conditions (excluding the wireframe room) for unadjusted variable error to increase for visual fix intervals of 150º but not for smaller angles – an effect that corresponded well to the latency and pointing error findings of Experiment 2. However, this effect only attained significance for the realistic other room condition. Anecdotally, it is worth noting that many participants voluntarily commented at the difficulty of this particular condition (e.g., "That third set was really hard, but I think I did pretty well on the other ones."). Also noteworthy is the observation that the magnitude of unadjusted variable error increases in the 150º conditions (9.18º, 8.88º, and 9.64º for the gradient, realistic other, and realistic actual room, respectively) were comparatively larger in magnitude than the effects obtained by other studies (4º - 6º, 4º, and 6.13º for Waller & Hodgson, 2006; Mou, et al., 2006; and the present Exp. 1, respectively). While this does not constitute conclusive evidence by any means, these observations are certainly consistent with the idea that high variability in Experiment 3 may have masked a true, but small effect that replicated the findings of Experiment 2. Unfortunately these conclusions must remain as only speculation for the time being.

Further compounding the interpretation of Experiment 3 is the unclear pattern of increases in latency across conditions. This measure had proven to be relatively robust in previous investigations of spatial updating (e.g., Amorim, et al., 1997; Hodgson, 2008) and in the previous experiments in the present investigation. The patterns of mean latency increases in Experiment 3 were relatively erratic across visual stimuli conditions, and did not conform to any predicted data pattern.

The pattern of distance errors was also relatively inconclusive in Experiment 3, with the exception that there was a clear trend for participants viewing the wireframe environment to exhibit larger absolute distance errors and and to shift their mean estimate towards under-estimation. For participants in every other condition, there was a (non-significant) trend towards overestimation, and relatively smaller (if any) increases in absolute error. It is unclear why participants in viewing the wireframe room performed so poorly relative to their counterparts in the other three conditions, but it may be an indication that the information available in the wireframe room was less useful than the other cues used in Experiment 3.

One a more general and positive note, it can be noted that despite a relative lack of consistent or interpretable trends, participant's latency increases were not significantly different from zero in all but one condition. The same was true for the adjusted increase in variable error, and for signed distance error in most conditions This suggests that the visual fixes may have been useful in almost all cases to keep people perceptually engaged with their environment and prevent disruption of the transient spatial system. What impairments there were seem to be only partial – affecting distance estimates here, or pointing error there – rather than inhibiting speed and accuracy across the board. Given that participants rotated more than 1800º with very little perceptual information, it can be considered somewhat remarkable that they did not perform more poorly in at least some conditions.

Experiment 4

Experiment 4 returns to an un-addressed difference between Experiments 1 and 2. Specifically, participants in Experiment 1 were allowed unrestricted vision of the redness gradient throughout the entirety of the pre- and post-rotation testing phases. Participants in Experiment 2 had no visual information during testing, despite being able to view intermittent reminders during rotation. Thus, while a brief glimpse of the environment (i.e., the photo-realistic model of the actual lab room) was not sufficient to keep people perceptually engaged in their environment if the visual fixes were too infrequent, it is possible that this same visual information – being so much more detailed, complex, and task-relevant than the redness gradient – may be sufficient to re-engage the transient spatial system if prolonged viewing of the environment is available during testing.

If people are able to maintain baseline performance after a blind rotation, this would be in contrast to what has been shown in the present Experiment 1 and in Wang and Spelke's (2000) fifth experiment, which showed that restoring access to a rather abstract visual gradient after a period of perceptual disconnect is not sufficient to restore performance to pre-rotation levels. Logically, however, there must be some level of perceptual information that is sufficient to restore people's transient knowledge of self-to-object spatial relations (otherwise our participants may still be wandering aimlessly trying to find their way home).

The rich visual landmarks of the virtual lab room have the potential to serve as associative memory cues and enable both accurate reorientation to the room in general and to the targets' locations within the room in particular. Such cues could enable efficient performance even after a period of prolonged disorientation in the absence of any visual information. Additionally, there is evidence to suggest that the geometry of the room may play a special role in reorientation (e.g., Cheng, 1986; Hermer & Spelke, 1994; 1996; Wang & Spelke, 2000), and thus may aid participants in the present experiment. Environmental geometry is readily perceivable in the simulated lab model but was not available in the visual gradient,

Alternatively, it may be that once knowledge of self-to-object bearings is disrupted, it cannot be restored until people once again view those particular objects and correct any memory-based error or distortions. While a more complex visual cue could provide structure to aid memory recall, it may still afford too much uncertainty and fail to engage a perceptual awareness of each object's location. In such a case it would not be expected that participants could maintain their baseline level of performance after rotation when the visual cue is omitted during rotation. Along these same lines, past research (Brockmole & Wang, 2003; Wang & Brockmole, 2003) has shown that people can be simultaneously well oriented to one environment (e.g., the immediate room) and poorly oriented with respect to another environment (e.g., the building or campus). Thus, it should not be expected a priori that participants who are well-oriented to the room will necessarily be well-oriented to the target objects.

In Experiment 4 these issues were explored by asking participants to engage in the same task as Experiment 1, but with a photo-realistic virtual model of the actual testing room (minus the target objects) used as a visual cue in place of the redness gradient. Spatial updating performance while the lab model is continually perceivable will serve as a baseline reference to determine whether a rich visual cue is sufficient to re-engage people's transient spatial knowledge after being fully disoriented.

Methods

Participants. Thirty eight undergraduate students (16 female) from Miami University participated in Experiment 4 either in exchange for credit in their Psychology course or for $10. The mean age of participants was 19.0 (SD = 0.72). Data from four participants were removed (2 female) either for failing to follow instructions or because of technical difficulties.

Materials and Procedures. Experiment 4 used the same materials and procedures as Experiment 1, with the exception that the virtual redness gradient was replaced with the photo-realistic lab model used in Experiments 2 and 3.

