Journal of Experimental Psychology:
Learning, Memory, and Cognition
2006, Vol. 32, No. 6, 1274–1290

0278-7393/06/$12.00 DOI: 10.1037/0278-7393.32.6.1274

Roles of Egocentric and Allocentric Spatial Representations in Locomotion and Reorientation

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Four experiments investigated the nature of spatial representations used in locomotion. Participants learned the layout of several objects and then pointed to the objects while blindfolded in 3 conditions: before turning (baseline), after turning to a new heading (updating), and after disorientation (disorientation). The internal consistency of pointing in the disorientation condition was relatively high and equivalent to that in the baseline and updating conditions, when the layout had salient intrinsic axes and the participants learned the locations of the objects on the periphery of the layout. The internal consistency of pointing was disrupted by disorientation when participants learned the locations of objects while standing amid them and the layout did not have salient intrinsic axes. It was also observed that many participants retrieved spatial relations after disorientation from the original learning heading. These results indicate that people form an allocentric representation of object-to-object spatial relations when they learn the layout of a novel environment and use that representation to locate objects around them. Egocentric representations may be used to locate objects when allocentric representations are not of high fidelity.

Keywords: spatial memory, navigation, disorientation, spatial frame of reference, spatial updating

Human navigation must depend on both egocentric and allocentric representations of the environment. Finding a path through closely spaced trees, for example, requires the computation of precise self-to-object spatial relations to guide locomotion (e.g., Andersen, Snyder, Bradley, & Xing, 1997). But planning a route to a distant goal and maintaining a sense of orientation in large-scale environments would seem to require enduring representations of the locations of objects relative to other objects (e.g., Loomis & Beall, 1998). Contemporary models of human spatial memory and navigation specify roles for both egocentric and allocentric representations of space. The models differ in the nature of those representations and in how they are used during navigation.

In Sholl's model (e.g., Easton & Sholl, 1995; Holmes & Sholl, 2005; Sholl, 2001; Sholl & Nolin, 1997), an egocentric self-reference system codes self-to-object spatial relations in body-centered coordinates, using the body axes of front–back, right–left, and up–down (e.g., Bryant & Tversky, 1999; Franklin & Tversky, 1990). This system provides a framework for spatially directed motor activity, such as walking, reaching, and grasping. Self-to-object spatial relations are continuously and efficiently updated as an observer moves through an environment. The spatial relations among objects are represented in an allocentric object-to-object system using an orientation-independent reference system. A dominant reference direction in this system is established by egocentric front when participants are perceptually engaged with the environment.[1]

Wang and Spelke (2000, 2002) have proposed a model of spatial memory and navigation that consists of three interrelated systems. According to this model, humans navigate by computing and dynamically updating spatial relations between their bodies and important objects in the surrounding environment. This dynamic egocentric system supports path integration, the primary mode of

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Preparation of this article and the research reported in it were supported in part by the One Hundred Talent Plan Fellowship of the Chinese Academy of Sciences and National Natural Science Foundation of China Grant 30470576 to Weimin Mou and National Institute of Mental Health Grant 2-R01-MH57868 to Timothy P. McNamara. We are grateful to Caren Rotello, Jeanne Sholl, and John Philbeck for their helpful comments on a previous version of this article.

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[1] Sholl's model predicts that if a person is perceptually engaged with and oriented in a familiar environment, self-to-object and object-to-object spatial relations should be retrieved and utilized efficiently from any facing direction, or heading, as long as the actual body heading and the imagined body heading are the same. This prediction was tested and disconfirmed by Mou, McNamara, Valiquette, and Rump (2004; see also Valiquette, McNamara, & Smith, 2003). For present purposes, we ignore this potential problem in the model and focus on the distinction between the self-reference system and the object-to-object system and on properties of the latter system other than its orientation independence.

navigation according to the model. A second system represents the appearances of familiar landmarks and scenes. These representations are viewpoint dependent and can be conceived of as visual–spatial snapshots of the environment (e.g., Burgess, Spiers, & Paleologou, 2004; Diwadkar & McNamara, 1997; Wang & Simons, 1999). Finally, the geometric shape of the environment (e.g., the shape of a room) is represented in an enduring allocentric system. The allocentric system does not represent the spatial relations among objects in the environment; its purpose is to support reorientation when the path integration system breaks down (e.g., Hermer & Spelke, 1994).

Mou, McNamara, Valiquette, and Rump (2004) recently proposed a third model of spatial memory and navigation. This model was inspired in part by theories of the relations between visually guided action and visual perception (e.g., Creem & Proffitt, 2001; Milner & Goodale, 1995; Rossetti, 1998; Rossetti, Pisella, & Pélisson, 2000). According to this model, the human navigation and spatial representation system comprises two subsystems: The egocentric subsystem computes and represents transient self-to-object spatial relations needed for locomotion. These spatial relations are represented at sensory–perceptual levels and decay relatively rapidly in the absence of perceptual support or deliberate rehearsal. The environmental subsystem is responsible for representing the enduring features of familiar environments. In this subsystem, the spatial structure of the environment is represented in an orientation-dependent manner using an intrinsic reference system (e.g., Shelton & McNamara, 2001). Interobject spatial relations are specified with respect to a small number (typically 1 or 2) of intrinsic reference directions or axes (e.g., Mou & McNamara, 2002).

As a person locomotes through a familiar environment, two types of updating occur. The momentary egocentric self-to-object spatial relations needed to control locomotion are updated as long as there is perceptual support. This updating process is efficient and requires minimal attentional control. The dominant perceptual input for sighted observers is vision, although proprioception and audition are useful as well (e.g., Loomis, Lippa, Klatzky, & Golledge, 2002). In the absence of visual support (e.g., walking in the dark), egocentric updating is more effortful and capacity limited (e.g., Rieser, Hill, Talor, Bradfield, & Rosen, 1992).

Egocentric updating allows people to stay on course and avoid obstacles, but it does not prevent the observer from getting lost. To stay oriented, one must know where one is with respect to familiar objects in the environment (e.g., Loomis & Beall, 1998). The spatial layout of those objects must be mentally represented over the long term. These representations are preserved in the environmental subsystem. Spatial updating in this subsystem consists of keeping track of location and orientation with respect to the intrinsic reference system used to represent the spatial structure of the environment. Self-to-object and object-to-object spatial relations are specified in the same intrinsic reference system. The body is treated like any other object in the environment. This proposed distinction between egocentric and environmental updating is similar to Sholl's (2001) distinction between updating at perceptual–motor and representational levels.

These three models are similar in many ways but differ in at least one key respect: According to Sholl's model (e.g., Sholl, 2001) and Mou and McNamara's model (e.g., Mou et al., 2004), object-to-object spatial relations are represented in an enduring form in a system that uses an allocentric reference system. In contrast, in Wang and Spelke's (2002) model, object-to-object spatial relations are not represented, and the enduring allocentric system represents only the shape of the environment.

Wang and Spelke (2000) investigated behavioral consequences of this key difference between these models. They showed that the internal consistency of pointing to objects in the immediate environment was disrupted by disorientation. For example, in their Experiment 1, participants pointed to six targets, first with their eyes open, then while blindfolded after a small rotation, and finally while blindfolded after being disoriented. The configuration error—which is defined as the standard deviation across target objects of the mean signed pointing errors and indicates the accuracy of the localization of each target in relation to the others—increased after disorientation. Wang and Spelke argued that if spatial memory is enduring and allocentric, the configuration error should not be increased by disorientation. Crucially, they also showed that disorientation did not affect the internal consistency of pointing judgments when participants pointed to the corners of the room in which they were tested. According to Wang and Spelke, the shape of the surrounding room was represented in the allocentric system.

It is not clear how Sholl's model (e.g., Sholl, 2001) and Mou and McNamara's model (Mou et al., 2004) could explain the increase in configuration error after disorientation. According to these models, an enduring allocentric spatial representation is maintained independently of a person's momentary location and orientation. When people temporarily lose their orientation with respect to the environment, the memory of the object-to-object spatial relations should be intact. After people gain their location and orientation with respect to the allocentric spatial memory, as when they recognize a landmark or are informed of their location and orientation, they should also recover all self-to-object spatial relations and regain their sense of where they are.

Holmes and Sholl (2005) hypothesized that allocentric object-to-object representations may take time to develop and that in the early stages of learning an environment, people may rely more on the self-reference system to locate objects around them. Disorientation may disrupt self-to-object spatial relations in the self-reference system, leading to an increase in configuration error. They tested this hypothesis by having participants point to locations in a highly familiar environment (their college campus) before and after disorientation. As predicted, disorientation did not affect configuration error. However, Holmes and Sholl were unable to obtain an effect of disorientation on configuration error in recently learned environments, even when the procedures closely matched Wang and Spelke's (2000).

Holmes and Sholl (2005) conjectured that their failure to replicate Wang and Spelke's (2000) findings might be attributable to the learning procedures. According to this explanation, Holmes and Sholl's procedures produced relatively imprecise object-to-object spatial representations. These representations were susceptible to categorical bias (e.g., Huttenlocher, Hedges, & Duncan, 1991), with the direction of bias varying across objects. These noisy but stable representations produced consistent levels of configuration error before and after disorientation. Wang and Spelke's procedures, however, produced relatively precise object-to-object spatial representations when locations of objects were spatially attended, as in the predisorientation phase. But when spatial attention was diverted by disorientation, the object-to-object spatial representations became less precise and more susceptible to categorical bias, resulting in higher levels of configuration error.

Our interpretation of Wang and Spelke's (2000) original findings, and of Holmes and Sholl's (2005) failure to replicate them, is similar to Holmes and Sholl's original hypothesis but focuses instead on participants' abilities to represent the overall layout of the objects to which they must later point. For convenience, our explanation is couched in terms of our model, but it could also be described in the context of Sholl's model.

