

Allocentric and Egocentric Updating of Spatial Memories

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In 4 experiments, the authors investigated spatial updating in a familiar environment. Participants learned locations of objects in a room, walked to the center, and turned to appropriate facing directions before making judgments of relative direction (e.g., “Imagine you are standing at X and facing Y. Point to Z.”) or egocentric pointing judgments (e.g., “You are facing Y. Point to Z.”). Experiments manipulated the angular difference between the learning heading and the imagined heading and the angular difference between the actual heading and the imagined heading. Pointing performance was best when the imagined heading was parallel to the learning view, even when participants were facing in other directions, and when actual and imagined headings were the same. Room geometry did not affect these results. These findings indicated that spatial reference directions in memory were not updated during locomotion.

Wayfinding and other actions in a familiar environment make use of remembered spatial relations among objects in that environment. As one moves through an environment, one must continuously update one’s location and orientation with respect to familiar elements of the landscape to avoid getting lost or disoriented (e.g., Golledge, 1999). The daily survival of prehistoric humans depended on these capabilities and skills. Today, people rely on spatial memories for activities as mundane as finding their way to work each morning and back home at the end of the day and as extraordinary as finding an exit from an office building during a raging fire. How is the spatial structure of the environment represented in memory, and how are remembered spatial relations used to guide wayfinding? These questions guided the research reported in this article.

Shelton and McNamara (2001) and Mou and McNamara (2002) proposed a new theoretical framework for understanding human spatial memory (see also Werner & Schmidt, 1999). According to this theory, learning the layout of a novel environment is similar to perceiving the shape of a novel object, in that the spatial structure of the environment must be interpreted in terms of a spatial reference system (e.g., Rock, 1973). An intrinsic reference system (e.g., rows and columns formed by chairs in a classroom) is selected using egocentric and environmental cues, such as viewing perspective and alignment with the walls of a room, respectively (e.g., Tversky, 1981). Egocentric cues are dominant because the spaces of human wayfinding rarely have directions or axes as salient as those defined by point of view (unlike honeybees, for

example, humans cannot perceive magnetic fields; Collett & Baron, 1994). Interobject spatial relations are defined with respect to the reference system selected. Spatial judgments that invoke this reference system can be made on the basis of retrieved spatial relations and are therefore faster and more accurate than those invoking a different reference system (e.g., Klatzky, 1998).

Consider, as an example, an experiment reported by Shelton and McNamara (2001, Experiment 3). Objects were placed on a square mat, which was oriented with the walls of the room. Two arrays of objects were used; one is illustrated in Figure 1. Participants learned the locations of the objects from two points of view: One viewing position was aligned (0°) with the mat and the walls of the room, and the other was misaligned (135°). Participants spent the same amount of time at each study view, and order of learning was counterbalanced across participants (0° – 135° vs. 135° – 0°). After learning the layout, participants were taken to a different room on a different floor of the same building and made judgments of relative direction using their memories (e.g., “Imagine you are standing at the clock and facing the shoe; point to the jar.”).

Figure 2 plots absolute angular error in pointing as a function of imagined heading for each of the two groups defined by the order in which the aligned and the misaligned views were learned. As shown in Figure 2, performance indicated that the aligned view (imagined heading = 0°) was represented in memory but that the misaligned view (imagined heading = 135°) was not. There was no behavioral evidence that participants had even seen the misaligned view, even for participants who learned the misaligned view first. These results did not occur because of some inherent difficulty in learning the layout of objects from the corner of the room. In another experiment (Shelton & McNamara, 2001, Experiment 2), participants learned the same layouts in the same room from a single misaligned point of view (e.g., only 135° in Figure 1). Performance in this experiment was excellent for the imagined heading of 135° (mean angular error = 9°) and equally poor for the remaining headings (mean angular error = 29°).

According to the theory, participants who first learned the aligned view (0°) represented the layout in terms of an intrinsic reference system aligned with their viewing perspective, the edges

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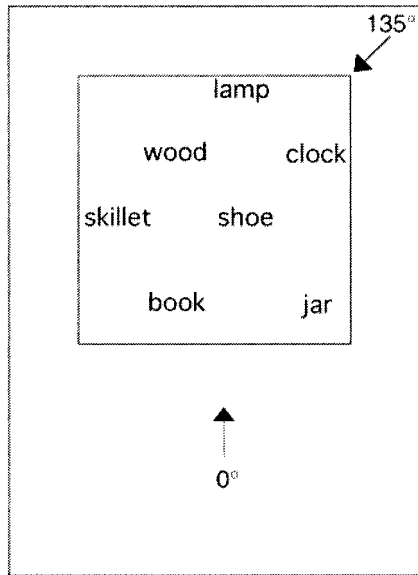


Figure 1. One of the layouts used by Shelton and McNamara (2001).

of the mat, and the walls of the room. When they moved to the misaligned view (135°), they continued to interpret the layout in terms of the reference system selected at the aligned view, just as if they were viewing a (now) familiar object at a novel orientation. Observers who first learned the misaligned view (135°) must have interpreted the layout in terms of an intrinsic reference system aligned with their viewing perspective, even though it was misaligned with the mat and the room. This conclusion follows from the results of the experiment described previously in which participants learned only the misaligned view; they had no difficulty

representing the layout of objects from that view. According to the theory, when participants were taken to the second, aligned view, they reinterpreted the spatial structure of the layout in terms of a reference system defined by the aligned view because it was aligned with salient axes in the environment (e.g., the edges of the mat and the walls of the room) and with egocentric experience (albeit a new experience). A new spatial reference system was selected, and the spatial layout was reinterpreted in terms of it. Apparently, there was little cost to reinterpretation, as performance was equivalent for the two groups (see Figure 2).

Mou and McNamara (2002) presented evidence that location and orientation are specified in intrinsic reference systems. They required participants to learn layouts like the one illustrated in Figure 3. Objects were placed on a square mat oriented with the walls of the room. Participants studied the layout from 315° and were instructed to learn the layout along the egocentric 315° axis or the nonegocentric 0° axis. This instructional manipulation was accomplished by pointing out that the layout could be seen in columns consistent with the appropriate axis (*clock-jar, scissors-shoe*, etc. vs. *scissors-clock, wood-shoe-jar*, etc.) and by asking participants to point to the objects in the appropriate order when they were quizzed during the learning phase. All participants viewed the layout from 315°. After learning, participants made judgments of relative direction using their memories of the layout.