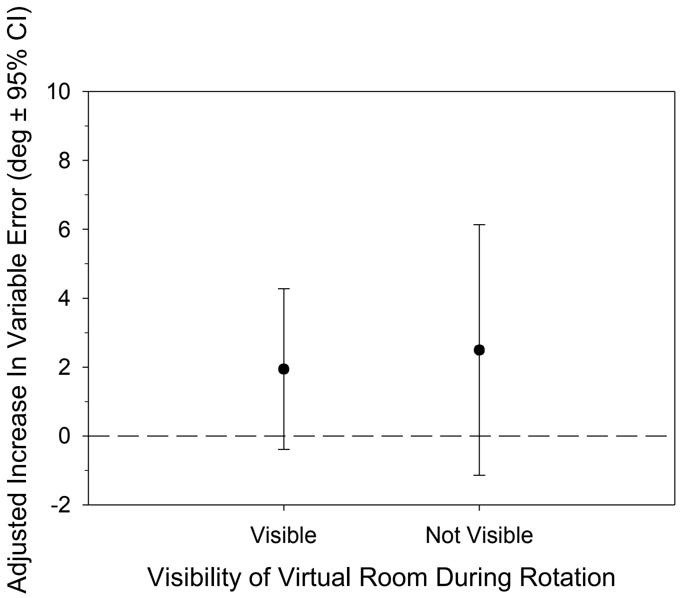

Figure 16: Adjusted variable error data for Exp. 4.

Results

As in previous experiments, participants were well oriented after the prolonged rotation. Mean heading error was -0.23º ± 0.86 and -0.48º ± 1.74 for the conditions in which the virtual room was visible and not visible, respectively, during rotation. In both cases, the 95% confidence intervals contained the 0º heading error predicted if participants were perfectly oriented.

The mean increase in variable error for each condition in Experiment 4 is plotted in Figure 16, adjusted to exclude any increase in within-object variability. Pre- and post-rotation means and confidence intervals are listed in Appendix A. In neither condition was the adjusted increase in variable error significantly higher than zero. When the virtual room was visible throughout the experiment, participants' unadjusted variable error increased by 2.76º ± 2.33, which included the 0.82º increase predicted by the rise in pointing error. Likewise, when the room was not visible during rotation, participants' unadjusted variable error increased by 3.89º ± 3.64, which included the 1.40º increase predicted by the rise in pointing error. The difference between the conditions was non-significant, and was estimated at 1.12º ± 4.27.

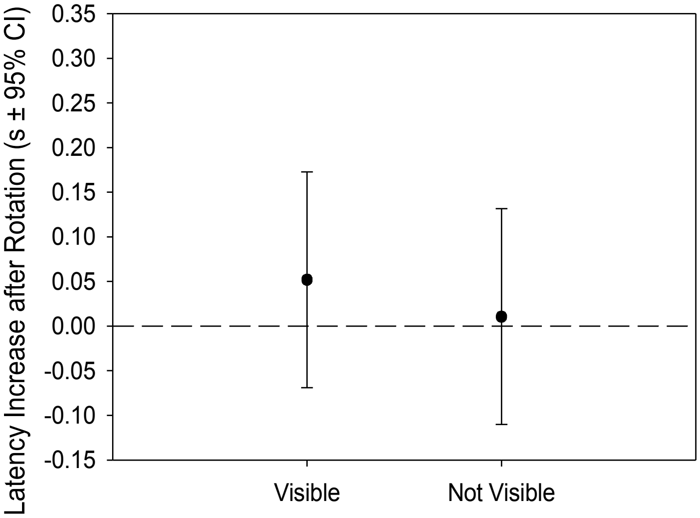

Figure 17: Latency data for Exp. 4.

Within-target pointing error increased by 1.63º ± 1.77 when the room was visible during rotation, and 2.78º ± 1.74 when it was not. The difference between these two conditions was not significant, and was estimated at

1.15º ± 2.47. Means and confidence intervals for each phase and condition are listed in Appendix B.

The mean increase in latency for each condition in Experiment 4 is depicted in Figure 17, and a complete listing of pre- and post-rotation means is available in Appendix C. Neither condition exhibited a significantly non-zero increase in latency after rotation. When the virtual room was visible throughout the experiment participants post-rotation responses slowed by non-significant 51 ms ± 121. Similarly, when the virtual room was not visible during the rotation but returned afterwards, post-responses slowed by 11 ms ± 121. The difference between the two conditions was also non-significant, and estimated at 41 ms ± 121.

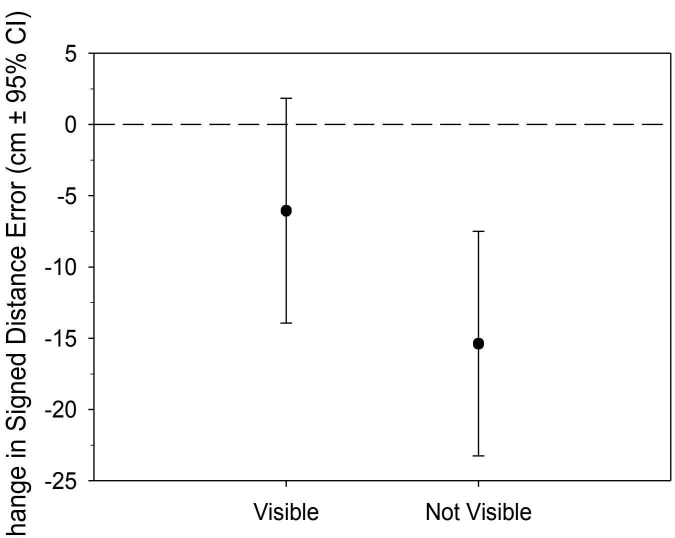

Figure 18: Signed distance data for Exp. 4.

The change in signed distance error for each condition in Experiment 4 is shown in Figure 18. Pre- and post-rotation means and confidence intervals are listed in Appendix D. The pattern of means did not entirely mirror the trends observed in adjusted variable error and in latency. When participants were able to view the virtual lab room throughout the rotation, mean distance error did not change appreciably (-6.05 cm ± 7.88; from -41.89 cm to -47.94 cm). However, distance error did change significantly when participants rotated blindly (-15.38 cm ± 7.88; from -38.82 cm to -54.20 cm). This latter difference was characterized both by relatively better pre-rotation performance and worse post-rotation performance than the other condition. The difference between the two conditions was significant, and was estimated at 9.32 cm ± 7.88.

Mean absolute distance errors for each phase and condition are listed in Appendix E. The pattern of changes in absolute error after rotation was opposite that of signed distance error. Absolute distance error increased significantly (7.33 cm ± 7.08; from 70.97 cm to 78.30 cm) when participants were able to view the room during rotation. In contrast, when participants rotated blindly, there was no significant increase in absolute distance error (6.03 cm ± 7.08; from 74.27 cm to 80.30 cm).