We hypothesize that people rely more on the egocentric subsystem than on the environmental subsystem when spatial representations in the environmental subsystem are inaccurate, imprecise, or otherwise of low fidelity. Disorientation would disrupt self-to-object spatial representations in the egocentric subsystem so that only imprecise object-to-object spatial representations can be used, leading to an increase in configuration error. An important feature of Wang and Spelke's (2000) experiments is that the spatial layout of the objects might have been difficult to apprehend. In Experiments 1, 2, 4, and 5, the objects were located outside of a chamber. Participants walked around the outside of the chamber to learn the locations of the objects and then entered the chamber to make their pointing judgments. In Experiments 6 and 7, objects were arrayed around the participant within a chamber or room. Under such conditions, people may have difficulty constructing a representation of object-to-object spatial relations. A relatively low fidelity allocentric representation might result, for example, from difficulties in selecting intrinsic reference directions. By contrast, the spatial layout of an enclosing room may be readily perceivable from virtually any viewpoint. Moreover, familiarity with rectilinear spaces may facilitate creating an allocentric representation of the room.

This explanation also may account for Holmes and Sholl's (2005) failures to replicate Wang and Spelke's (2000) findings. Not only was the campus highly familiar to participants, but their knowledge of its layout was probably facilitated at some point by consulting maps (which are easily accessible, for example, on the Boston College Web site). In Experiments 3–6, the objects were placed against the walls of a rectangular room at regular angular intervals around the participant's pointing location. In Experiment 7 (see Holmes & Sholl, 2005, Figure 10), the objects could be perceptually organized into a rectangular array of rows and columns. Hence, even in the light of Holmes and Sholl's important findings, there are reasons to believe that configuration error was not increased by disorientation in their experiments, because participants were able to form high-fidelity allocentric representations of the layout of the objects.

The goal of this study was to test this conjecture. In Experiment 1, participants learned the layout of nine objects from a viewing position on the periphery of the array. The objects were arrayed in a regular formation that could be organized into columns and rows (see Figure 1). We hypothesized that the peripheral learning perspective and the regularity of the layout would facilitate the construction of a high-fidelity allocentric representation of the objects' locations and, consequently, that disorientation would not affect the internal consistency of pointing to objects. After learning the layout of the objects, participants walked to the middle of the array without changing heading and then pointed to objects while blindfolded under three conditions: before turning (baseline), after turning to a heading misaligned with salient intrinsic axes of the array of objects (updating), and after being disoriented (disorientation). The results showed that the internal consistency of pointing was the same in the baseline, updating, and disorientation conditions.

It was also observed that after disorientation, participants pointed to objects as if they were facing the original learning view or in a direction orthogonal to the learning view (we refer to such headings as *aligned*). This strategy of using an aligned subjective heading might have benefited the disorientation condition relative

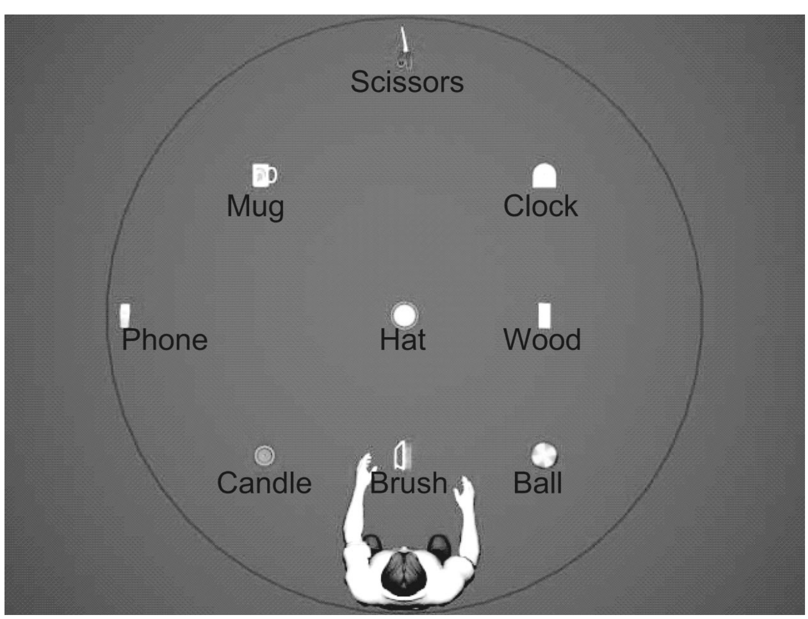

Figure 1. Layout of objects used in Experiments 1 and 2.

to the updating condition, in which the subjective heading was misaligned (±135°) with the learning view. Many studies have shown that retrieving the locations of target objects from imagined headings aligned with the learning view, especially the heading corresponding to the learning view, is easier than retrieving the locations of target objects from misaligned headings (e.g., Easton & Sholl, 1995; Levine, Jankovic, & Palij, 1982; Mou & McNamara, 2002; Mou et al., 2004; Rieser, 1989; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Valiquette, McNamara, & Smith, 2003). The benefit of using a felicitous imagined heading in the disorientation condition might have masked the costs of disorientation (see also Holmes & Sholl, 2005, p. 1082). In Experiment 2, participants were required to take a subjective heading different from their learning view in the updating and the disorientation conditions. The results still showed that the internal consistency of pointing in the disorientation condition was relatively high and equivalent to internal consistency in the baseline and updating conditions. This finding indicates that the failure to observe a decrease in the internal consistency of pointing after disorientation was not caused by participants' use of aligned subjective headings in the disorientation condition of Experiment 1.

In Experiments 3 and 4, participants learned the locations of four objects while standing amid them; the layout did not have salient intrinsic axes. The internal consistency of pointing was disrupted by disorientation only when participants were forced to adopt a subjective heading different from their learning view. We were, therefore, able to replicate Wang and Spelke's (2000) original results under certain conditions.

Experiment 1

Participants learned the layout of nine objects from a single viewpoint and then walked to stand in the center of the collection of objects. Participants pointed to objects under three experimental conditions: In the baseline condition, participants pointed to objects while facing in the learning orientation; in the updating condition, participants turned to a new facing direction before pointing; and in the disorientation condition, participants were disoriented and then pointed to objects without any restrictions on which subjective heading to adopt. According to Wang and Spelke's (2002) model, the configuration error will be bigger in the disorientation condition than in the updating condition. According to Mou et al.'s (2004) model, the configuration error in the disorientation condition will be the same as that in the updating condition.

Method

Participants. Twenty university students (10 men, 10 women) participated in return for monetary compensation.

Apparatus and design. The objects were arrayed in a cylinder 3.0 m in diameter constructed from a reinforced cloth and a black fabric, which blocked the lights from outside. The layout consisted of a configuration of nine objects (Figure 1). Objects were selected with the restrictions that they be visually distinct, fit within approximately 0.3 m on each side, and not share any obvious semantic associations. The hat was placed in the middle of the cylinder. The distance from the hat to the brush and to the wood was 0.7 m, and from the hat to the phone and to the scissors was 1.4 m. A video camera was mounted on the ceiling just above the hat, providing an overhead view of the layout. A light was placed on the ceiling near the camera for illumination inside the cylinder.

Each trial was constructed from a warning indication ("Start") and a target object (e.g., "Please point to the wood"). Trials were presented by a computer outside the cylinder via a wireless earphone. A switch, which was connected to the computer and held in the left hand of the participant, was used by participants to indicate that they were ready to start after they heard the warning indication. A stylus 0.2 m long with a laser pointer was held by the right hand of the participants to point to the target object. A switch was mounted next to the button of the laser pointer so that they could be pressed together. The red spot emitted by the laser pointer was captured by the video camera and was used to measure the pointing direction. The switch on the stylus was used to measure the pointing latency.

The primary independent variable was the locomotion of the participant just before the presentation of the trials. In the baseline condition, participants stood near the hat and maintained their learning orientation (facing the scissors). In the updating condition, participants turned to face a new heading (ball or candle) before pointing to objects. In the disorientation condition, participants turned in place until they were disoriented, were turned by the experimenter to face the candle or the ball, and then pointed to objects. In each locomotion condition, four blocks of trials were included, each involving seven target objects, which excluded the object in front of the participant and the hat.

The following dependent variables were measured (see Table 1 for definitional formulas): (a) *signed pointing error*, defined as the signed angular difference between the judged direction of the target object and the actual direction of the target object; (b) *pointing latency*, measured as the latency from presentation of the target object to the press of the switch on the stylus; (c) *heading error*, defined as the mean of the means per target object of the signed pointing errors; (d) *configuration error*, defined as the standard deviation of the means per target object of the signed pointing errors; And (e) *pointing variability*, defined as the square root of the mean of the variances per target object of the signed pointing errors.

The actual direction of a target object was defined with respect to the learning heading (baseline) or the ±135° headings (updating and disorientation). The judged direction was defined with respect to the participant's egocentric heading. Heading error measures the constant error in pointing judgments. To make pointing judgments after disorientation, participants must adopt a subjective heading in imagination. We assumed that heading error measured the difference between the participant's actual heading and the heading assumed by the participant while pointing. Heading error would presumably be small in the baseline and the updating conditions, because participants know which direction they are facing, but large and variable across participants in the disorientation condition, because participants have no idea which direction they are actually facing. Configuration error is a measure of the internal consistency of pointing judgments. Pointing variability is a measure of the precision of pointing judgments. This measure is similar to Wang and Spelke's (2000) pointing error measure but has the advantage of having an easily computed expected value (as described in the General Discussion). Our measures of configuration error and pointing variability were based on population estimates rather than on sample estimates for the same reason. As discussed in the General Discussion, configuration error can be interpreted as a measure of the inaccuracy of remembered directions of target objects relative to the subjective heading.