One important result (see Figure 4) was the crossover interaction for imagined headings of 315° and 0°: Participants who were instructed to learn the layout along the egocentric 315° axis were better able to imagine the spatial structure of the layout from the 315° heading than from the 0° heading, whereas participants who were instructed to learn the layout along the nonegocentric 0° axis were better able to imagine the spatial structure of the layout from the 0° heading than from the 315° heading (which is the heading they actually experienced). Put another way, participants in the 0°

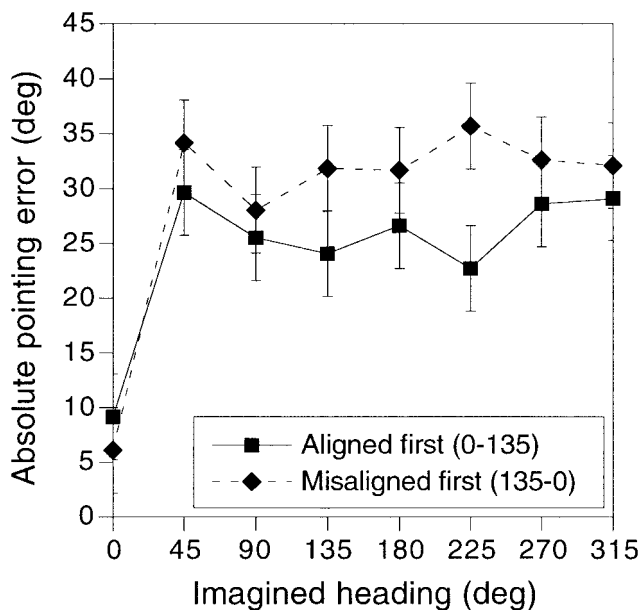


Figure 2. Angular error in judgments of relative direction in Shelton and McNamara's (2001) third experiment. (Error bars in all figures are confidence intervals corresponding to ± 1 SEM as estimated from the analysis of variance.) deg = degrees.

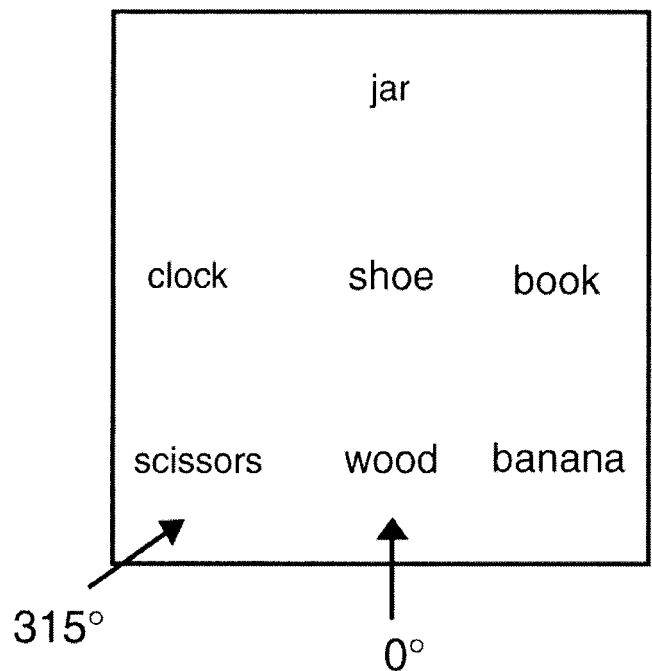


Figure 3. Layout of objects used by Mou and McNamara (2002).

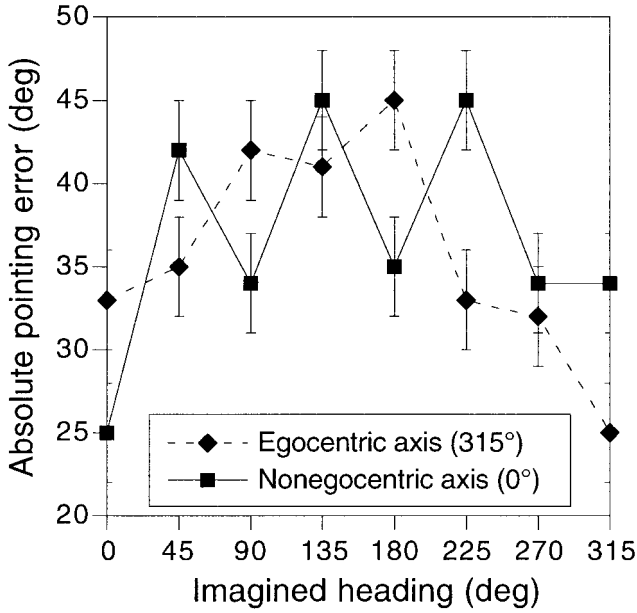


Figure 4. Angular error in judgments of relative direction in Mou and McNamara’s (2002) second experiment. deg = degrees.

group were better on an unfamiliar heading than on a familiar heading.

A second important finding was that there was no apparent cost to learning the layout along a nonegocentric axis. Overall error in pointing did not differ between the two groups.

A third important finding was the different patterns of results for the two groups: In the 315° group, performance for novel headings depended primarily on the angular distance between the novel heading and the familiar heading of 315°, whereas in the 0° group, performance was better for novel headings orthogonal or opposite to 0° (90°, 180°, and 270°) than it was for other novel headings,

producing a distinctive sawtooth pattern. The sawtooth pattern in the 0° group also appeared when the objects were placed on the bare floor of a cylindrical room (Mou & McNamara, 2002, Experiment 3), which indicates that this pattern was produced by the intrinsic structure of the layout and not by the mat or the walls of the enclosing room. Mou and McNamara speculated that the sawtooth pattern arises when participants are able to represent the layout along two intrinsic axes (0°–180° and 90°–270°). Performance might have been better for the imagined heading of 0° because this heading was emphasized in the learning phase. The sawtooth pattern did not occur in the 315° group because the 45°–225° axis is less salient and is misaligned with the edges of the mat and the walls of the room. (It is not clear why a sawtooth pattern did not appear in Shelton and McNamara’s, 2001, original aligned–misaligned view experiment [see Figure 2]. Subsequent replications of this experiment have obtained a sawtooth pattern, as well as better performance for 0° than for 135°.)

A model consistent with this theoretical framework is illustrated schematically in Figure 5. Figure 5A corresponds to Mou and McNamara’s (2002) egocentric 315° learning condition; Figure 5B corresponds to their nonegocentric 0° learning condition. These representations preserve interobject distance and direction and are formalized as networks of nodes interconnected by vectors. Spatial relations will be represented between some but not all pairs of objects; for simplicity, the spatial relation between just two objects is illustrated. Each node represents an object. Vector magnitude and direction represent interobject distance and direction. Direction is defined with respect to one or more intrinsic reference directions, which are indicated by solid and dashed gray arrows. The network formalism was chosen for convenience and because it has been used in other models (e.g., Easton & Sholl, 1995; Sholl & Nolin, 1997).