Discussion

Experiment 4 investigated whether complex visual information enabled people to re-engage their transient spatial knowledge after it had been disrupted by disorientation. This was done by giving participants visual access to a photo-realistic virtual model of the testing room either throughout the entire experiment or only during the testing phases (i.e., not during the rotation). In both conditions, participants maintained their baseline level of performance after a potentially disorienting rotation of up to several thousand degrees; there was no significant increase in latencies or adjusted variable error in either condition. It can be noted, though, that there was a small but significant increases in within-target pointing error as well as a shift towards underestimation in signed distance error for the condition in which participants rotated blindly, suggesting that there may have been a small degree of impairment when participants became disoriented and then reoriented, but not when they had continual perceptual access to the room. Interestingly, there was also a small but significant increase in absolute distance error in the opposite condition. It is unclear why participants in this condition would have performed worse than those deprived of visual cues. It is also unclear why the trends in distance error are inconsistent with each other as well as with the primary measures of variable error and latency.

It is important to note that these results contrast with the results of Experiment 1 and of Wang and Spelke’s (2000) Experiment 5. In both of the later experiments, participants who rotated blindly showed significant increases in variable error and / or latency despite the renewed availability of the visual cue during testing. Here, participants in the blind rotation condition not only reoriented successfully but also pointed just as efficiently and precisely as they had prior to becoming disoriented. The results of Experiment 4 suggest that regaining vision of the room, but not of the to-be-remembered objects, was sufficient to re-engage participants' perceptual awareness of the targets’ locations. The driving force behind this effect remains unclear, however. The return to baseline performance may have been because participants had encoded objects' locations in a room-centric (i.e., non-egocentric) fashion or because the room cues sufficiently specified the participants' current orientation and enabled precise use of a self-centered (i.e., egocentric representation), or for some other reason.

Returning to part of the impetus for Experiment 3, a visual gradient and a detailed, photo-realistic model of the actual testing environment differ on many dimensions. The realistic model simultaneously (a) is more complex; (b) contains specific landmarks to demarcate the space and act as associative cues; (c) contains geometric environmental structure; (d) contains intrinsic axes; (e) is more relevant to the task; and (f) provides a more familiar type of orientation information, as most of us are unaccustomed to navigating solely through gradients. This is by no means and exhaustive list, and the inquisitive reader may find additional meaningful differences. It seems most likely that the presence of multiple room landmarks as well as the virtual model's close correspondence to the physical testing environment played key roles, but further research is needed to confirm these speculations. For the present purposes, it is at least informative that there exists some level of information *excluding* the to-be-remembered objects that can successfully re-engage the transient spatial updating system and restore the precise and efficient level of performance that existed prior to disruption taking place.

General Discussion

The experiments contained in this dissertation were based in large part on the recent, influential, two-systems approach to spatial cognition (Avraamides & Kelly, 2008; Burgess, 2006; Waller & Hodgson, 2006), and were designed to explore the interplay between transient and enduring representations of spatial knowledge. In the course of exploring the interface between these two systems, there were five major issues or research questions to be addressed. These are discussed in turn below.

First, because Wang and Spelke's (2000) configuration error effects have been controversial and sometimes hard to replicate – and in particular because there are no extant replications of Wang and Spelke's Experiments 4 and 5 – it was necessary to attempt to replicate their results and firmly establish the effect in question. It was also desired to extend their effect to other measures (i.e., latency and distance error). The present Experiment 1 successfully replicated this effect by showing a significant increase in variable error only when the perceptual gradient was removed during rotation. This effect was larger than the increase predicted solely by any increase in random, within-target pointing error. Importantly, Experiment 1 also extended Wang and Spelke's original findings by demonstrating that the same effect could be obtained in latency and in signed distance error as well as the traditional measure of variable error. Participants not only pointed with less precision after rotating blindly, but also responded less quickly and exhibited a shift in distance bias.

Second, a major aim of the present studies was to investigate whether intermittent visual fixes during movement were sufficient to keep participants perceptually engaged with their environment. Experiment 2 and 3 addressed this issue and unequivocally demonstrated that people were indeed able to update their spatial relationship to the target objects using only occasional, brief reminders of their current heading. In Experiment 2, for example, people maintained their baseline level of performance in latency, variable error, and signed distance error when they were presented with a brief glimpse of their surroundings (i.e., a virtual model of the testing room) after every 75º of rotation. This is a simple, but relatively profound finding that speaks to the flexibility and efficiency of human navigational ability. A 400 ms glimpse of the environment presented in stroboscopic fashion during a prolonged rotation might be more reasonably expected to induce disorientation and simulator sickness. Instead, people were able to glean useful orientation information from the glimpses and use them to maintain a perceptual awareness of multiple unseen objects' bearings with high precision[1]. Along these same lines, it can be seen that participants receiving only occasional reminders were extremely well oriented to their environment after each potentially-disorienting rotation. Mean heading errors in all conditions were very near to the 0º error predicted by perfect orientation.

Third, the present investigation sought to determine how often these visual fixes must be presented to be useful. Latency data in Experiment 2 indicated that only visual fixes given every 75º were helpful. That is, participants exhibited significant post-rotation latency increases for visual fix intervals of 150º or larger, but maintained their baseline level of efficiency when visual fixes were available every 75º. Likewise, in most conditions of Experiment 3, there was a trend for participants to show increases in variable error at visual fix intervals of 150º, but to maintain baseline levels of variable error with smaller visual fix angles. Unfortunately, the discordance among various measures in Experiments 2 and 3 preclude making any firm conclusions on the exact threshold for which visual fixes must be presented. There is at least enough converging evidence in the data, however, to suggest that the previous threshold identified by Waller & Hodgson (2006) of 90º provides a useful approximation. The latency data, and to a lesser extent,

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[1] An alternative way to assess this claim would be to analyze mean absolute pointing error, which is a combination of mean heading error (i.e., overall bias) and variable error (i.e., standard deviation from a target). Given that the mean heading error was essentially zero in all conditions, such analyses would be redundant with those of variable error.

the within-target pointing data of Experiment 2 indicated that people could maintain baseline performance when visual fixes were presented within 90º of rotation, but not at wider intervals. Likewise in Experiment 3, there was some evidence of disrupted performance at visual fix intervals of 150º, but not more frequent visual fixes. There was relatively little evidence of disruption in the 112.5º condition, which is greater than 90º but still relatively near. Again, however, it must be emphasized that the data trends in Experiment 3 were largely inconsistent and inconclusive. Thus, the above observations must be treated as speculative until further data are available. It will be more informative to rely on the relatively clearer results of Experiment 2, and their close correspondence to the results of Waller & Hodgson's (2006) Experiment 4.