Procedure. Before entering the study room, each participant was instructed to learn the locations of the objects for a spatial memory test. Twelve practice trials using three objects not in the layout were used to familiarize participants with the use of the switch in the left hand to initiate trials and the stylus in the right hand to point to target objects. The participant was blindfolded outside of the study room and led to the learning position via an entrance to the cylinder near the learning position (Figure 1). The blindfold was removed, and the names of the objects were provided by the experimenter. Participants viewed the layout for 30 s before being asked to name and point, with eyes closed, to the objects. Participants received five such learning–testing sessions.

After learning the locations of the objects, participants walked, with eyes open, to the middle of the cylinder (next to the hat) while maintaining their

Table 1
Definitional Formulas for Dependent Variables

Variable	Formula
Signed pointing error for object i on trial j	e_{ij} = judged direction − actual direction
Mean signed pointing error for object i	$\bar{e}_{i.} = \dfrac{\sum_j e_{ij}}{T}$
Heading error	$\bar{e}_{..} = \dfrac{\sum_i \bar{e}_{i.}}{N}$
Configuration error	$\sqrt{\dfrac{\sum_i (\bar{e}_{i.} - \bar{e}_{..})^2}{N-1}}$
Pointing variability	$\sqrt{\dfrac{\sum_i \left(\dfrac{\sum_j (e_{ij} - \bar{e}_{i.})^2}{T-1}\right)}{N}}$

Note. T = number of pointing trials per object; N = number of target objects.

learning heading (facing the scissors). They were blindfolded and given the switch, the stylus, and the earphone. For all participants, the order of conditions was baseline, updating, and disorientation. In all three locomotion conditions, participants maintained the location in the middle of the cylinder (near the hat). In the baseline condition, participants faced the original learning heading throughout the pointing trials. In the updating condition, participants turned left (225°) to face the ball or right (225°) to face the candle (counterbalanced across participants). They were not told to turn toward a particular object but instead instructed to turn until the experimenter stopped them (e.g., "Please turn left until I stop you"). Therefore, participants were not informed explicitly about the direction they actually faced in the updating condition. In the disorientation condition, participants rotated in place by themselves, reporting the object in front after every minute, until they reported incorrectly and were disoriented. Participants were then turned by the experimenter to face the direction ±135° away from the learning view. Participants who faced the ball in the updating condition were turned to face the candle, and those who faced the candle in the updating condition were turned to face the ball. Participants were not informed about the direction they actually faced in the disorientation condition. The updating condition was comparable to the disorientation condition except for the difference of locomotion.

The experimenter initiated each pointing trial by pressing the return key on the computer. Participants were instructed to press the switch held in the left hand if they heard "Start" via the earphone and were ready to continue. The target object was given over the earphone once the left-hand switch was pressed. Participants were instructed to point to the target object using the stylus as accurately as possible and to press the switch and the button on the stylus once they were satisfied with their pointing response. Participants were also instructed to press the button of the laser pointer for several seconds so that the red spot emitted by the laser pointer would be clearly visible on the video recording. No feedback was provided about the accuracy of pointing responses.

Results

The dependent variables were analyzed in mixed-model analyses of variance (ANOVAs) with terms for gender and locomotion condition. Locomotion condition was within subject.

Heading error. The mean absolute heading errors in the baseline, updating, and disorientation conditions were 9°, 22°, and 102°, respectively. The main effect of locomotion condition was significant, $F(2, 36) = 63.25$, $p < .001$, $MSE = 807.55$. Pairwise comparisons showed that heading error was lower in the baseline and updating conditions than in the disorientation condition, $ts(36) \geq 8.93$. The difference between baseline and updating was not significant, $t(36) = 1.46$. No other effects were significant.

The subjective heading is defined as the heading adopted by participants in working memory while making their pointing judgments. We estimated the subjective heading as the difference between the participant's actual heading and the heading error. The distribution of the subjective heading in each condition is plotted in Figure 2A–2C as a function of actual heading. In Figure 2, all of the headings were presented with respect to the learning heading. A positive sign refers to headings clockwise from the learning heading, whereas a negative sign refers to headings counterclockwise from the learning heading. As shown in Figure 2A, participants exhibited subjective headings in the baseline condition that were nearly the same as the learning heading (all within ±22.5° around the scissors).[2] As shown in Figure 2B, the variability of subjective headings in the updating condition was larger than that in the baseline condition, but subjective headings were still centered on the actual heading. As shown in Figure 2C, participants exhibited much larger errors in their subjective headings in the disorientation condition. However, even in this condition, subjective headings were not random. Most participants took the learning heading or the headings orthogonal to the learning heading (e.g., −90°) as their subjective heading. The number of participants who took the learning heading as their subjective heading in the dis-

[2] We divided the subjective heading into eight categories (centered on 0, 45, −45, 90, −90, 135, −135, and 180), and a subjective heading within ±22.5° around some direction will be counted as that direction.

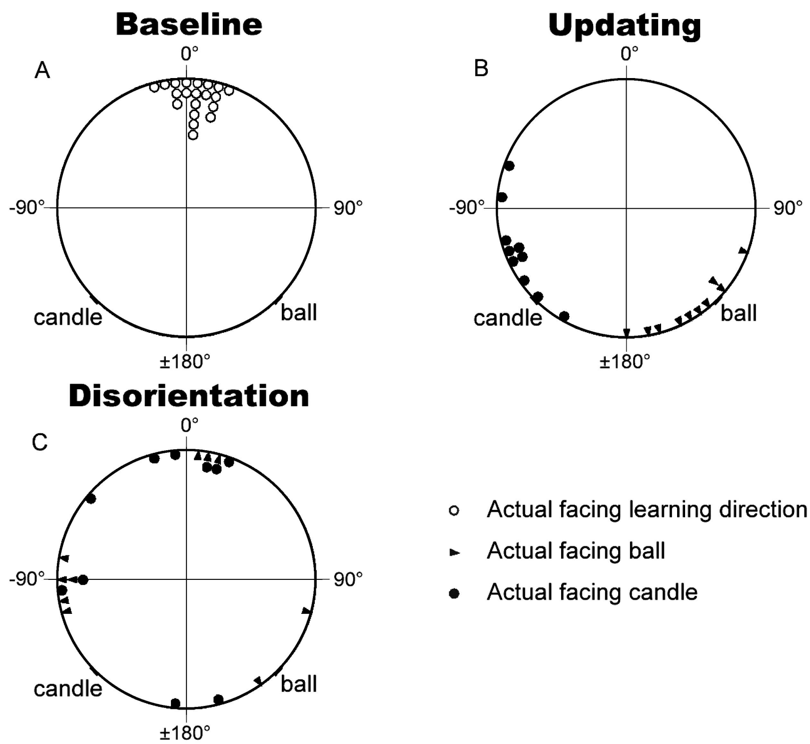

Figure 2. Subjective heading as a function of actual heading and locomotion condition in Experiment 1. Each dot represents the subjective heading of one participant.

orientation condition (8 of 20) was significantly above chance level, $\chi^2(1, N = 20) = 13.83$, $p < .001$. Put another way, 40% of the participants pointed to objects in the disorientation condition as if they were facing the learning heading.

Configuration error. Configuration error is plotted in Figure 3A as a function of locomotion condition. As shown in the figure, the differences between the three conditions were small. The main effect of locomotion was not significant, $F(2, 36) = 0.88$, $p > .05$, $MSE = 35.88$. No other effects were significant.

Pointing variability. Pointing variability is plotted in Figure 3B as a function of locomotion condition. The main effect of locomotion was significant, $F(2, 36) = 4.74$, $p < .05$, $MSE = 54.60$. Pointing variability was lower in the baseline condition than in the updating and disorientation conditions, $ts(36) \geq 2.59$, but the difference between the latter two conditions was not evident, $t(36) < 1$. No other effects were significant.

Pointing latency. Pointing latency is presented in Table 2 as a function of locomotion condition. The main effect of locomotion was significant, $F(2, 36) = 6.18$, $p < .01$, $MSE = 0.39$. Pointing latencies were faster in the baseline and disorientation conditions than in the updating condition, $ts(36) \geq 2.24$, but the former two conditions did not differ significantly, $t(36) = 1.21$. No other effects were significant.

Discussion

The most important finding in Experiment 1 was that the disorientation condition was as good as the updating condition in terms of configuration error and pointing variability. These results show that disorientation did not disrupt the internal consistency of pointing any more than turning to a new facing direction. Nearly half of the participants (8 of 20) used the learning view as their subjective heading in the disorientation condition, and almost the same number (7 of 20) used a heading orthogonal to the learning view (–90°) as their subjective heading. As discussed in the General Discussion, we doubt that participants who used the learning heading as their subjective heading retrieved static, viewpoint-dependent representations to make their pointing judgments (e.g., Diwadkar & McNamara, 1997; Shelton & McNamara, 1997; Wang & Spelke, 2002). Hence, this finding indicates that participants were able to recover allocentric spatial relations from the original learning view or from a heading orthogonal to the learning view after disorientation. These findings are consistent with the claim that the locations of objects were represented in an orientation-dependent representation using an intrinsic reference system (e.g., Mou & McNamara, 2002; Mou et al., 2004; Shelton & McNamara, 2001).