In Figure 5A, the reference direction of 315° is the intrinsic direction emphasized during learning. The angular direction from Object 3 to Object 2, α_{32} , is defined with respect to this reference direction. α_{32} is the direction from 3 to 2 relative to the reference

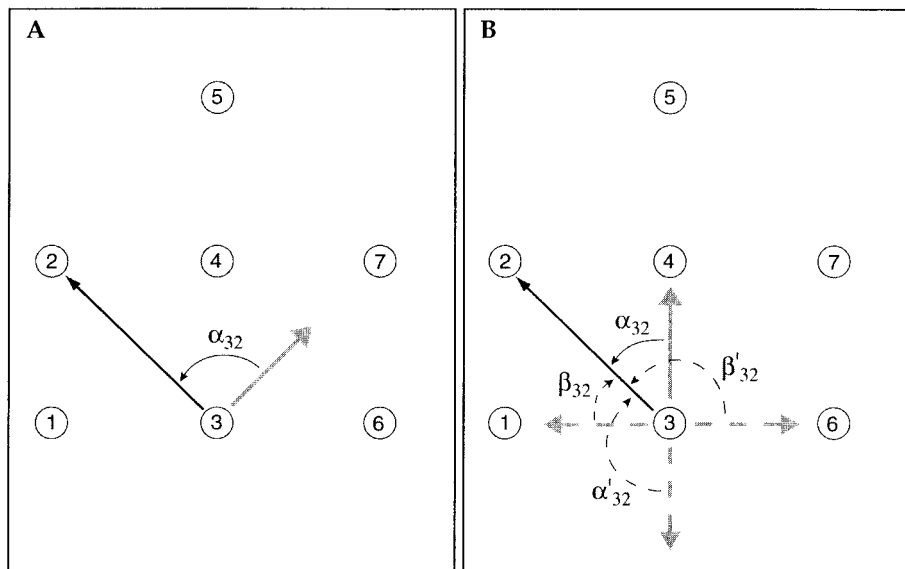


Figure 5. Models of interobject spatial representations.

direction, not the angle formed by objects 7, 3, and 2. In effect, the representation specifies that 2 is due west of 3. Because this relative direction is represented in memory, it can be retrieved. Hence, a judgment of relative direction such as “Imagine standing at 3, facing 7; point to 2” should be relatively fast and accurate. Performance should be good because the imagined heading is parallel to the dominant reference direction, allowing the relative direction from 3 to 2 to be retrieved. However, a judgment such as “Imagine standing at 3, facing 4; point to 2” should be relatively difficult because the direction from 3 to 2 is not defined with respect to the direction from 3 to 4. This relative direction must be inferred. Apparently these inferential processes are more complex than adding and subtracting angles, as angular error in pointing nearly doubles for unfamiliar headings, even though participants are instructed to be as accurate as possible. An effect of angular distance (e.g., the egocentric axis group in Figure 4) can be explained by assuming that the efficiency of inferential processes scales with the similarity between the needed and the represented response directions.

The same principles apply to Figure 5B. However, this figure captures the assumption that the direction from 3 to 2 is defined with respect to the dominant reference direction of 0° (α_{32}) and is defined to some extent, or with some probability, with respect to reference directions of 90° (β_{32}), 180° (α'_{32}), and 270° (β'_{32}). Using this representation, “Imagine standing at 3, facing 7; point to 2” would be relatively difficult, whereas “Imagine standing at 3, facing 4; point to 2” would be relatively easy. To the extent that the direction from 3 to 2 is also represented relative to 90°, then “Imagine standing at 3, facing 1; point to 2” would also be relatively easy.

These representations assume that angular direction is defined along the shortest arc (0°–180°); hence, values would have to be marked in some manner (e.g., sign) to maintain internal consistency. This model is one of many consistent with the theory and the data. Many crucial aspects of the model remain to be specified (e.g., how matches and mismatches between imagined headings and reference directions are recognized, how spatial relations are retrieved, and how relative direction is inferred when it is not represented); even so, it provides a useful conceptual framework for interpreting many of our findings and is described in as much detail as any alternative model.

The goal of the experiments reported in this article was to determine whether spatial reference systems are updated during locomotion. Suppose, for example, that the learning procedures yielded a representation similar to that in Figure 5B but with a single reference direction of 0°. Suppose further that the learner walked from the study position (e.g., near Object 3, facing Object 4) to the center of the layout (i.e., near Object 4) maintaining an orientation of 0° and then turned to a heading of 225° (i.e., facing Object 6). The question is: Will the dominant reference direction in the mental representation be updated to correspond to the learner’s new body orientation?

The answer to this question is not clear from past research. Shelton and McNamara’s (2001) findings indicated that the initially selected reference system was not typically updated during locomotion. Participants in one of their experiments learned the locations of objects in a cylindrical room from three points of view, the order of which was counterbalanced across participants (0°–90°–225° vs. 225°–90°–0°). Participants spent the same amount of time at each study view and walked (blindfolded and

escorted by the experimenter) from study view to study view. After the learning phase was completed, participants were taken to another room on a different floor of the building to be tested. Performance in judgments of relative direction indicated that only the first study view was represented in memory (0° or 225°). There was no behavioral evidence that participants had even seen the second and the third study views. These findings indicated that the reference direction selected at the first study view was not updated as participants moved to subsequent study views. If updating had occurred, one would expect performance to have been best on the third study view or perhaps, equally good on all three study views. The results of the aligned–misaligned view experiment discussed previously (see Figures 1 and 2) indicated that reference directions were updated only when the first study view was misaligned but a subsequent study view was aligned with salient frames of reference in the environment (e.g., the edges of a mat on which objects were placed and the walls of the surrounding room).

There is, however, a large body of evidence indicating that reference directions are updated during locomotion, at least under certain conditions (e.g., Farrell & Robertson, 1998; Presson & Montello, 1994; Rieser, 1989; Rieser, Guth, & Hill, 1986; Sholl & Bartels, 2002; Simons & Wang, 1998; Waller, Montello, Richardson, & Hegarty, 2002; Wang & Simons, 1999).¹ For example, participants in one of Waller et al.’s (2002) experiments learned four-point paths like the one illustrated in Figure 6. In the stay condition, participants remained at the study position and made pointing judgments from headings of 0° and 180° (“aligned” vs. “misaligned”); e.g., “Imagine you are at 4, facing 3; point to 1” vs. “Imagine you are at 3, facing 4; point to 1”). The results in this condition replicated those of several other studies of spatial memory in showing that performance was better for the imagined heading of 0° than it was for the imagined heading of 180° (e.g., Levine, Jankovic, & Palij, 1982). In the rotate–update condition, participants learned the layout and were then told to turn 180° in place so that the path was behind them. In this condition, performance was better for the heading of 180° (the new egocentric heading) than it was for the heading of 0° (the original learning heading). This result indicated that participants had updated the dominant reference direction in memory as they turned.

A possible limitation of all previous investigations of spatial memory and spatial updating (including our own) is that they did not jointly manipulate two variables known to influence the efficiency of processing of spatial knowledge. Research on spatial memory has demonstrated that performance in judgments of relative direction, in particular, is affected by the disparity between the learning heading and the imagined heading at the time of test (e.g., Shelton & McNamara, 2001). According to the theory described previously, the learning heading typically determines the dominant reference direction in memory. The disparity between the imagined heading and the dominant reference direction affects spatial processes involved in retrieving or inferring interobject spatial relations. Research on spatial updating, however, has dem-

¹ Research on path integration paints a less rosy picture of spatial updating (e.g., Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Loomis et al., 1993; May & Klatzky, 2000). In most of this research, however, the path layout was acquired during, not prior to, locomotion. Visual preview of the walking space facilitates path integration (e.g., Philbeck, Klatzky, Behrmann, Loomis, & Goodridge, 2001).