The fourth aim of the present study was to determine whether people's ability to use intermittent visual fixes depends on the type (or quality) of visual cues. Experiment 3 was designed to explore this issue by giving different groups of participants either abstract, non-specific heading information (redness gradient), environmental geometry and a single directional cue (wireframe grid room), environmental geometry and multiple landmarks (realistic other room), or environmental geometry and landmarks that corresponded to the physical testing environment (realistic actual room). Unfortunately, there were little to no interpretable trends in the data of Experiment 3 that would suggest a change in the threshold required to maintain one's transient spatial knowledge. The strongest indication of this was the trends in pointing error data for the redness gradient and realistic actual model of the testing room. Pointing error in the former increase relatively sooner than the latter. However, because pointing error has historically been treated as a source of random error to be factored out, and because this changing data pattern did not continue through the intermediate levels of visual stimulus quality, no strong conclusions can reasonably be made. Additional research will be required to determine whether and how the quality of perceptual information influences people's maintenance of transient spatial knowledge and the tendency to switch to an enduring spatial representation.

Finally, the present study sought to determine whether sufficiently detailed visual information – short of showing the to-be-remembered targets – could re-engage people's transient spatial knowledge once it had been disrupted. The answer to this final question was addressed by Experiment 4, and was 'yes.' Participants in Experiment 4 performed equally well when rotating with vision of the virtual lab room and when rotating blindly. Having visual access to the structure and landmarks of the virtual room were sufficient to enable precise and efficient pointing responses. This was in sharp contrast to the present Experiment 1 and to Wang and Spelke's (2000) Experiments 4 and 5, in which participants were only able to maintain baseline-level performance after rotating when they could view a visual gradient throughout the duration of movement; when people in these experiments rotated blindly, their performance was significantly impaired despite a clear ability to reorient to the environment as a whole.

Alternative methods of measurement. Beyond the major research questions that this dissertation set out to address, the present study also explored the use of multiple converging measures to asses people's performance in a relatively classic spatial updating paradigm. Wang and Spelke (2000) first reported that the effect of disorientation on spatial updating in *configuration error*, and this measure has been the primary metric used in the body of follow-up studies based on their influential work (e.g., Avraamides & Kelly, 2008; Holmes & Sholl, 2005; Mou, et al., 2006; Waller & Hodgson, 2006). This dissertation made use of several additional, complementary metrics that will be considered in turn.

The present experiments extended beyond measuring only angular estimates and truly did enable an investigation of people's knowledge of the targets' configuration by also measuring *distance error*. By the nature of how people's pointing responses were measured, it was possible to determine not only the direction of their pointing estimate, but the precise location on the lab floor at which they pointed. In the present investigation, two variations of distance errors were analyzed: signed distance error (i.e., mean bias) and absolute distance error (i.e., mean deviation). Each of these two measures was independent of traditional bearing estimates. Measuring both distance and direction assessed complementary halves of people's configural knowledge. This was a novel approach to measuring people's egocentric pointing estimates in a spatial updating paradigm that, with additional refinement, may prove to be a useful metric.

In principle, a disruption of people's configural knowledge (e.g., due to disorientation) could manifest itself both in less precise distance estimates and in less precise angular estimates. In such a case any effects obtained in variable error (or latency) should be detectable in distance error as well. It is possible, however, that distance and direction judgments are made independently and with different fidelity. In Experiment 1, for example, when collapsed across conditions the changes in signed distance error correlated relatively well with the increases in variable error ($r = 0.55$, $p < 0.01$), pointing error ($r = 0.43$, $p = 0.08$), and latency ($r = 0.27$, $p =$

0.18). Likewise, the changes in absolute distance error correlated positively with the increases in variable error ($r = 0.59$, $p < 0.01$), pointing error ($r = 0.29$, $p = 0.17$), and latency ($r = 0.29$, $p = 0.17$). Generally speaking, signed distance error (i.e., mean bias) tended to fluctuate more predictably with experimental manipulations and was more closely aligned with the data trends observed in the primary metrics of variable error and latency than absolute distance error (i.e., mean deviation).

In sum, patterns of distance error changes after rotation – particularly those of signed distance error – provided at least some degree of converging evidence of the major data trends in all four experiments. Although this convergence was not perfect across experiments, it was encouragingly strong in Experiment 1. It may be that some degree of refinement and replication will be necessary to establish distance error as a robust and useful measure in spatial updating paradigms. For example, more elaborate instructions or practice with feedback may improve the precision and, thus, reliability of distance estimates made in this manner. It may also be the case that other types of distance metrics may prove to be more robust. For example, the present study intentionally used measures of relative distance error that were independent of bearing estimates, but similar measures could be constructed that analyzed the absolute distance error from the physical location to the estimated location rather than a difference in radii. Likewise, an analysis of pitch angle could yield a simple distance error metric that would be similar to those used here.

A second, and relatively more successful new measure of participants' performance in this paradigm was to asses post-rotation increases in *latency*. The rationale for including a response time metric was based largely on the findings of Amorim, et al. (1997) and of Hodgson and Waller (2006; see also Hodgson, 2008) that post-hoc reconstruction of spatial information from an enduring memory representation takes additional processing time relative to merely accessing information that is perceptually available or currently the subject of active processing (i.e., in working memory). Thus, latency increases were predicted to mirror the effects of variable error and perhaps be a more sensitive measure in some cases. This was the case for three of the four experiments. In Experiments 1 and 4, latency increases exhibited an identical data pattern as variable error increases and provided important converging evidence. In Experiment 2, where there was a relatively high level of variability in error estimates that may have masked a true pattern of means, the theoretically predicted effect was obtained in latencies. The one experiment in which the predicted data trend failed to reach significance in latencies was Experiment 3. However, this Experiment as a whole was generally characterized by erratic data patterns in all dependent measures and in this regard latency was consistent with other measures. Thus, across the body of work presented here it seems that latency measures can serve either as a beneficial supplement to traditional measures of variable error or as a reliable replacement. Indeed, the results of Experiment 2 suggest that latency effects may be more robust than those of variable error (i.e., configuration error).