Previous research has shown that headings parallel or orthogonal to the learned heading—which we refer to as aligned headings—can be privileged in memory (e.g., Mou & McNamara, 2002). Most of the participants in Experiment 1 seemed to have adopted an aligned subjective heading of 0°, ±180°, or –90° (see Figure 2C) in the disorientation condition. Even if the disorientation condition were normally more difficult than the updating condition, performance in the two conditions might have been equivalent in Experiment 1 because in the disorientation condition, participants pointed to objects as if they were oriented toward a relatively easy aligned heading, whereas in the updating condition, participants were required to

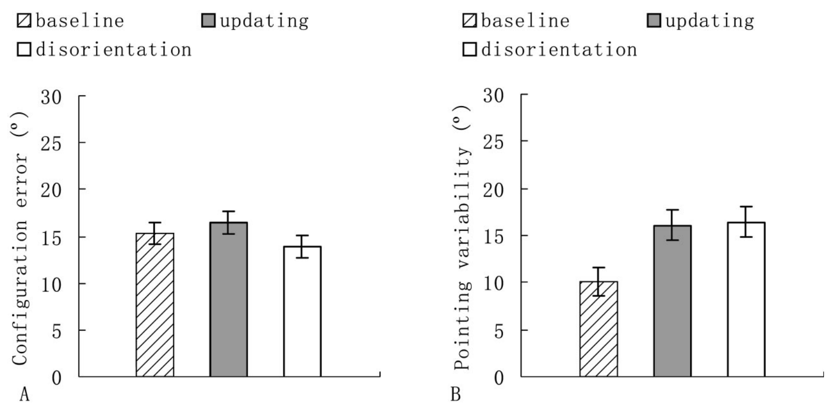

Figure 3. Configuration error and pointing variability as a function of locomotion condition in Experiment 1. (Error bars are confidence intervals corresponding to ± 1 *SEM*, as estimated from the analysis of variance.)

point to objects from a relatively difficult misaligned heading (e.g., Holmes & Sholl, 2005).

In Experiment 2 we removed this confound by asking participants to point to objects in the disorientation condition as if they were facing one of the misaligned headings of $\pm 135°$. The goal of Experiment 2 was to determine whether participants would be able to recover spatial relations from a misaligned heading identified by the experimenter after they had been disoriented. To the extent that they could, the results would provide converging evidence that pointing after disorientation relies heavily on an allocentric representation of the environment.

Experiment 2

Method

Participants. Twenty university students (10 men, 10 women) participated in return for monetary compensation.

Apparatus, design, and procedure. The apparatus, design, and procedure were similar to those used in Experiment 1 with the following changes: (a) A joystick was used as the pointing apparatus instead of the stylus and video capture system to avoid the time-consuming off-line coding of the pointing direction; (b) participants were informed explicitly about the direction they actually faced in the updating condition before they turned their body (e.g., “Please turn left until you are facing the ball”); and (c) after disorientation, participants were instructed to turn to face the ball (or candle) if they faced the candle (or the ball) in the updating condition (e.g., “Please turn left until you *believe* you are facing the ball”).

Table 2
Mean (and Standard Deviation) Response Latency (in Seconds) as a Function of Locomotion Condition in Experiments 1–4

	Locomotion		
Experiment	Baseline	Updating	Disorientation
1 (n = 20)	2.651 (1.361)	3.333 (1.711)	2.891 (1.691)
2 (n = 20)	1.498 (0.697)	2.316 (0.973)	2.447 (1.319)
3 (n = 40)	1.026 (0.771)	1.198 (0.884)	1.312 (0.909)
4 (n = 40)	1.180 (0.717)	1.467 (0.851)	1.426 (0.616)

Participants held the joystick against their front waist. They were instructed to click the trigger on the joystick when they heard the warning (“Start”). Then the name of the target object was presented (e.g., “Please point to the mug”), and they were instructed to point to the direction of the target object as accurately as possible. They were discouraged from pointing too quickly. As in Experiment 1, participants pointed to seven objects excluding the hat and the one object that was to the front of the (actual/subjective) heading in each locomotion condition.

Results and Discussion

The dependent variables were analyzed in mixed-model ANOVAs with terms for gender and locomotion condition. Locomotion condition was within subject.

Heading error. The mean absolute heading errors in the baseline, updating, and disorientation conditions were 5°, 12°, and 14°, respectively. The main effect of locomotion was significant, $F(2, 36) = 5.28$, $p < .01$, $MSE = 83.20$. Pairwise comparisons showed that participants exhibited smaller heading errors in the baseline condition than in the updating and disorientation conditions, $ts(36) \geq 2.42$. The difference between the latter two conditions was not evident, $t(36) < 1$. No other effects were significant. The low heading error in the disorientation condition shows that subjective headings were very close to the named heading of $\pm 135°$.

The distribution of participants’ subjective headings in each condition is plotted in Figure 4A–4C as a function of actual heading. Participants had very accurate subjective headings in the baseline condition (Figure 4A). In the updating condition, subjective headings were more variable but still clustered near the actual heading (Figure 4B). As shown in Figure 4C, in the disorientation condition subjective headings were still clustered near the named heading, suggesting that participants took the subjective heading named by the experimenter.

Configuration error. Configuration error is plotted in Figure 5A as a function of locomotion condition. As shown in the figure, the difference among the three conditions was small. The main effect of locomotion was not significant, $F(2, 36) = 1.06$, $p > .05$, $MSE = 29.83$. No other effects were significant.

Pointing variability. Pointing variability is plotted in Figure 5B as a function of locomotion condition. The main effect of

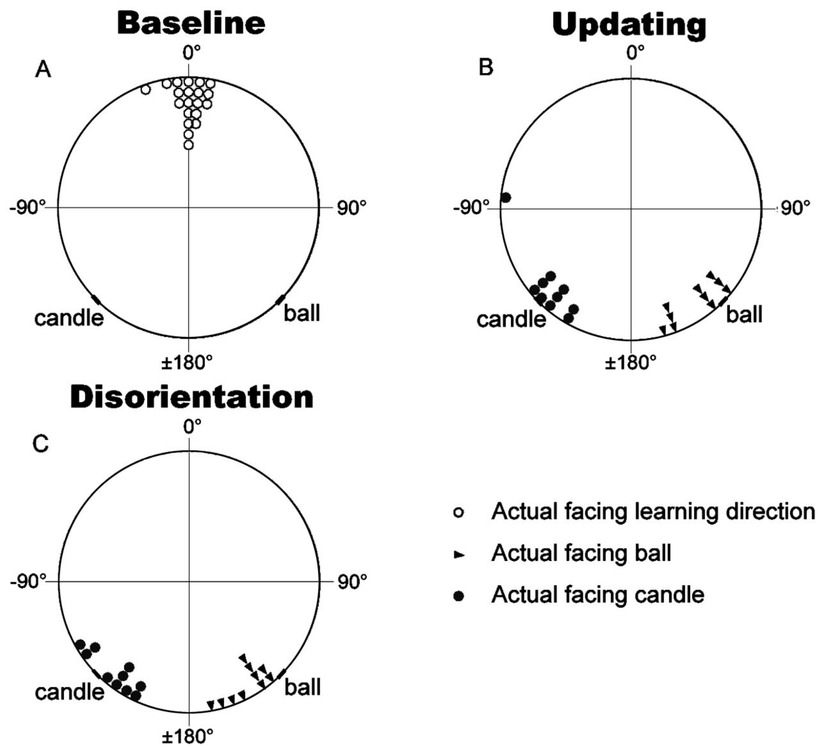

Figure 4. Subjective heading as a function of actual heading and locomotion condition in Experiment 2. Each dot represents the subjective heading of one participant.

locomotion was not significant, $F(2, 36) = 2.40$, $p > .05$, $MSE = 35.47$. No other effects were significant.

Pointing latency. Pointing latency is presented in Table 2 as a function of locomotion condition. The main effect of locomotion was significant, $F(2, 36) = 8.90$, $p < .001$, $MSE = 0.59$. Participants responded faster in the baseline condition than in the updating and disorientation conditions, $ts(36) \geq 3.37$. The difference between the latter two conditions was not significant, $t(36) < 1$. No other effects were significant.

In the previous two experiments, participants had the opportunity to select a well-defined intrinsic frame of reference because they could see the layout of the objects in its entirety from a single perspective and because the objects could be organized into columns and rows (e.g., Mou & McNamara, 2002). It is possible that when people are not able to interpret the layout of objects in terms of a well-defined intrinsic frame of reference and few objects need to be tracked, perceptual-level egocentric updating plays a more important role in spatial updating. If so, one might predict that performance in the updating condition would be better than performance in the disorientation condition. After disorientation, participants would rely solely on an allocentric spatial representation that is of relatively low fidelity. But in the updating condition,

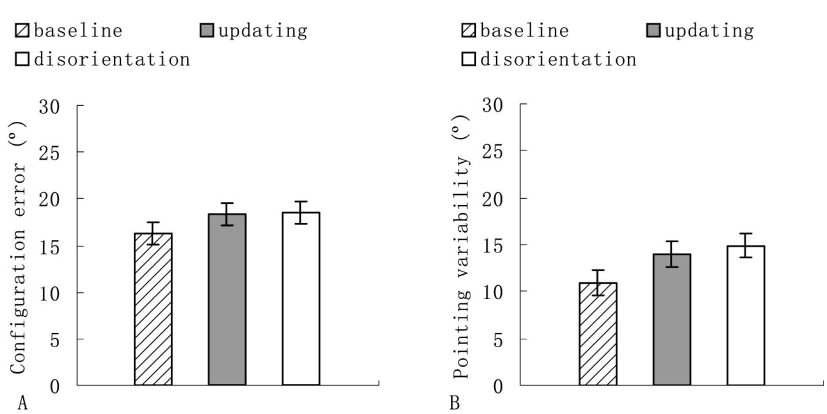

Figure 5. Configuration error and pointing variability as a function of locomotion condition in Experiment 2. (Error bars are confidence intervals corresponding to ±1 *SEM*, as estimated from the analysis of variance.)

participants could also use perceptual-level self-to-object spatial representations to make pointing judgments, if such spatial relations were available and of sufficiently small number that they could be updated efficiently. This difference may explain why Wang and Spelke (2000) observed larger configuration error after disorientation than before disorientation when pointing to objects. Experiment 3 tested this hypothesis.

Experiment 3

Participants learned an irregular array of four objects inside the cylindrical room and then pointed to objects as in Experiments 1 and 2. As in Experiment 1, participants were free to use any subjective heading they wished in the disorientation condition.

Method

Participants. Forty university students (20 men, 20 women) participated in return for monetary compensation.