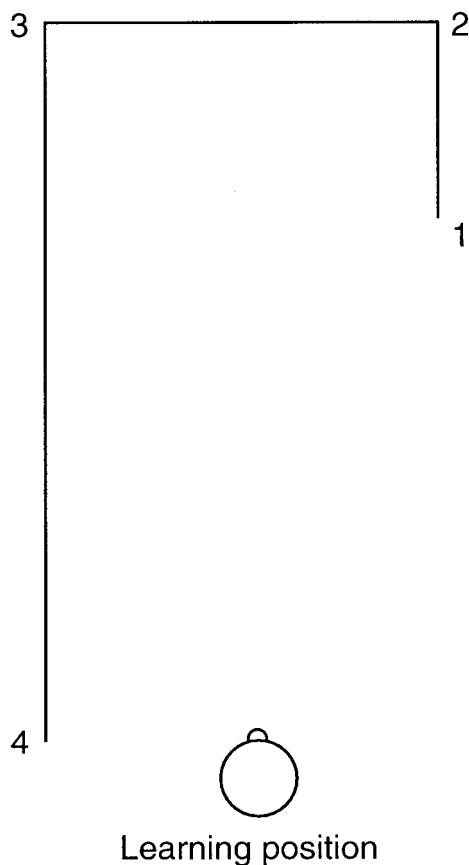


Figure 6. Example of a four-point path learned by participants in Waller, Montello, Richardson, and Hegarty's (2002) experiments. Adapted from "Orientation Specificity and Spatial Updating of Memories for Layouts," by D. Waller, D. R. Montello, A. E. Richardson, and M. Hegarty, 2002, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28, p. 1052. Adapted with permission of the author.

onstrated that performance is affected by the disparity between the actual heading at the time of test and the imagined heading at the time of test (e.g., Rieser, 1989). Our conjecture is that this variable affects processes involved in aligning an egocentric frame of reference with interobject spatial relations for the purpose of making the pointing judgment. The egocentric frame of reference may correspond to the actual or the imagined body (e.g., Paillard, 1991). For example, in judgments of relative direction ("Imagine you are standing at X and facing Y. Point to Z."), egocentric front must be aligned with the $X \rightarrow Y$ direction. Although other alignment processes also may be required (e.g., the origin of an egocentric frame of reference must be aligned with the location of X), they are not intrinsically correlated with the disparity between the actual and the imagined headings.

For an example of the importance of manipulating these variables independently, one should consider, again, Waller et al.'s (2002) experiments.² Beginning with the stay condition: In the 0° ("aligned") condition, the imagined heading of 0° was the same as the original learning heading and the actual body heading; in the 180° ("misaligned") condition, the imagined heading of 180° differed from the original learning heading and the actual body heading. Hence, one cannot know whether the difference in per-

formance between 0° and 180° was caused by spatial processes involved in retrieving or inferring interobject spatial relations, alignment processes involved in aligning an egocentric frame of reference with the $X \rightarrow Y$ direction, or both. In the rotate-update condition, the imagined heading of 0° is the same as the learning heading but differs from the actual heading (because participants turned 180° in place), whereas the imagined heading of 180° is different from the learning heading but is the same as the actual heading. In this case, the two variables work against each other. For now, the only point we wish to make is that interpreting the findings is difficult because the variable defined by the difference between the learning heading and the imagined heading and the variable defined by the difference between the actual heading and the imagined heading are confounded across experimental conditions. We return to this issue in the General Discussion in the context of the results of the present experiments. We wish to emphasize that this problem exists in all previous investigations of spatial memory and spatial updating, including our own.

The primary goal of the present experiments was to assess the contributions of spatial processes and alignment processes to performance in spatial memory and updating tasks. Participants learned the locations of objects in a large room from a single stationary viewing position (see Figure 7), walked to the center of the layout (near *Shoe* in Figure 7), and turned to appropriate facing directions before making pointing judgments. The design of the experiments is illustrated in Figure 8. The independent variables were (a) the angular difference between the learning heading and the imagined heading at the time of test and (b) the angular difference between the actual body heading at the time of test and the imagined heading at the time of test. The independent variables were defined in terms of allocentric headings rather than angular distances so that the results would be directly comparable to previous findings (e.g., Mou & McNamara, 2002; Shelton & McNamara, 1997, 2001; Valiquette, McNamara, & Smith, 2003). Moreover, the use of allocentric headings makes no assumptions about the underlying processes involved (e.g., mental rotation vs. other inferential processes). Because the learning heading was 0° in all conditions, the difference between the learning heading and the imagined heading is referred to as *imagined heading* for convenience.

Imagined heading was manipulated within participants. The heading of 0° was parallel to the learning heading and by hypothesis parallel to the dominant reference direction in memory. The heading of 90° was selected because it was parallel to an intrinsic

² Applying this analysis to Shelton and McNamara's (1997, 2001) and Mou and McNamara's (2002) experiments is more complicated because participants were tested in a room different from the learning room. The difference between the learning heading and the imagined heading is well defined, but the difference between the actual heading and the imagined heading is not, because the participant's actual heading in the testing room presumably has little to do with performance in the task. However, participants may use various cues in the testing room to reinstate the learning environment and make their pointing judgments as if they were still in the learning room, facing in the learning orientation (or orientations). In this scenario, one can define a subjective heading in place of the actual heading. The same analysis can be used to interpret results from experiments in which participants were disoriented before testing (e.g., Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Sholl & Nolin, 1997; Waller et al., 2002).

axis of the layout that was salient by virtue of being aligned with the walls of the room (Experiments 1 and 2 only). The heading of 225° also corresponded to a natural intrinsic axis of the layout of objects (e.g., phone → brush; wood → shoe → jar), but this axis was not highlighted by alignment with the walls of the room. On the basis of previous findings (Mou & McNamara, 2002; Shelton & McNamara, 2001; Valiquette et al., 2003), we expected that participants would represent, to some extent, the layout of objects along the 90°–270° axis at the time of learning (as illustrated in Figure 5B). Actual–imagined (A-I) heading was manipulated between participants (to ensure that testing could be completed in a single session) and had values of 0° (the imagined heading was the same as the participant’s actual facing direction) and 225° (the imagined heading was 225° to the left of the participant’s actual facing direction; see Figure 8).