Finally, it is worth discussing the role of *pointing error*, or within-target variability. Historically, investigations in this paradigm have treated the variability arising from inconsistent pointing estimates to the same object on multiple trials much like a source of random noise to be subtracted out of the final estimate of variable error. There are many reasons why this may be the case. People may have difficulty reproducing an identical motor response even if they fully intend on pointing to the same location due to fatigue, postural sway, or because of vestibular disturbances left over from an extended period rotation. Wang and Spelke (2000) additionally noted that participants who are disoriented may change their estimate of their own post-rotation heading on a trial-by-trial basis. Even minor fluctuations in perceived heading direction could introduce additional within-target pointing error that would, in turn, increase the amount of overall variable error. Equally possible, however, is the situation in which people refine their estimate of an object's location – either by an incremental adjustment or a wholesale change of mind – and thus *intend* to point to a different location.

Wang and Spelke (2000) correctly pointed out that their paradigm was not able to distinguish between these sources of pointing error, and that because it represented a potential confound it should be ensured that any claims of increased variable error were greater than that predicted by increased pointing error alone. In the present investigation, however, it can be argued that several aspects of the experimental design *do* allow the sources of pointing error increases to be ruled out. Specifically, the argument that participants may change their estimate of egocentric heading when disoriented is largely irrelevant in the present experiments, because participants were extremely well oriented after rotation in all conditions. Additionally, Wang and Spelke (2006, Exp 2) ruled out vestibular disturbances from prolonged rotation as an underlying source of variable error increases, and all participants in the present investigation were given a rest period of at least 25 s to recover from any dizziness before continuing. The remaining sources of pointing error variability are (a) fluctuations due to postural sway and arm instability, which can reasonably be expected to random and homogeneous across both testing phases and across all experimental conditions; (b) fluctuations due to arm fatigue, which may be expected to increase from pre- to post-rotation testing but should also be homogeneous across all conditions; and finally, (c) people's tendency to change their estimate of a target's location. This last source of error could logically be expected to arise when people's transient spatial knowledge is disrupted. Despite enduring memory being relatively static when compared to the dynamic nature of perceptual information, there is likely to be some degree of uncertainty when retrieving and / or reconstructing objects' locations from a relatively coarse enduring memory representation. By extension, it is logical that there may be some fluidity and refinement of each object's location estimate over time. By ruling out alternative explanations for post-rotation increases in pointing error, it is reasonable to make conclusions relating data trends in pointing error to the hypotheses at stake.

In the present Experiment 2, for example, the predicted data trend was obtained for within-object pointing error despite being absent from the measure of between-object variable error (i.e., adjusted increase in variable error). The effect in pointing error also closely matched the trends seen in response latency. Likewise, in Experiment 3, there was a strong trend in the overall variable error of angular responses in three of the four visual stimuli conditions for participants to be significantly less precise with 150º visual fix intervals (mean increases of 9.81º ± 4.38, 8.88º ± 5.62, and 9.64º ± 8.95 of unadjusted variable error in the redness gradient, realistic other room, and realistic actual room, respectively). The majority of these effects were due to the large increases in within-object pointing error relative to smaller visual fix intervals, rather than an increase in between-object variable error. If the source of pointing error was purely random trial-to-trial fluctuation, there is no reason why it should have fluctuated predictably with the experimental manipulations and closely mirrored the data trends in other dependent measures. It seems more likely that pointing error represents a valid source of variance in this and other investigations of spatial updating, and that it can contribute to our understanding of people's spatial processes and representations.

Alternative explanations. The results of Experiments 1 - 4 thus far have been interpreted in the framework of the two-systems approach to spatial cognition espoused by Burgess (2006) and by Waller and Hodgson (2006). However, it is beneficial to consider how the present results could be interpreted by other models. This could be considered a series of straw-man arguments to a certain extent, as no current theories adhere to a strict one-system approach. Examining the shortcomings of a strict egocentric or strict cognitive map theory, however, will help to illustrate the need for two parallel and, more importantly, balanced systems. For example, Wang and Spelke's (2000; 2002) egocentric theory of spatial updating does grant a role of at least a geometric module to supplement purely transient spatial codes. However, they exclude the role of enduring representations such as a cognitive map to the point that they jokingly offered to "forgive [other researchers] for continuing to believe in cognitive maps" in their acknowledgments (Wang & Spelke, 2002, p. 380). While this jest should surely not be taken as an overgeneralized representation of their theory, it does illustrate the general rift in thinking that has historically divided the spatial cognition literature. Burgess (2006) proposed a much more balanced approach in which egocentric and allocentric representations operate in parallel and each contribute to task demands as necessary to enable successful, adaptable spatial performance. The following consideration of alternative explanations to the two-systems framework will help illustrate the need for such balance.

First, consider a strict egocentric theory (e.g., Wang & Spelke, 2000; 2002) explanation of the data in Experiments 1 – 4. Given a large, potentially disorienting rotation, egocentric updating theory predicts that people's performance will suffer unless there is some source of information to keep people perceptually engaged and enable successful updating of targets' locations throughout the rotation. In other words, egocentric theory predicts Wang and Spelke's original disorientation effect. In its most extreme interpretation, such a theory would predict deterioration of performance to chance levels that would correspond, for example, to unadjusted variable error of around 104º (it is unclear what chance performance would look like in terms of distance error or response latency). It is reasonable, however, to expect lower levels of variable error to the extent that people are able to make reasonable guesses (rather than purely random ones) on the basis of non-spatial information from an enduring memory, such as remembering the order of targets.

Such a theory does reasonably well at explaining the results of Experiment 1 and 2, but clearly performance did not deteriorate to chance when egocentric disruption occurred. The glaring shortcoming of egocentric updating theory comes in the data of Experiment 4. Without resorting to an enduring spatial representation, any egocentric theory would be hard pressed to explain how people were able to become disoriented and then regain baseline (i.e., undisrupted) performance after viewing a visual cue *other than* the targets whose representations had been lost. Even if the stored representation is something egocentric in nature, such as a remembered visual snapshot containing the target and some surrounding landmark information, this representation is still an enduring one and goes against the grain of a strict, moment-to-moment egocentric system of spatial cognition such as that put forth by Wang & Spelke (2000; 2002). It is partially for this reason that the current investigation uses the terms transient and enduring, rather than egocentric and allocentric.

Non-egocentric theories fare relatively worse in explaining the present data. Keeping in mind that Wang and Spelke's (2000) data was originally put forth as a proof against the use of an allocentric or other cognitive-map type of representation, the replication of their data pattern in the present Experiment 1 is relatively damning. If people were truly relying on the same allocentric, intrinsic, or cognitive-map-like representation both before and after rotation, then there is no reason that disorientation should disrupt performance. Further compounding the difficulties of non-egocentric theories is the finding that people's performance is not only disrupted in terms of their relative precision in bearing estimates, but also in terms of their response latencies and, in some cases, distance estimates.