Apparatus, design, and procedure. The apparatus, design, and procedure were similar to those used in Experiment 1. As illustrated in Figure 6, five objects were removed from the layout used in Experiment 1. The mug was moved 0.4 m, and the clock was moved 0.2 m away from the location of the hat in Experiment 1 so as to make the layout less regular. Participants learned the layout from inside at the position 0.3 m to the left of the center of the cylinder so that the mug, the ball, and the participant (and the clock, the candle, and the participant) were not collinear.

Participants stood at the position illustrated in Figure 6. They viewed the layout for 30 s before being asked to name and point to the objects with their eyes closed. Participants were allowed to turn their heads but not their bodies to view the locations of the objects during the learning phase. Participants received five such learning–testing sessions.

After learning the locations of the objects, participants were blindfolded and given the joystick and the earphone. As in Experiment 2, a joystick was used as the pointing apparatus instead of the stylus and video capture system to avoid the time-consuming off-line coding of pointing directions. For all participants, the order of conditions was baseline, updating, and disorientation. In all three locomotion conditions, participants maintained their learning location. In the baseline condition, participants faced the original learning heading throughout the pointing trials. In the updating condition, participants turned left (235°) to face the ball or right (210°) to face the candle (counterbalanced across participants). They were not told to turn toward a particular object but instead instructed to turn until the experimenter stopped them (e.g., "Please turn left until I stop you"). Therefore, participants were not informed explicitly about the direction they actually faced in the updating condition. In the disorientation condition, participants rotated in place by themselves, reporting the object in front after every minute, until they reported incorrectly and were disoriented. Participants were then turned by the experimenter to face the direction 125° or –150° away from the learning view (facing the ball or the candle, respectively). Participants who faced the ball in the updating condition were turned to face the candle, and those who faced the candle in the updating condition were turned to face the ball. Participants were not informed about the direction they actually faced in the disorientation condition. The updating condition was comparable to the disorientation condition except for the difference of locomotion.

Participants held the joystick against their front waist. They were instructed to click the trigger on the joystick when they heard the warning ("Start"). Then the name of the target object was presented (e.g., "Please point to the mug"), and they were instructed to point to the direction of the target object as accurately as possible. They were discouraged from pointing too quickly. Participants pointed four times to each of the four objects. Dependent variables were the same as in Experiments 1 and 2.

Results and Discussion

The dependent variables were analyzed in mixed-model ANOVAs with terms for gender and locomotion condition. Locomotion condition was within subject.

Heading error. The mean absolute heading errors in the baseline, updating, and disorientation conditions were 7°, 32°, and 123°, respectively. The main effect of locomotion was significant, $F(2, 76) = 247.08$, $p < .001$, $MSE = 610.45$. Pairwise comparisons showed that participants exhibited smaller heading errors in the baseline condition than in the updating and disorientation conditions, $ts(76) \geq 4.55$. The difference between the latter two conditions was also significant, $t(76) = 16.57$. No other effects were significant.

The distribution of participants' subjective headings in each condition is plotted in Figure 7A–7C as a function of actual heading. Participants had very accurate subjective headings in the baseline condition (Figure 7A). In the updating condition, subjective headings were more variable but still tended to be clustered near the actual heading (Figure 7B). In the disorientation condition, participants had larger errors in their subjective headings (Figure 7C). Even in this condition, however, participants did not adopt subjective headings randomly. Twenty-one of 40 participants adopted the learning view as their subjective heading; these participants pointed to objects as if they were facing the learning heading. This number was significantly above chance level, $\chi^2(1, N = 40) = 58.51$, $p < .001$.

Configuration error. Configuration error is plotted in Figure 8A as a function of locomotion condition. The main effect of locomotion was significant, $F(2, 76) = 3.44$, $p < .05$, $MSE = 49.70$. Pairwise comparisons showed that configuration error was significantly smaller in the baseline than in the disorientation condition, $t(76) = 2.62$. No other comparisons were significant, $ts(76) \leq 1.34$. No other effects were significant.

Pointing variability. Pointing variability is plotted in Figure 8B as a function of locomotion condition. The main effect of locomotion was significant, $F(2, 76) = 4.08$, $p < .05$, $MSE = 80.64$. Pairwise comparisons showed that pointing variability was larger in the disorientation than in the baseline condition, $t(76) = 2.84$. No other comparisons were significant, $t(76) \leq 1.67$. No other effects were significant.

Pointing latency. Pointing latency is presented in Table 2 as a function of locomotion condition. The main effect of locomotion was significant, $F(2, 76) = 4.47$, $p < .05$, $MSE = 0.19$. Pairwise comparisons showed that the difference between the disorientation condition and the baseline condition was significant, $t(76) = 2.93$. No other comparison was significant, $ts(76) \leq 1.76$. No other effects were significant.

We predicted that configuration error would be worse in the disorientation condition than in the updating condition, and although this pattern appeared in the means, it was not statistically significant. As in Experiment 1 in the disorientation condition, many participants adopted the learning view as their subjective heading; in contrast, in the updating condition, none of the participants adopted the learning view as their subjective heading. It is possible that any advantage produced by the availability of perceptual-level egocentric spatial relations in the updating condition was mitigated by the requirement to point from an unfamiliar

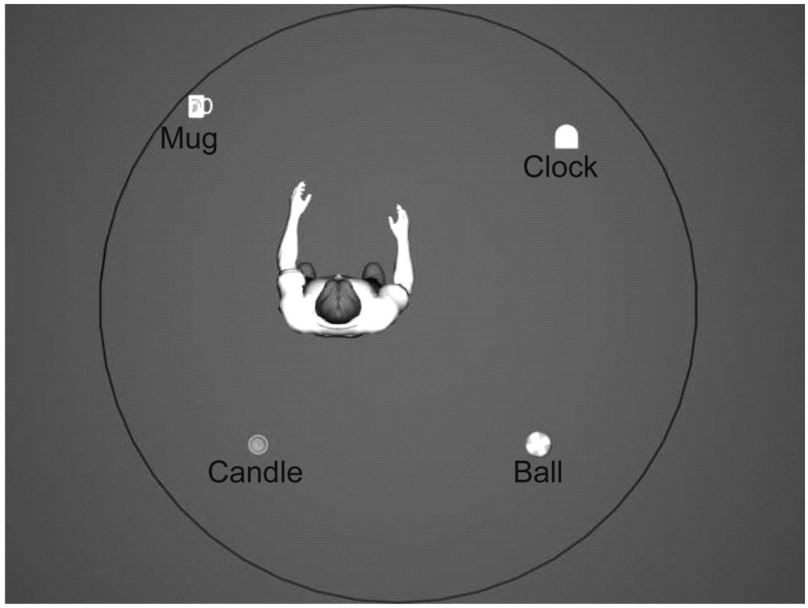

Figure 6. Layout of objects used in Experiments 3 and 4.

heading (e.g., Mou et al., 2004). The results of Experiment 2 suggested that any such effect must be very small, as configuration error did not increase in the disorientation condition relative to the updating condition when participants were required to adopt a misaligned heading in both conditions. However, there are enough methodological differences between Experiment 3 and Experiments 1 and 2 to justify controlling for this potential confound. In Experiment 4, the potential benefit of accessing an allocentric spatial representation from a familiar heading in the disorientation condition was removed. All participants were required to adopt a

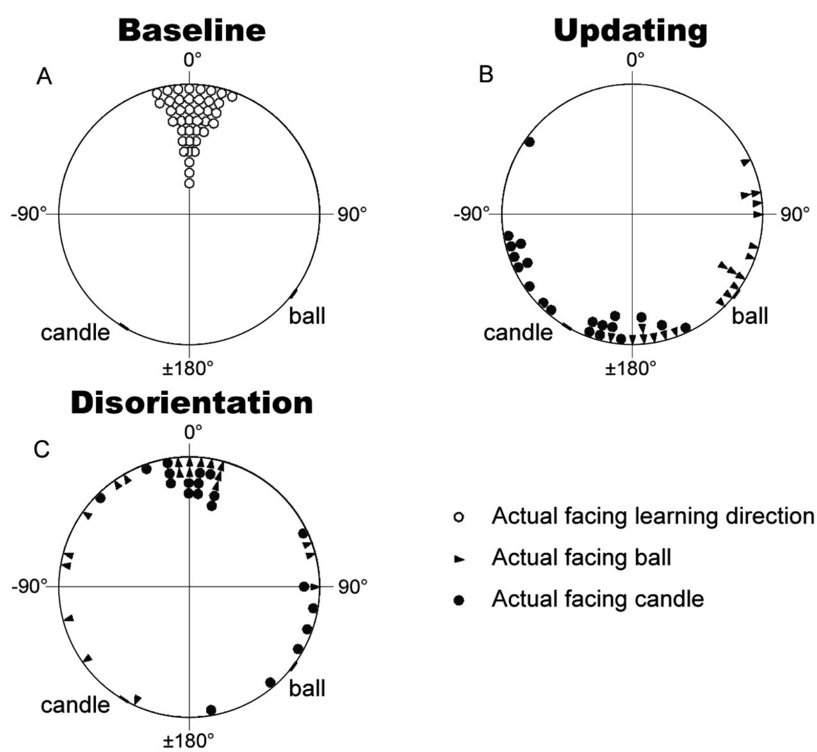

Figure 7. Subjective heading as a function of actual heading and locomotion condition in Experiment 3. Each dot represents the subjective heading of one participant.