A unique strength of the design in Figure 8 is that it allowed us to assess the independent and interactive effects of (a) the difference between the learning heading and the imagined heading and (b) the difference between the actual heading and the imagined heading, while replicating conditions used in previous investigations of spatial memory and updating. Conditions 1, 2, and 3 correspond to standard investigations of spatial updating (e.g., Rieser, 1989; Waller et al., 2002); Conditions 1 and 4 correspond to Farrell and Robertson’s (1998) ignore conditions, in which participants rotate their bodies but make pointing judgments as if they have not rotated; and Conditions 1 and 6 correspond to imagination conditions, in which participants make pointing judgments from imagined headings but are not allowed to rotate their bodies (Rieser, 1989; Waller et al., 2002).³

If the dominant reference direction in the mental representation is updated to correspond to the learner’s actual heading, then pointing judgments should be equally efficient for the imagined headings of 0°, 90°, and 225°. When A-I heading = 0°, the

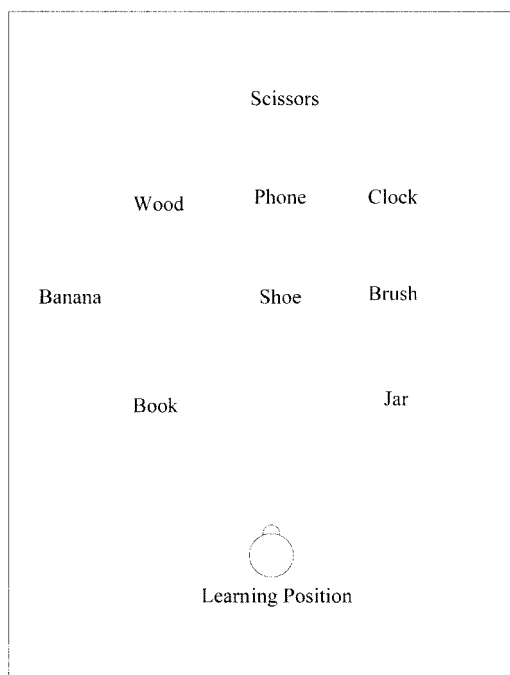


Figure 7. Layout of objects used in present experiments.

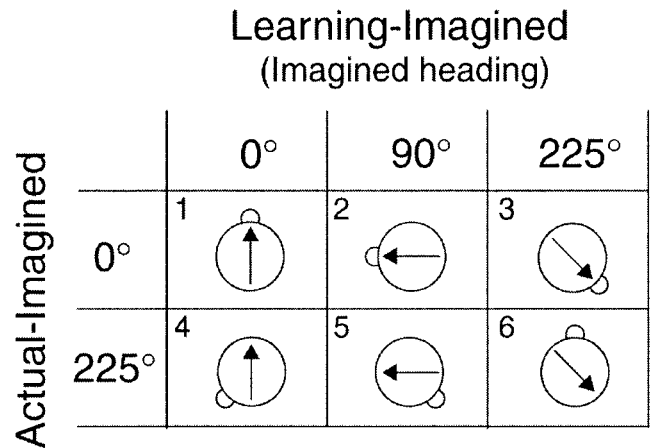


Figure 8. Design of the experiments. Head–nose icons indicate actual headings; arrows indicate imagined headings. Headings and differences between headings are measured counter-clockwise to maintain consistency with previous experiments. Learning–imagined heading was manipulated within participants; A-I was manipulated between participants. Conditions are numbered for ease of reference.

imagined heading is always parallel to the dominant reference direction, affording efficient access to interobject spatial relations. When A-I heading = 225°, the imagined heading differs by a constant amount from the dominant reference direction, which by hypothesis is parallel to the actual heading. Pointing judgments may be less efficient when the actual and the imagined headings differ than when they are the same (e.g., Rieser, 1989), but pointing should not be affected by imagined heading if the dominant reference direction corresponds to the learner’s actual heading. In contrast, if the dominant reference direction is established by the original learning heading (i.e., 0°) and is not updated during locomotion, then pointing judgments should be more efficient for the imagined heading of 0° than for other imagined headings, even when the actual and the imagined headings are the same. To the extent that the spatial layout is represented along the 90°–270° axis, as hypothesized, performance for the imagined heading of 90° may approach the level of performance for the imagined heading of 0°, even if the dominant reference direction is not updated. The experiments reported in this article tested these predictions.

Experiment 1

In Experiment 1, participants made judgments of relative direction (e.g., “Imagine you are standing at X and facing Y. Point to Z.”). This pointing task has egocentric components, as interobject spatial relations must be mapped onto an egocentric frame of

³ As pointed out by David Waller (personal communication, April 29, 2003), because Waller et al. (2002) used imagined headings of 0° and 180°, their stay and rotate-update conditions can be reconceptualized in terms of manipulations of learning–imagined heading and actual–imagined heading. Their main effects are equivalent to our interactions and vice versa. The advantages of our design are that the traditional spatial updating conditions (1, 2, and 3 in Figure 8) are manipulated within participants and that learning–imagined heading is manipulated parametrically.

reference to make the pointing judgment, but the spatial information needed to make the judgment consists of spatial relations among three objects in the environment. We therefore assumed that performance in this task is primarily sensitive to how object-object spatial relations are represented in memory.

Method

Participants. Forty undergraduates at Vanderbilt University (20 women and 20 men) participated as partial fulfillment of a requirement of their introductory psychology courses.

Materials and design. A configuration of nine objects was constructed (see Figure 7). Objects were selected with the restrictions that they be visually distinct, fit within approximately 1 ft² (.09 m²), and not share any obvious semantic associations.

Each test trial was constructed from the names of three objects in the layout and required participants to point to an object as if standing in a particular position within the layout (e.g., "Imagine you are standing at the jar, facing the brush. Point to the book."). The first two objects established the imagined heading (e.g., jar and brush), and the third object was the target (e.g., book).

The design is illustrated in Figure 8. The independent variables were (a) the angular difference between the learning heading and the imagined heading at the time of test (imagined heading = 0°, 90°, and 225°) and (b) the angular difference between the actual body heading at the time of test and the imagined heading at the time of test (A-I = 0° and 225°). Imagined heading was manipulated within participants; A-I heading was manipulated between participants.

Pointing direction was counterbalanced across imagined headings to ensure that all headings were equally difficult in terms of the pointing response. Participants received 24 test trials, 8 at each imagined heading. The dependent measures were the angular error of the pointing response, measured as the absolute angular difference between the judged pointing direction and the actual direction of the target, and pointing latency. Accuracy was emphasized over speed, and therefore, the primary dependent variable was pointing error.

Procedure. Participants were randomly assigned to each condition of A-I heading with the constraint that each group contained an equal number of men and women.

After providing informed consent, participants learned to use the joystick by completing a set of practice trials constructed from names of buildings on the Vanderbilt University campus. After participants completed the practice trials, the experimenter escorted them to the learning room. Participants were blindfolded while being escorted into the learning room and to the learning position.

When the participant was standing on the learning position and facing 0°, the blindfold was removed, and the learning phase began. Participants were instructed to learn the locations of the nine objects. They were allowed to study the layout for 30 s and were then asked to point to and name the objects while keeping their eyes closed. This study-test sequence was discontinued when the participant could point to and name all of the objects twice in a row.