In conclusion, then, both types of representations are necessary to fully explain the data at hand. Clearly, there is some form of transient (and likely egocentric) representation that is being disrupted in the absence of adequate perceptual support. Equally clear, however, is that knowledge of the targets' configuration is not lost. Pointing performance in some conditions may have been reliably slower and less precise, but it cannot be considered truly 'bad' performance. The magnitude of impairment is relatively small in most measures – only a few degrees of lost precision and a few hundred milliseconds delay – and does not begin to approach chance-level performance. A more parsimonious explanation of the present data is that people initially relied on a precise, transient representation, and that when disrupted, switched their reliance to the use of a relatively coarser, enduring memory representation that required some degree of time-consuming retrieval and processing.

Concluding remarks. The Experiments contained within this dissertation were designed to explore the interaction of transient and enduring spatial representations, and also to expand a classic spatial updating paradigm to include alternative metrics and develop a powerful, flexible testing platform through the use of virtual reality. Experiments 1 and 4 together are informative about the quality and availability of perceptual information that is required to keep the transient system engaged or to bring it back online after it has been disrupted. Experiment 2 indicated that intermittent visual fixes were sufficient to keep people perceptually engaged and that there was a threshold beyond which the visual fixes were not effective. Experiment 3 unfortunately suffered from unusually high variability and lacked enough internal consistency to be fairly interpreted, but did contain some occasional data trends that were consistent with the results of Experiment 2.

The virtual reality based research platform proved to be very successful in the present experiments. Experiment 1 confirmed that the same effects could be obtained with simulated visual cues rather than the physical apparatus used by Wang and Spelke (2000), and the flexibility afforded by the system allowed precise control over the visibility of sophisticated cues that provided controlled perceptual access to a representation of the physical testing environment or other cues. This type of platform can lay the groundwork for innovative new research programs that further manipulate the visual information available to participants during movement. For example, future research could be envisioned that investigated the time-course of visual fixes rather than the angular separation, that presented intermittent visual reminders at predefined distances during translational movement, or that manipulated the veracity of visual fixes such that the perceived visual rotation was greater or less than the physically performed movement. It would even be possible to explore the use of auditory cues in keeping people perceptually engaged.

In closing, the present investigations provide some initial insight into the interaction between two systems of spatial cognition. Much work remains to be done, however, both in terms of further defining the nature and characteristics of each system and in terms of exploring the interplay between them. For example, it will be informative to more fully discern the relative contribution of visual, vestibular, inertial, auditory, and other spatial senses to transient spatial knowledge. It will likewise be informative to tease apart the prevalence of various types of reference frames in enduring spatial representations and explore the factors that lead to choosing one reference frame over another. Finally, it will be a great benefit to our knowledge of human spatial ability to more fully understand how these two classes of representations are encoded in parallel, how they serve to supplement each other, and what factors affect the representation that is primarily employed in a given task.

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APPENDIX A

Variable Error Data (mean ± 95% confidence interval)

Experiment 1 (n = 28)

Condition	Pre-Rotation	Post-Rotation	Increase	Adjusted Increase
Gradient Visible	14.43° ± 3.07	18.77° ± 2.98	4.33° ± 3.79*	3.30° ± 3.79
Gradient Not Visible	14.47° ± 2.73	20.51° ± 3.50	6.13° ± 4.13*	4.59° ± 4.13*

Experiment 2 (n = 28)

Condition	Pre-Rotation	Post-Rotation	Increase	Adjusted Increase
75°	22.38° ± 4.81	24.39° ± 4.36	2.01° ± 4.47	0.92° ± 4.47
150°	21.75° ± 4.85	29.35° ± 5.41	7.61° ± 5.82*	3.64° ± 5.82
225°	21.99° ± 5.47	28.00° ± 5.51	6.01° ± 5.26*	2.18° ± 6.27
300°	20.12° ± 4.62	23.14° ± 4.60	3.02° ± 4.17	1.23° ± 4.17

Experiment 3 (n = 107)

Condition	Pre-Rotation	Post-Rotation	Increase	Adjusted Increase
Redness Gradient				
37.5°	28.19° ± 6.63	27.03° ± 5.36	-1.15° ± 6.10	-0.40° ± 6.10
75.0°	15.93° ± 4.20	19.55° ± 5.00	3.62° ± 6.78	2.28° ± 6.78
112.5°	22.84° ± 5.00	25.48° ± 5.22	2.65° ± 4.39	-0.22° ± 4.39
150.0°	17.06° ± 3.77	26.87° ± 5.33	9.81° ± 4.38*	4.00° ± 4.38
Wireframe Room				
37.5°	19.12° ± 4.86	22.82° ± 4.87	3.70° ± 5.80	1.70° ± 5.80
75.0°	24.74° ± 5.74	31.63° ± 6.08	6.89° ± 6.96	3.84° ± 6.96
112.5°	19.75° ± 4.52	30.21° ± 6.81	10.46° ± 7.20*	6.24° ± 7.20
150.0°	23.14° ± 6.09	24.56° ± 4.77	1.42° ± 7.61	-2.70° ± 7.61
Realistic Other Room				
37.5°	22.25° ± 3.93	27.22° ± 6.11	4.97° ± 6.08	1.57° ± 6.08
75.0°	17.92° ± 4.49	21.09° ± 3.98	3.17° ± 3.86	1.66° ± 3.86
112.5°	18.01° ± 3.94	18.87° ± 3.29	0.86° ± 4.04	-0.70° ± 4.04
150.0°	19.87° ± 3.33	28.75° ± 5.36	8.88° ± 5.62*	6.46° ± 5.62*
Realistic Actual Room				
37.5°	20.61° ± 6.22	22.30° ± 3.70	1.69° ± 5.11	-0.11° ± 5.11
75.0°	24.44° ± 5.78	22.96° ± 4.31	-1.48° ± 6.24	-3.49° ± 6.24
112.5°	24.07° ± 6.35	27.11° ± 6.29	3.05° ± 7.48	0.55° ± 7.48
150.0°	20.88° ± 6.17	30.53° ± 7.35	9.64° ± 8.95*	3.64° ± 8.95

Experiment 4 (n = 34)