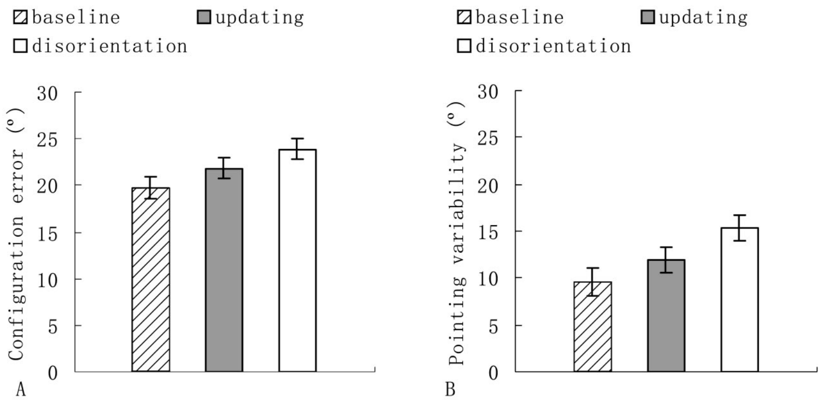

Figure 8. Configuration error and pointing variability as a function of locomotion condition in Experiment 3. (Error bars are confidence intervals corresponding to ±1 *SEM*, as estimated from the analysis of variance.)

novel subjective heading in the disorientation condition with the method used in Experiment 2.

Experiment 4

Method

Participants. Forty university students (20 men, 20 women) participated in return for monetary compensation.

Apparatus, design, and procedure. The apparatus, design, and procedure were similar to those used in Experiment 3 with the following modifications: (a) In the updating condition, participants were instructed to turn to face the ball or candle by themselves (e.g., "Please turn left until you are facing the ball"), and (b) after disorientation, participants were instructed to turn to face the ball (or candle) if they faced the candle (or the ball) in the updating condition (e.g., "Please turn left until you *believe* you are facing the ball"). Participants were not informed of their actual facing direction in the disorientation condition and, hence, remained disoriented.

Results and Discussion

The dependent variables were analyzed in mixed-model ANOVAs with terms for gender and locomotion condition. Locomotion condition was within subject. In the following data analyses, we excluded the data of pointing to the front objects, because these objects were used to establish the subjective heading in the disorientation condition.

Heading error. The mean absolute heading errors in the baseline, updating, and disorientation conditions were 9°, 17°, and 24°, respectively. The main effect of locomotion was significant, $F(2, 76) = 10.40$, $p < .01$, $MSE = 211.89$. Pairwise comparisons showed that participants had smaller heading errors in the baseline condition than in the updating and the disorientation conditions, $ts(76) \geq 2.40$. The difference in the latter two conditions was also significant, $t(76) = 2.11$. No other effects were significant.

The distribution of participants' subjective headings in each condition is plotted in Figure 9A–9C as a function of actual heading. Participants had very accurate subjective headings in the baseline condition (Figure 9A). In the updating condition, subjective headings were more variable but still clustered near the actual heading (Figure 9B). As shown in Figure 9C, in the disorientation condition subjective headings were more variable but still clustered near the actual heading suggesting that participants followed instructions and adopted the heading provided by the experimenter as their subjective heading.

Configuration error. Configuration error is plotted in Figure 10A as a function of locomotion condition. The main effect of locomotion was significant, $F(2, 76) = 3.47$, $p < .05$, $MSE = 76.23$. Pairwise comparisons showed that configuration error was significantly larger in the disorientation condition than in the baseline and updating conditions, $ts(76) \geq 2.04$, and did not differ significantly between the latter two conditions, $t(76) < 1$. No other effects were significant.

Pointing variability. Pointing variability is plotted in Figure 10B as a function of locomotion condition. The main effect of locomotion was significant, $F(2, 76) = 4.09$, $p < .05$, $MSE = 46.69$. Pairwise comparisons showed that pointing variability was larger in the disorientation condition than in the baseline and the updating conditions, $ts(76) \geq 2.12$. Pointing variability in the latter two conditions did not differ significantly, $t(76) < 1$. No other effects were significant.

Pointing latency. Pointing latency is presented in Table 2 as a function of locomotion condition. The main effect of locomotion was significant, $F(2, 76) = 5.29$, $p < .01$, $MSE = 0.18$. Pairwise comparisons showed that pointing latency was shorter in the baseline condition than in the disorientation and updating conditions, $ts(76) \geq 2.59$. The latter two conditions did not differ significantly, $t(76) < 1$. No other effects were significant.

In this experiment, we replicated Wang and Spelke's (2000) finding that configuration error is larger after disorientation than after updating. This result suggests that perceptual-level egocentric updating may facilitate egocentric pointing before disorientation. One possible concern about the increase in configuration error in the disorientation condition relative to the updating condition is that it was accompanied by an increase in pointing variability. Configuration error is a measure of the variability of a set of means, and therefore it will be affected by the standard errors of the means. The standard errors of the means are a function of the variances of the signed pointing errors, of which pointing variability is the root mean. All else equal, an increase in pointing variability will result in an increase in configuration error. We address this issue in depth later in the article.

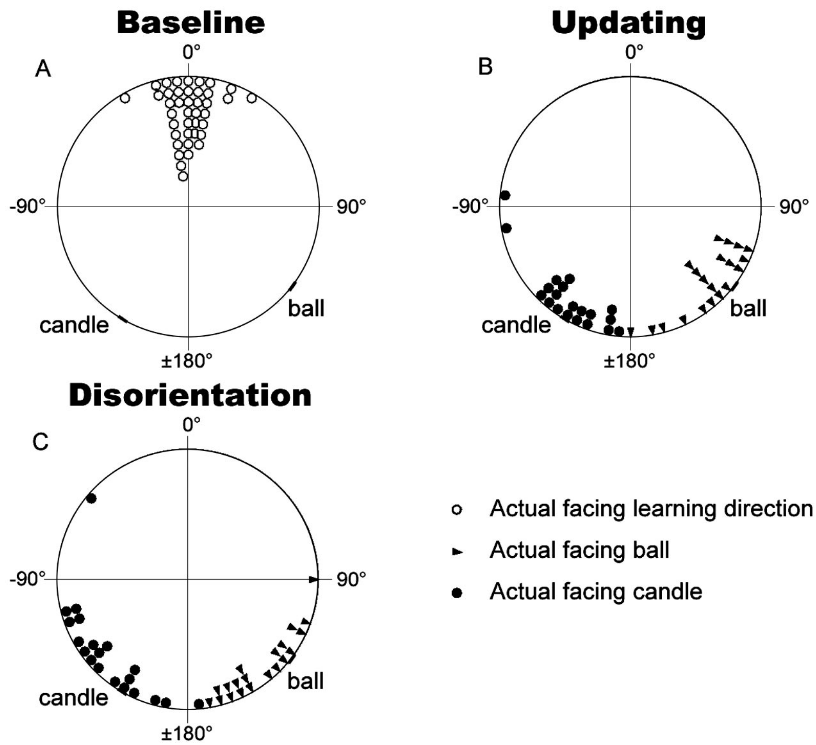

Figure 9. Subjective heading as a function of actual heading and locomotion condition in Experiment 4. Each dot represents the subjective heading of one participant.

General Discussion

Several important findings were observed in this study: (a) The internal consistency of pointing was relatively high in all experiments and was not disrupted by disorientation when participants were able to select, at the time they learned the layout of objects, a salient intrinsic frame of reference. (b) After disorientation, participants often made their pointing judgments as if they were facing the learning heading when there was not a named subjective heading. (c) The internal consistency of pointing was significantly higher before disorientation than after disorientation only when participants learned an object array without a salient intrinsic axis while standing in the midst of the array and they were told to make their pointing judgments from a heading that differed from the learning view. (d) In all experiments, the configuration error in the disorientation condition was quite low (14° in Experiment 1, 19° in Experiment 2, 24° in Experiment 3, and 25° Experiment 4) compared with the expected configuration error of randomly pointing (about 104°).[3] Collectively, these findings suggest that people keep track of their location and orientation in a familiar environment by updating their position in an enduring allocentric representation of the environment. The contribution of egocentricrepresentations may be limited to situations in which allocentric representations are not of high fidelity.

Each of these findings is challenging to explain in Wang and Spelke's (2002) model. To the extent that pointing judgments relied on spatial representations in the dynamic egocentric system, they should have been disrupted by disorientation, regardless of properties of the layout of objects or whether participants learned the array from an external or internal perspective. It is also not clear how pointing judgments could have been as accurate as they were or why many participants would use the learning view as the subjective heading if pointing judgments were based solely on the dynamic egocentric system. These results cannot be explained by appealing to the allocentric system, as it represents only geometric properties of the surrounding environment and therefore does not represent the information needed to support pointing to individual objects.

It may be possible to explain the present results in Wang and Spelke's (2002) model if one assumes that participants relied on the viewpoint-dependent system to make pointing judgments under certain conditions (see also Wang & Spelke, 2000, pp. 245–246). It seems quite plausible that participants would store visual–spatial memories of the layout of the objects from the learning viewpoint. Although representations in this system are hypothesized to be egocentric, they are static and therefore should not be disrupted by disorientation. Perhaps such representations played a more important role when the layout of the objects could be perceived from a single vantage point, as in Experiments 1 and 2, mitigating the effects of disorientation on the internal consistency of pointing. These representations might have biased participants to use the learning view as the subjective heading even in conditions in which pointing was based primarily on the dynamic

[3] If people point to objects randomly, the signed pointing error is in the uniform distribution with the range from –180° to 180°. The expectation of the standard deviation is 180°/√3.