After participants had learned the layout, they closed their eyes while the experimenter placed near the middle of the layout a Macintosh PowerBook, which was used to present test trials and collect pointing responses. Participants then opened their eyes and walked to the center of the layout (next to *Shoe* in Figure 7). They were allowed to turn their heads to review the layout from the testing position but were required to maintain a body orientation of 0°.

Test trials were presented in a random order. If a trial required an actual heading other than 0°, the participant was asked to turn to the appropriate facing direction (e.g., "Please turn to the left until you are facing the banana."). In the A-I = 0° group, the actual heading was always the same as the imagined heading. In the A-I = 225° group, the actual heading and the imagined heading always differed by 225° counterclockwise. Hence,

imagined headings of 0° (e.g., at brush, facing clock), 90° (e.g., at phone, facing wood), and 225° (e.g., at banana, facing book) required actual body headings of 135°, 225°, and 0°, respectively (see Figure 8). After participants had adopted the appropriate actual heading, they were allowed to turn their heads to review the layout. Participants closed their eyes after reviewing the layout and then indicated to the experimenter that they were ready for the test trial to be presented. The experimenter initiated the trial. The judgment of relative direction was presented over the speaker of the laptop. Participants pointed with an analog joystick held in their hands at waist level. Participants were repeatedly reminded to hold the joystick in a fixed orientation with respect to their bodies. Participants opened their eyes after each trial and resumed the heading of 0°. All locomotion was visually guided.⁴

Results and Discussion

Absolute angular error and latency of judgments of relative direction are plotted in Figures 9 and 10 as a function of A-I heading and imagined heading. Means for each participant and each condition were analyzed in mixed-model analyses of variance (ANOVAs) with terms for gender, A-I heading (0° and 225°), and imagined heading (0°, 90°, and 225°).

In angular error, only the main effect of imagined heading was significant, $F(2, 72) = 43.84, p < .01, MSE = 75.37$. Planned pairwise comparisons of levels of imagined heading showed that within the A-I = 0° condition, 0° and 90° did not differ ($t < 1$) and both differed from 225°, $ts(72) \geq 5.03, ps \leq .01$. Within the A-I = 225° condition, the difference between 0° and 90° was marginally significant, $t(72) = 1.92, p < .10$, and both 0° and 90° differed significantly from 225°, $ts(72) \geq 5.02, ps \leq .01$.

In pointing latency, the three main effects were statistically reliable: imagined heading, $F(2, 72) = 34.68, p < .01, MSE = 1.28$; A-I heading, $F(1, 36) = 7.15, p < .05, MSE = 14.63$; and gender, $F(1, 36) = 4.46, p < .05$ (men = 3.56 s and women = 5.03 s). Planned pairwise comparisons of levels of imagined heading showed that within the A-I = 0° condition, 0° and 90° did not differ ($t < 1$) and both differed from 225°, $ts(72) \geq 4.61, ps \leq .01$. Within the A-I = 225° condition, imagined headings were ordered, 0° < 90°, $t(72) = 3.38, p < .01$, and 90° < 225°, $t(72) = 3.22, p < .01$.

The most important result of Experiment 1 was that participants were able to recover the spatial layout of the objects more efficiently from views parallel to the learning view (0°)—and by hypothesis, parallel to the dominant reference direction in memory—than from views misaligned with the learning view (225°). This effect occurred even when participants were actually facing the direction they were asked to imagine facing (A-I = 0°). This result indicates that the dominant reference direction in memory was not updated as participants walked and turned in the room.

Another important finding was that performance was better when the actual and imagined headings were the same (A-I = 0°) than it was when they were different (A-I = 225°). This effect was statistically reliable in latency but not in angular error. Apparently, a cost was incurred by the need to align egocentric front with the X → Y direction specified in the judgment of relative direction. This effect was not caused by imagined translation (Easton &

⁴ We attempted to measure orientation time and pointing latency separately (e.g., Roskos-Ewoldsen et al., 1998; Waller et al., 2002). Orientation times were highly variable and did not aid in the interpretation of pointing performance. In the interest of brevity, they are not reported.

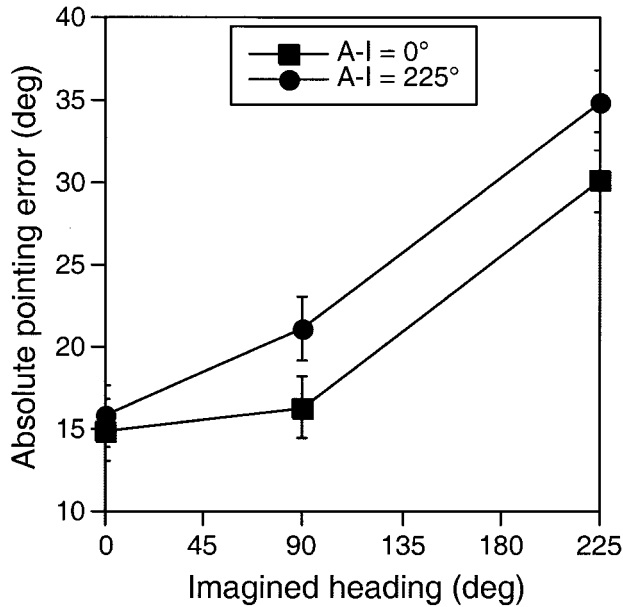


Figure 9. Angular error of judgments of relative direction as a function of actual-imagined (A-I) heading and imagined heading in Experiment 1. deg = degrees.

Sholl, 1995; Rieser, 1989), as the average distance from the actual standing location to the imagined standing location (X) was the same across levels of imagined heading. This effect indicates that participants updated their egocentric orientation with respect to the objects when they rotated; they knew that their actual facing direction was not the same as the imagined heading. This effect does not imply that the reference directions in the mental representation were updated.

A third important finding was that in both dependent variables, performance was equally good for imagined headings of 0° and 90° in the A-I = 0° condition. As discussed previously, this effect indicates that participants represented the layout in terms of reference directions of 0° and 90° (see, e.g., Figure 5B). Although performance for novel aligned headings is not typically as good as is that for the learning heading (e.g., nonegocentric axis group in Figure 4), it can be under certain circumstances. For example, in Mou and McNamara's (2002) first experiment, participants learned a layout similar to the one illustrated in Figure 3, except that the objects were letters on disks. The regular spacing of the disks and their placement on the square mat made the 0°-180° and 90°-270° axes very salient. Participants studied the layout from 315° and were instructed to learn it along the 0°-180° axis. Angular errors in judgments of relative direction were 22°, 27°, 34°, and 22° for imagined headings of 0°, 90°, 180°, and 270°, respectively. Performance for two of the novel aligned headings, 270° and 90°, was as good as, or nearly as good as, that for 0°. The heading of 90° was not highlighted in such an obvious manner in the present experiment, but participants did experience this heading at the time of testing. It is possible that these experiences provided an additional cue to represent the spatial structure of the layout along the 90°-270° axis (e.g., Shelton & McNamara, 1997).