Condition	Pre-Rotation	Post-Rotation	Increase	Adjusted Increase
Room Visible	12.97° ± 2.37	15.37° ± 2.83	2.76° ± 2.33*	1.94° ± 2.33
Room Not Visible	13.24° ± 2.46	17.13° ± 3.39	3.89° ± 3.64*	2.50° ± 3.64

* - Denotes a significant increase, $p < 0.05$

APPENDIX B

Pointing Error Data (mean ± 95% confidence interval)

Experiment 1 (n = 28)

Condition	Pre-Rotation	Post-Rotation	Increase
Gradient Visible	12.05º ± 1.81	15.24º ± 2.38	3.20º ± 2.84*
Gradient Not Visible	14.47º ± 2.73	20.51º ± 3.50	3.57º ± 3.10*

Experiment 2 (n = 28)

Condition	Pre-Rotation	Post-Rotation	Increase
75º	11.79º ± 2.41	13.98º ± 2.64	2.19º ± 3.15
150º	11.09º ± 1.60	19.03º ± 4.88	7.94º ± 5.44*
225º	13.29º ± 3.07	20.95º ± 3.87	7.97º ± 4.78*
300º	11.62º ± 2.38	15.21º ± 3.53	3.59º ± 3.68

Experiment 3 (n = 107)

Condition	Pre-Rotation	Post-Rotation	Increase
Redness Gradient			
37.5º	11.56º ± 2.12	10.05º ± 1.94	-1.51º ± 2.61
75.0º	11.57º ± 2.29	14.26º ± 3.46	2.68º ± 4.33
112.5º	9.96º ± 2.09	15.71º ± 3.21	5.75º ± 3.84*
150.0º	10.76º ± 2.05	22.38º ± 4.87	11.62º ± 6.25*
Wireframe Room			
37.5º	11.31º ± 2.20	15.31º ± 3.21	4.00º ± 4.34
75.0º	11.78º ± 2.30	17.90º ± 3.99	6.12º ±5.56*
112.5º	11.64º ± 3.25	20.10º ± 5.21	8.45º ± 7.53*
150.0º	11.60º ± 3.26	19.85º ± 4.46	8.24º ± 6.61
Realistic Other Room			
37.5º	11.25º ± 1.85	18.04º ± 3.97	6.79º ± 4.41*
75.0º	10.72º ± 2.42	13.75º ± 3.20	3.03º ± 4.89
112.5º	9.52º ± 1.82	12.64º ± 2.79	3.11º ± 3.17
150.0º	11.01º ± 2.47	15.84º ± 3.32	4.83º ± 4.54*
Realistic Actual Room			
37.5º	12.83º ± 2.63	16.44º ± 3.41	3.60º ± 4.30
75.0º	10.63º ± 2.16	14.65º ± 2.27	4.02º ± 2.52*
112.5º	11.55º ± 2.90	16.54º ± 3.79	4.98º ± 4.83*
150.0º	10.02º ± 2.01	22.04º ± 4.67	12.02º ± 4.97*

Experiment 4 (n = 34)

Condition	Pre-Rotation	Post-Rotation	Increase
Room Visible	7.43º ± 1.10	9.06º ± 1.52	1.63º ± 1.77
Room Not Visible	8.59º ± 1.17	11.38º ± 1.45	2.78º ± 1.74*

* - Denotes a significant increase, $p < 0.05$

APPENDIX C

Latency Data (mean ± 95% confidence interval)

Experiment 1 (n = 29)

Condition	Pre-Rotation	Post-Rotation	Increase
Gradient Visible	3.26 s ± 0.19	3.45 s ± 0.16	135 ms ± 137
Gradient Not Visible	3.30 s ± 0.14	3.38 s ± 0.16	189 ms ± 137*

Experiment 2 (n = 28)

Condition	Pre-Rotation	Post-Rotation	Increase
75º	2.81 s ± 0.19	2.86 s ± 0.18	53 ms ± 138
150º	2.71 s ± 0.13	3.14 s ± 0.27	433 ms ± 174*
225º	2.79 s ± 0.16	2.95 s ± 0.14	165 ms ± 145*
300º	2.76 s ± 0.14	3.08 s ± 0.22	326 ms ± 168*

Experiment 3 (n = 107)

Condition	Pre-Rotation	Post-Rotation	Increase
Redness Gradient			
37.5º	2.64 s ± 0.18	2.69 s ± 0.10	45 ms ± 176
75.0º	2.58 s ± 0.13	2.72 s ± 0.15	144 ms ± 138*
112.5º	2.69 s ± 0.21	2.77 s ± 0.15	80 ms ± 169
150.0º	2.65 s ± 0.10	2.74 s ± 0.19	87 ms ± 117
Wireframe Room			
37.5º	2.64 s ± 0.15	2.62 s ± 0.18	-28 ms ± 149
75.0º	2.61 s ± 0.12	2.84 s ± 0.14	225 ms ± 133*
112.5º	2.65 s ± 0.24	2.75 s ± 0.15	101 ms ± 143
150.0º	2.55 s ± 0.19	2.66 s ± 0.23	118 ms ± 179
Realistic Other Room			
37.5º	3.11 s ± 0.19	3.25 s ± 0.21	100 ms ± 195
75.0º	3.10 s ± 0.19	3.31 s ± 0.22	227 ms ± 240
112.5º	3.05 s ± 0.13	3.09 s ± 0.21	43 ms ± 133
150.0º	2.93 s ± 0.15	2.96 s ± 0.16	38 ms ± 161
Realistic Actual Room			
37.5º	2.87 s ± 0.22	2.77 s ± 0.19	-108 ms ± 189
75.0º	2.57 s ± 0.12	2.48 s ± 0.12	-96 ms ± 108
112.5º	2.71 s ± 0.13	2.73 s ± 0.15	12 ms ± 120
150.0º	2.85 s ± 0.19	2.86 s ± 0.22	18 ms ± 157

Experiment 4 (n = 34)

Condition	Pre-Rotation	Post-Rotation	Increase
Room Visible	3.24 s ± 0.18	3.29 s ± 0.11	52 ms ± 121
Room Not Visible	3.27 s ± 0.13	3.29 s ± 0.16	11 ms ± 121

* - Denotes a significant increase, $p < 0.05$

APPENDIX D

Signed Distance Error Data (mean ± 95% confidence interval)

Experiment 1 (n = 28)