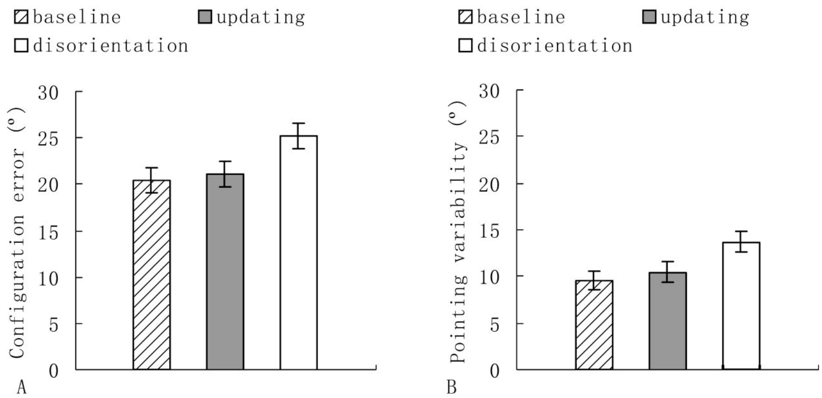

Figure 10. Configuration error and pointing variability as a function of locomotion condition in Experiment 4. (Error bars are confidence intervals corresponding to ±1 *SEM*, as estimated from the analysis of variance.)

egocentric system (e.g., Experiments 3 and 4). One challenge for the model is to explain how such static representations were updated when participants walked from the periphery of the array, where they learned the objects' locations in Experiments 1 and 2, to its center, where they made their pointing judgments, and more generally, how this system interacts with the dynamic egocentric system to support navigation and reorientation. These challenges are not insurmountable, but they are not easy to solve either.

The present findings would also be difficult to explain in a purely egocentric model in which spatial memories consisted of enduring self-to-object spatial relations. To the extent that such representations were not disrupted by disorientation, the model could readily account for the results of Experiments 1 and 2. However, such a model would not be able to explain why disorientation had no effects in Experiments 1 and 2 but significant effects in Experiments 3 and 4. We believe that purely egocentric models of human spatial memory and navigation are no longer tenable in light of recent findings on the nature of spatial memories and updating (e.g., Mou & McNamara, 2002; Mou et al., 2004; Shelton & McNamara, 2001; Werner & Schmidt, 1999).

For the most part, the present findings can be explained in Sholl's model (e.g., Holmes & Sholl, 2005), and the explanation is similar to the one offered by our model. However, Sholl's model cannot easily explain why participants would show such a strong bias to adopt an aligned heading as their subjective heading after disorientation. The object-to-object system is orientation independent in Sholl's model and therefore does not have privileged reference directions (e.g., Sholl & Nolin, 1997, p. 1495). After disorientation, the self-reference system operates only at the representational level and can be freely repositioned in the object-to-object system at any remembered location and orientation (e.g., Holmes & Sholl, 2005; Sholl & Nolin, 1997). The enclosing room could not have made some directions more salient than others because the room was cylindrical. More generally, Sholl's model has difficulty accounting for the large body of evidence showing that spatial memories are orientation dependent even when multiple views are experienced and the spaces are well learned (for a review, see McNamara, 2003).

The present experiments also do not provide much support for Holmes and Sholl's (2005) explanation of the discrepancy between their findings and Wang and Spelke's (2000). Participants pointed to objects with their eyes closed in the learning and the test phases of all of the experiments. According to Holmes and Sholl, this feature of the procedures should have produced imprecise allocentric representations in all of the experiments and, as a consequence, no difference between baseline or updating and disorientation in configuration error.

As a supplement to the spatial representation and navigation model proposed by Mou et al. (2004), the findings of this study provide the foundations for a model of pointing to objects after disorientation. When a person points to the location of target object i on trial j, the signed pointing error (e_{ij}) can be conceptualized in the following manner (see Figure 11):

$$e_{ij} = \theta + \eta_i + \delta_{ij},$$

where $\theta \in [-\pi, \pi]$ is the difference between the actual heading and the subjective heading; $\eta_i \in [-\pi, \pi]$ is the difference between the remembered direction and the actual direction of target i relative to the subjective heading; and $\delta_{ij} \in [-\pi, \pi]$ is random error including motion error.

The angle η_i can be parameterized as follows,

$$\eta_i = \alpha_2 - \alpha_1,$$

where α_2 is the remembered direction of the target with respect to the subjective heading and α_1 is the actual direction of the target with respect to the subjective heading. As discussed subsequently, the relative importance of allocentric and egocentric representations in determining the remembered direction of an object, and hence η_i, can depend on aspects of the environment (e.g., whether the layout has salient intrinsic axes).

The random variable $|\theta|$ is a measure of disorientation, whereas $|\eta_i|$ is a measure of the inaccuracy of the remembered direction of target object i. Parameters of this model can be estimated from the dependent measures collected in these experiments, as follows:

1. θ is equivalent to heading error and can be estimated by the mean of the mean signed pointing errors, $\bar{e}_{..}$.

2. An estimate of η_i can be derived by noting that the mean signed pointing error for object i is

$$\bar{e}_{i.} = \theta + \eta_i + \bar{\delta}_{i.}$$

If one assumes that the random errors, δ_{ij}, are distributed with mean 0 ($\mu_{\delta_i} = 0$), which is a plausible assumption, then

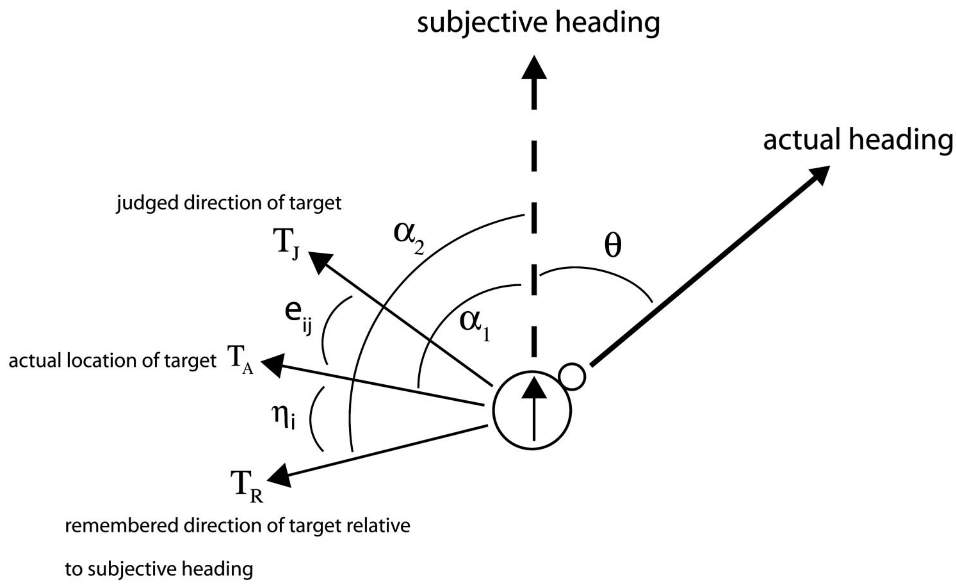

Figure 11. Model of pointing to objects using spatial memory.

$$\eta_i \approx \bar{e}_{i.} - \theta \approx \bar{e}_{i.} - \bar{e}_{..}.$$

This relation implies that configuration error is sensitive to the magnitudes of the inaccuracies in remembered directions of target objects:

$$\text{configuration error} = \sqrt{\frac{\sum_i (\bar{e}_{i.} - \bar{e}_{..})^2}{N-1}} \approx \sqrt{\frac{\sum_i (\eta_i)^2}{N-1}}.$$

3. These relations imply that

$$\delta_{ij} \approx e_{ij} - \bar{e}_{i.},$$

which in turn implies that pointing variability is sensitive to random errors in pointing judgments:

$$\text{pointing variability} = \sqrt{\frac{\sum_i \left(\frac{\sum_j (e_{ij} - \bar{e}_{i.})^2}{T-1}\right)}{N}} \approx \sqrt{\frac{\sum_i \left(\frac{\sum_j (\delta_{ij})^2}{T-1}\right)}{N}}.$$

The correspondence between parameters and dependent variables is given in Table 3.

According to the model (e.g., Mou et al., 2004), people represent object-to-object spatial relations with respect to an intrinsic frame of reference. When people rotate physically, they update their heading with respect to the intrinsic frame of reference in memory. Given their heading with respect to the intrinsic framework and the object-to-object spatial relations in the memory representation, people can calculate any self-to-object spatial relation. In the baseline and updating conditions of Experiment 1, participants knew which direction they were facing, and therefore the expected value of $|\theta|$ should be approximately equal to zero, $\mu_{|\theta|} \approx 0$. In the disorientation condition, participants did not know which direction they were facing, and therefore, $\mu_{|\theta|} > 0$ in that condition. This pattern was observed in absolute heading error, which estimates $|\theta|$. By theoretical conjecture, participants in Experiment 1 were able to form high-fidelity allocentric representations, which were not disrupted by rotation or disorientation. This conjecture implies that the absolute magnitudes of η_i, and therefore configuration error, should be small and approximately the same across the baseline, updating, and disorientation conditions. The higher pointing variability in the updating and disorientation conditions than in the baseline condition is attributed to random error in pointing judgments. We suspect that these effects are caused by body rotation, which occurred in the updating and disorientation conditions but not in the baseline condition.

Experiment 2 can be analyzed similarly. The key difference between Experiment 2 and Experiment 1 is that participants in the disorientation condition of Experiment 2 were given a subjective heading by the experimenter. This manipulation reduced the absolute magnitude of θ in the disorientation condition but had little effect otherwise, as expected.

We hypothesized that participants in Experiments 3 and 4 would not be able to form a high-fidelity allocentric representation because the layout of objects was irregular and they stood in the center while learning it. Under such conditions, people may rely instead on perceptual-level self-to-object spatial relations to point, if such spatial relations are available. Such egocentric spatial relations should have

Table 3
Correspondence Between Parameters and Dependent Variables

Parameter	Dependent variable
θ	$\bar{e}_{..}$ (heading error)
η_i	$\bar{e}_{i.} - \bar{e}_{..}$
δ_{ij}	$e_{ij} - \bar{e}_{i.}$

Note. See Table 1 for definitions of dependent variables.

been easier to maintain in Experiments 3 and 4 than in Experiments 1 and 2 because a smaller number of objects was used. Disorientation, of course, would destroy such spatial representations. Hence, $|\eta_i|$ would be greater in the disorientation condition than in the updating condition; accordingly, configuration error would be larger in the disorientation condition than in the updating condition, as observed. In addition, pointing to a target object based on an online egocentric representation is assumed to have smaller random error than pointing based on an allocentric representation, which may explain why pointing variability was larger in the disorientation condition (egocentric representations not available) than in the baseline and the updating conditions, which did not differ (egocentric representations available).