It is not clear why a similar effect did not appear in the A-I = 225° condition. Patterns of performance suggest that alignment of egocentric front with X → Y was relatively easy for the imagined

heading of 0°. It is possible that when the imagined heading was 0°, participants in the A-I = 225° condition partly compensated for rotation of the body (they were actually facing 135°; see Figure 8) by imagining themselves facing the familiar orientation of 0°.

Experiment 2

Judgments of relative direction require participants to retrieve or infer object-to-object spatial relations from memory. The results of Experiment 1 indicated that the spatial reference system used to represent object-to-object spatial relations was not updated during locomotion. Experiment 2 examined updating of self-to-object spatial relations by having participants point to objects egocentrically (e.g., "You are facing Y; point to Z."). Another way to conceive of the difference between judgments of relative direction used in Experiment 1 and egocentric pointing judgments used in Experiment 2 is that the former task requires imagined translation, whereas the latter task does not.

Method

Participants. Forty undergraduates at Vanderbilt University (20 women and 20 men) participated as partial fulfillment of a requirement of their introductory psychology courses.

Materials, design, and procedure. Materials, design, and procedure of Experiment 2 were similar to those of Experiment 1. A 10th object was added to the layout at the learning position so that egocentric pointing direction could be counterbalanced across all imagined headings. Participants were tested on 21 trials, 7 at each imagined heading. Each test trial was constructed from the names of the heading object and the target object and required participants to point to an object from where they stood. In the A-I = 0° group, judgments were worded, "You are facing Y; point to Z," whereas in the A-I = 225° group, they were worded, "Imagine you are facing Y; point to Z."

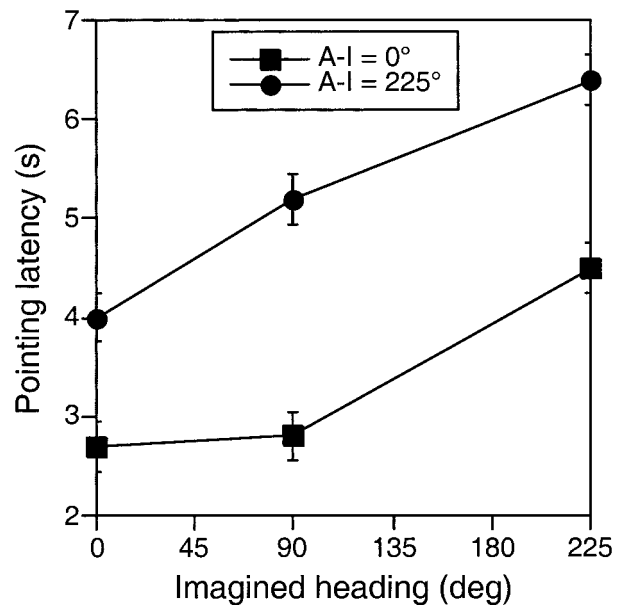


Figure 10. Latency of judgments of relative direction as a function of actual-imagined (A-I) heading and imagined heading in Experiment 1. deg = degrees.

Results and Discussion

Absolute angular error and latency of egocentric pointing judgments are plotted in Figures 11 and 12 as a function of A-I heading and imagined heading. Means for each participant and each condition were analyzed in mixed-model ANOVAs with terms for gender, A-I heading (0° and 225°), and imagined heading (0° , 90° , and 225°).

In pointing error, significant effects were obtained for imagined heading, $F(2, 72) = 17.64$, $p < .01$, $MSE = 42.60$, and A-I heading, $F(1, 36) = 18.97$, $p < .01$, $MSE = 120.72$. The interaction between these effects was also significant, $F(2, 72) = 3.20$, $p < .05$. An interaction contrast that compared the magnitude of the difference between 0° and 90° across the two groups was reliable, $F(1, 72) = 6.25$, $p < .05$, and accounted for 98% of the variance in the omnibus interaction. Planned pairwise comparisons of levels of imagined heading showed that within the A-I = 0° condition, 0° and 90° did not differ significantly ($t < 1$) and both differed from 225° , $t(72) \geq 2.96$, $ps \leq .01$. Within the A-I = 225° condition, 0° differed from 90° and 225° , $t(72) \geq 4.01$, $ps \leq .01$, and 90° and 225° did not differ ($t < 1$). The main effect of gender was reliable, $F(1, 36) = 6.57$, $p < .05$. Men's judgments were more accurate than were women's (17.4° vs. 22.6° , respectively). The interaction between imagined heading and gender was significant, $F(2, 72) = 3.39$, $p < .05$, with different magnitudes of imagined heading effect for men and women. This interaction did not compromise any of the major conclusions about the effect of imagined heading.

In pointing latency, the main effect of imagined heading was significant, $F(2, 72) = 14.40$, $p < .01$, $MSE = 1.17$, and the main effect of A-I heading was significant, $F(1, 36) = 26.35$, $p < .01$, $MSE = 7.07$. Planned pairwise comparisons of levels of imagined heading showed that within the A-I = 0° condition, the difference between 0° and 90° was not significant ($t < 1$), the difference

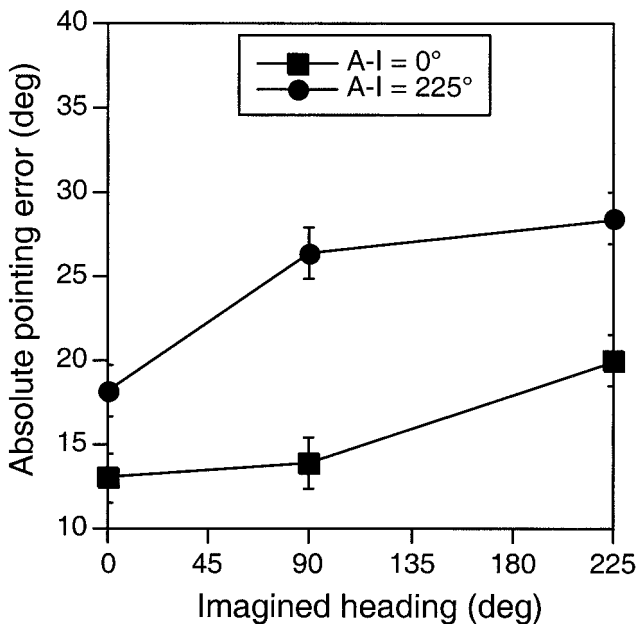


Figure 11. Angular error of egocentric pointing judgments as a function of actual-imagined (A-I) heading and imagined heading in Experiment 2. deg = degrees.