Condition	Pre-Rotation	Post-Rotation	Increase
Gradient Visible	-5.79 cm ± 14.28	-7.76 cm ± 13.71	1.10 cm ± 9.43
Gradient Not Visible	-15.19 cm ± 13.27	7.98 cm ± 15.61	24.43 cm ± 9.43*

Experiment 2 (n = 28)

Condition	Pre-Rotation	Post-Rotation	Increase
75°	-11.52 cm ± 29.01	16.71 cm ± 36.42	28.23 cm ± 35.19
150°	-22.01 cm ± 25.61	-6.90 cm ± 49.61	15.11 cm ± 37.64
225°	-9.27 cm ± 49.35	-6.28 cm ± 48.17	2.99 cm ± 28.02
300°	-20.70 cm ± 33.33	33.14 cm ± 54.43	53.84 cm ± 40.39*

Experiment 3 (n = 107)

Condition	Pre-Rotation	Post-Rotation	Increase
Redness Gradient			
37.5°	-72.79 cm ± 21.77	-84.65 cm ± 11.72	-11.86 cm ± 18.27
75.0°	-72.29 cm ± 23.25	-78.81 cm ± 26.42	-6.53 cm ± 22.23
112.5°	-61.22 cm ± 22.82	-71.16 cm ± 19.52	-9.94 cm ± 19.11
150.0°	-81.70 cm ± 14.30	-83.93 cm ± 13.77	-2.23 cm ± 12.48
Wireframe Room			
37.5°	-38.69 cm ± 32.00	-3.22 cm ± 29.34	35.48 cm ± 16.07
75.0°	-15.70 cm ± 37.71	41.40 cm ± 44.19	57.10 cm ± 26.52
112.5°	-31.35 cm ± 26.43	19.59 cm ± 40.17	50.94 cm ± 23.46
150.0°	-15.19 cm ± 33.88	17.20 cm ± 35.54	32.30 cm ± 41.77
Realistic Other Room			
37.5°	-86.27 cm ± 16.42	-87.96 cm ±17.01	-2.42 cm ± 16.55
75.0°	-78.61 cm ± 17.21	-89.72 cm ± 15.63	-11.11 cm ± 15.74
112.5°	-93.93 cm ± 16.85	-93.99 cm ± 11.43	-0.06 cm ± 10.34
150.0°	-94.57 cm ± 13.63	-96.75 cm ± 9.77	-2.18 cm ± 10.71
Realistic Actual Room			
37.5°	-108.67 cm ± 15.86	-117.06 cm ± 13.57	-8.39 cm ± 10.92
75.0°	-103.15 cm ± 13.54	-122.19 cm ± 15.72	-19.05 cm ± 9.75
112.5°	-100.97 cm ± 12.32	-111.48 cm ± 13.85	-10.51 cm ± 8.87
150.0°	-75.54 cm ± 18.05	-84.91 cm ± 30.09	-10.48 cm ± 17.19

Experiment 4 (n = 34)

Condition	Pre-Rotation	Post-Rotation	Increase
Room Visible	-41.89 cm ± 9.70	-47.94 cm ± 8.11	-6.05 cm ± 7.88
Room Not Visible	-38.82 cm ± 8.48	-54.20 cm ± 8.90	-15.38 cm ± 7.88*

* - Denotes a significant change, $p < 0.05$

APPENDIX E

Absolute Distance Error Data (mean ± 95% confidence interval)

Experiment 1 (n = 28)

Condition	Pre-Rotation	Post-Rotation	Increase
Gradient Visible	80.09 cm ± 11.28	100.67 cm ± 11.48	22.80 cm ± 7.98*
Gradient Not Visible	83.13 cm ± 9.57	110.42 cm ± 14.83	26.91 cm ± 7.98*

Experiment 2 (n = 28)

Condition	Pre-Rotation	Post-Rotation	Increase
75°	132.68 cm ± 24.03	171.52 cm ± 28.46	38.83 cm ± 32.34*
150°	139.07 cm ± 20.76	159.32 cm ± 44.26	20.25 cm ± 33.88
225°	152.59 cm ± 44.26	163.89 cm ± 44.98	11.30 cm ± 25.34
300°	120.37 cm ± 30.13	184.40 cm ± 47.30	64.03 cm ± 38.46*

Experiment 3 (n = 107)

Condition	Pre-Rotation	Post-Rotation	Increase
Redness Gradient			
37.5°	132.68 cm ± 24.03	171.52 cm ± 28.46	5.79 cm ± 15.77
75.0°	139.07 cm ± 20.76	159.32 cm ± 43.00	0.96 cm ± 16.53
112.5°	152.59 cm ± 44.26	163.89 cm ± 44.94	9.76 cm ± 15.11
150.0°	120.37 cm ± 30.13	184.40 cm ± 47.30	8.16 cm ± 9.29
Wireframe Room			
37.5°	123.87 cm ± 30.60	165.75 cm ± 19.39	41.88 cm ± 15.41*
75.0°	127.33 cm ± 26.21	185.59 cm ± 39.60	58.25 cm ± 22.62*
112.5°	124.49 cm ± 22.91	182.12 cm ± 32.78	57.63 cm ± 22.29*
150.0°	141.95 cm ± 31.63	177.60 cm ± 28.63	35.98 cm ± 35.03*
Realistic Other Room			
37.5°	109.82 cm ± 7.63	117.08 cm ± 9.12	7.83 cm ± 11.26
75.0°	105.81 cm ± 13.13	116.89 cm ± 8.27	11.07 cm ± 10.42*
112.5°	108.22 cm ± 7.90	112.73 cm ± 7.98	4.50 cm ± 7.83
150.0°	111.74 cm ± 9.78	112.02 cm ± 7.46	0.28 cm ± 8.49
Realistic Actual Room			
37.5°	116.77 cm ± 12.93	126.25 cm ± 10.61	9.48 cm ± 8.95*
75.0°	115.27 cm ± 10.95	129.00 cm ± 12.17	13.73 cm ± 8.79*
112.5°	115.21 cm ± 7.29	125.84 cm ± 9.03	10.63 cm ± 7.81*
150.0°	108.51 cm ± 11.43	133.65 cm ± 19.19	26.13 cm ± 15.53*

Experiment 4 (n = 34)

Condition	Pre-Rotation	Post-Rotation	Increase
Room Visible	70.97 cm ± 6.02	78.30 cm ± 4.49	7.33 cm ± 7.08*
Room Not Visible	74.27 cm ± 7.91	80.30 cm ± 6.68	6.03 cm ± 7.08

* - Denotes a significant change, $p < 0.05$