A limitation of the present experiments is that the fidelity of allocentric representations was manipulated and measured indirectly. According to this model of pointing, configuration error after disorientation is a measure of the fidelity of participants' allocentric representations of the layout of the objects (i.e., η_i). It is therefore possible in the context of the model to assess whether our hypothesized manipulation of the fidelity of allocentric representations had an effect by comparing configuration error in the disorientation condition across experiments. The best experiments to use for this comparison are Experiments 2 and 4. The configuration error in the disorientation condition was significantly smaller in Experiment 2 than in Experiment 4 (19° vs. 25°), $F(1, 58) = 4.46$, $p < .05$. This result provides evidence that participants had higher fidelity allocentric representations in Experiment 2 than in Experiment 4, consistent with our hypothesis.

In the discussion of Experiment 4, we identified an important problem in the interpretation of the increase in configuration error caused by disorientation. This effect might have been caused by the corresponding increase in pointing variability. Wang and Spelke (2000) addressed this issue by testing whether the observed increase in configuration error exceeded the increase predicted from the difference in pointing variability. Their approach tested the null hypothesis that inaccuracies in remembered directions of target objects had no influence on configuration error. Wang and Spelke's analyses indicated that disorientation affected the remembered locations of objects, not just the precision of pointing.

Another way to clarify the ambiguity in the interpretation of differences in configuration error is to attempt to estimate the effects of inaccuracies in remembered directions of target objects on configuration error. Our approach relied on the parallels between, on the one hand, the present model of error in pointing judgments, configuration error, and pointing variability and, on the other hand, the design model equation for the ANOVA, MS_{Tr}, and MS_E, respectively. As a reminder, the design equation for a single-factor design in the ANOVA is

$$Y_{ij} = \mu + \alpha_j + \varepsilon_{ij},$$

where μ is the population mean (analogous to θ), α_j is the treatment effect for level j and is equal to $\mu_j - \mu$ (analogous to η_i), and ε_{ij} is the error effect (analogous to δ_{ij}). Configuration error (ce) and pointing variability (pv) are functions of MS_{Tr} and MS_E from the ANOVA. Specifically,

$$ce^2 = \frac{1}{T} MS_{Tr},$$

$$pv^2 = MS_E,$$

where T is the number of pointing trials per object. Continuing the analogy,

$$E(ce^2) = \frac{1}{T} E(MS_{Tr}) \approx \frac{1}{T}(\sigma_\delta^2 + T\sigma_\eta^2),$$

$$E(pv^2) = E(MS_E) \approx \sigma_\delta^2.$$

These relations imply that

$$\sigma_\eta^2 \approx E(ce^2) - \frac{1}{T} E(pv^2).^4$$

The difference between estimates of σ_η^2 in two experimental conditions is given by

$$\Delta\hat{\sigma}_\eta^2 = \Delta ce^2 - \frac{1}{T}\Delta pv^2.$$

A statistical test of the null hypothesis that $\Delta\hat{\sigma}_\eta^2 = 0$ can be used to determine whether two experimental conditions differ in the contributions of inaccuracies in remembered directions of target objects (σ_η^2) to configuration error. We wish to emphasize that this approach is approximate and depends on assumptions that may well be violated. The advantage of this approach over the analysis suggested by Wang and Spelke (2000) is that it directly estimates the effect of inaccuracies in remembered directions of target objects, σ_η^2, and does not assume that these effects are zero.

The values of this statistic for the disorientation and updating conditions were computed and analyzed in each of the experiments. The results are summarized in Table 4. As shown in the table, the estimated value of $\Delta\hat{\sigma}_\eta^2$ differs significantly from zero only in Experiment 4, although the value is numerically greater in Experiment 3 than in Experiments 1 and 2. This result indicates that, at least in Experiment 4, participants' memories of the directions of target objects were disrupted more by disorientation than by turning to a new heading. The negative estimate in Experiment 1 is analogous to an F ratio of less than 1 and could result from violations of assumptions, error in estimation, or both. In terms of the data, the negative estimate means that the difference in configuration error was smaller than expected given the magnitude of the difference in pointing variability.

Just as the model explains the findings of Experiment 4 in this study, it can readily explain Wang and Spelke's (2000) challenging finding that the coherence of pointing to objects is disrupted by disorientation. In their experiments, participants learned a layout of objects without good intrinsic structure while standing inside the layout. As in Experiment 4 of this study, participants under those conditions were not able to form an allocentric representation with high fidelity. Under such conditions, people may rely instead on perceptual-level self-to-object spatial relations if they are available. Hence, configuration error and pointing variability ("pointing error" in their terminology) increased after disorientation as they reported. Participants might have had a better allocentric representation when they remembered the locations of the corners (their Experiments 6 and 7) because corners are integral components of the surrounding room, which has a readily perceiv-

[4] This analysis is identical to the one used to estimate power in the ANOVA (e.g., Kirk, 1995, pp. 142–143).

Table 4
Difference of Representation Inaccuracies Between the Disorientation and Updating Conditions

Experiment	$\Delta\hat{\sigma}^2_\eta$	t
1	−117	$t(19) = 1.83$
2	23	$t(19) = 0.38$
3	91	$t(39) = 0.92$
4	215	$t(39) = 2.10^{*}$

* $p < .05$.

able shape. As in Experiments 1 and 2 of the current project, when people had allocentric representations with high fidelity, the configuration error and pointing variability were the same before and after disorientation.

Although the findings from the present experiments place limits on the generality of Wang and Spelke's (2000) conclusions, they also point to fundamental affinities between their theory and ours. Both theories contain a transitory egocentric system that can be disrupted by disorientation and an enduring allocentric system that is less susceptible to disruption by disorientation. Both theories claim that people use the allocentric system to reorient. The present findings, as well as studies showing that people can point to the remembered locations of objects accurately after long delays (e.g., Shelton & McNamara, 2001), indicate that the allocentric system specifies the locations of objects and landmarks in addition to environmental shape. This conclusion forces a revision to Wang and Spelke's (2002) theory. On the other hand, the present results vindicate Wang and Spelke's conjecture that people reorient with respect to environmental shape. Our findings indicate that the "shape" of an environment may be defined by configurations of objects or landmarks in addition to surfaces.

It is still not clear what factors determine how well people are able to represent locations of objects allocentrically and the extent to which perceptual-level egocentric representations contribute to pointing to objects. The following features differed between Experiments 2 and 4:

1. *Learning position*: In Experiment 2, participants learned the objects' locations while standing outside of the array, so they could see the whole array from a single viewpoint and thus had a better view of object-to-object spatial relations. In contrast, in Experiment 4, participants learned the objects' locations while standing in the midst of the array and therefore had to rotate their head to view the whole array.

2. *Geometry of the array*: The array in Experiment 2 had very salient intrinsic axes (column by column, row by row; see Figure 1), whereas the array in Experiment 4 did not have salient intrinsic axes.

3. *Number of objects*: In Experiment 2, people learned nine objects, whereas in Experiment 4, people learned four objects. More accurate egocentric self-to-object spatial relations might be maintained at the perceptual level when fewer objects need to be updated egocentrically.

4. *Testing location*: In Experiment 2, the testing location of the participants was occupied by an object during the learning phase, whereas in Experiment 4, the testing location of the participants was not occupied by an object during the learning phase.

We speculate that the number of objects may not be a key factor, because significant effects of disorientation have been observed with various numbers of objects (four objects in Experiment 4 of this study and in Wang & Spelke's Experiments 6 and 7; six objects in Wang & Spelke's Experiments 1–5) and nonsignificant effects of disorientation have been observed with various numbers of objects (four objects in Experiment 3 of this study; six objects in Holmes & Sholl's experiments; nine objects in Experiments 1 and 2 of this study). We also suspect that the learning position may not be a key factor, because both significant effects (Wang & Spelke, 2000; Experiment 4 of present study) and nonsignificant effects (Holmes & Sholl, 2005) of disorientation have been obtained when participants learned the objects' locations while standing in the midst of the array. Ongoing experiments in our laboratories are systematically investigating these factors.

Our explanation of the present data assumes that when people are oriented but have formed low-fidelity allocentric representations of the space, they locate objects by using perceptual-level egocentric representations. When people are disoriented, however, they must rely on allocentric representations, even if those representations have low fidelity. The use of higher fidelity egocentric representations before disorientation but lower fidelity allocentric representations after disorientation is the cause of the increase in configuration error after disorientation observed in Experiment 4. We recognize that the present experiments do not provide direct evidence for the use of egocentric representations before disorientation. A pure allocentric model may be able to account for the present findings. For instance, perhaps low-fidelity allocentric representations (e.g., Experiment 4) are more affected by disorientation than are high-fidelity allocentric representations (e.g., Experiment 2). We hypothesized that egocentric representations were involved because, as discussed at the beginning of this article, all current theories of spatial memory and navigation include an egocentric component, and there is ample evidence of the use of egocentric codes in other domains. Additional experimental evidence is needed to confirm or disconfirm whether egocentric spatial representations are used to point to objects when people are oriented and have formed low-fidelity allocentric spatial representations.

Although these experiments raised several important questions, they also provided answers to the major issues identified in the introduction. The results indicate that people orient and reorient in familiar environments by using spatial information in enduring allocentric representations in addition to egocentric representations. Getting lost in a familiar environment does not destroy the allocentric spatial representation. Once people regain their location and orientation with respect to the allocentric spatial representation, they regain the spatial relations between themselves and the familiar objects in the environment and know where they are located.

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Received December 16, 2005
Revision received March 18, 2006
Accepted March 21, 2006 ■