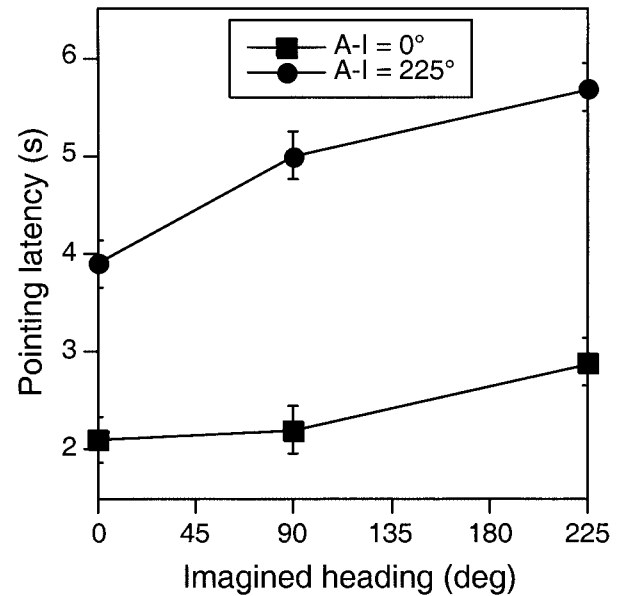


Figure 12. Latency of egocentric pointing judgments as a function of actual-imagined (A-I) heading and imagined heading in Experiment 2. deg = degrees.

between 90° and 225° was marginally significant, $t(72) = 1.89$, $p < .10$, and the difference between 0° and 225° was significant, $t(72) = 2.23$, $p < .05$. Within the A-I = 225° condition, $0^\circ < 90^\circ$, $t(72) = 3.18$, $p < .01$, and $90^\circ < 225^\circ$, $t(72) = 2.18$, $p < .05$.

The results of Experiment 2 indicated that self-to-object spatial relations were not updated efficiently, even when participants locomoted using vision. Although the magnitude of the effect of imagined heading was smaller in this experiment than in Experiment 1, it was still substantial and statistically reliable. In angular error, for example, effect size $f = .53$. This value substantially exceeds the criterion of $.40$ for a large effect (Cohen, 1988). For comparison, $f = .71$ in Experiment 1.

The effect of imagined heading in Experiments 1 and 2 was not caused by accumulation of error with increasing magnitudes of actual (i.e., physical) rotation. Across the two experiments, the correlations between performance and the magnitude of actual rotation was $.08$ for angular error and $.09$ for latency (performance in 12 experimental conditions contributed to each correlation). It is also unlikely that the effect was caused by misalignment between the participant's body and the walls of the room. Correlations between performance and a dichotomous measure of body-room alignment (facing directions of 0° and 90° were categorized as aligned; 135° and 225° were categorized as misaligned) were $.11$ for angular error and $.22$ for latency.

Performance in the A-I = 225° conditions illustrates both points: The magnitude of actual rotation was 135° , 225° , and 0° for imagined headings of 0° , 90° , and 225° (see Figure 8). Similarly, the participant's body was misaligned with the walls for imagined headings of 0° and 90° but aligned with the walls for the imagined heading of 225° (see Figure 8). Despite these relations, pointing error and latency in the A-I = 225° condition increased across levels of imagined heading. These results cannot be dismissed simply because the actual and the imagined headings differed, as they differed by a constant amount, just as in the A-I = 0°

condition. If updating occurred as participants walked and turned with vision, such that the dominant reference direction in memory was always parallel to the person's actual heading (as hypothesized by Sholl & Nolin, 1997), then the difference between the updated dominant reference direction and the imagined heading would have been the same for all imagined headings. Hence, an effect of imagined heading would not be predicted on the basis of recovery of interobject spatial relations from memory. To the extent that the magnitude of actual rotation or misalignment with the walls were factors, performance should have been worse for the imagined heading of 0° (actual rotation = 135°, body misaligned with walls) than it was for the imagined heading of 225° (actual rotation = 0°, body aligned with walls). In fact, the opposite pattern was obtained. One should note that our previous research (Mou & McNamara, 2002; Shelton & McNamara, 2001) has shown that alignment of learning views with the room can influence how layouts are interpreted and mentally represented, but we have never obtained evidence of poorer performance when participants learn layouts from misaligned views.

To determine how the room geometry might have influenced the patterns of results in Experiments 1 and 2, we replicated the A-I = 0° condition of each experiment in a cylindrical room. The layout of objects was placed in a cylindrical room constructed in the original learning room. Participants were escorted into both the laboratory and the cylinder blindfolded and never saw the rectangular room. All learning and testing was conducted in the cylinder. Otherwise, the design and the procedures matched those used in Experiments 1 and 2.

Experiment 3

Experiment 3 replicated the A-I = 0° condition of Experiment 1 in a cylindrical room; in particular, participants were tested using judgments of relative direction. Because the 90° heading was no longer highlighted by virtue of its alignment with the walls, we predicted that performance for this heading would be worse than performance for the 0° heading.

Method

Participants. Participants were 12 graduate students and staff members in the Department of Psychology at Vanderbilt University. One participant was dropped because of excessive error in pointing judgments, leaving a final sample of 11 participants.

Materials, design, and procedure. Materials, design, and procedure were identical to those used in Experiment 1, with the following exceptions: Only the A-I = 0° condition was tested; all learning and testing took place in a 3.3 m cylindrical room. The walls of the cylinder were made of heavy fabric hung from the ceiling. Participants were blindfolded before entering the laboratory and then escorted to the entrance of the cylinder, which was near the wood in Figure 7 (i.e., the heading of 225°). Once inside, they were escorted around the perimeter to the learning position, which was slightly "south" of the line formed by book and jar. The blindfold was not removed until this point.

Results and Discussion

Absolute angular error and latency of judgments of relative direction are plotted in Figures 13 and 14 as a function of imagined heading. Means for each participant and each condition were analyzed in mixed-model ANOVAs with terms for gender and imagined heading (0°, 90°, and 225°).

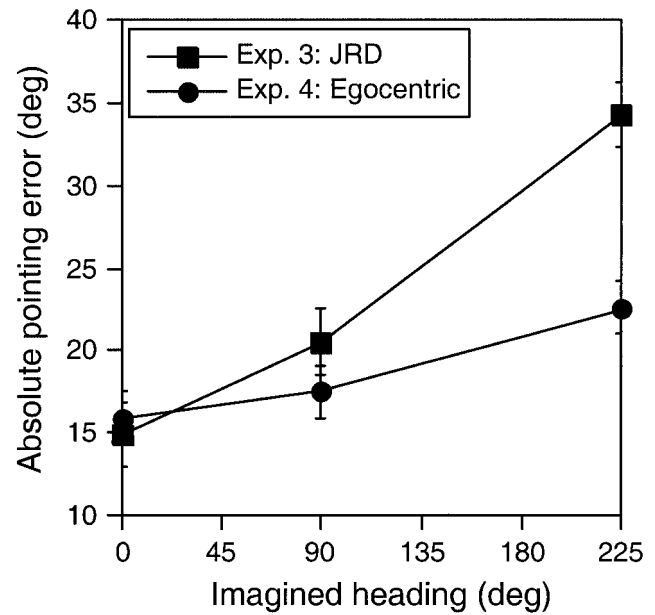


Figure 13. Angular error of judgments of relative direction (JRD, Experiment 3) and egocentric pointing judgments (Egocentric, Experiment 4) as a function of imagined heading in the cylindrical room experiments. Exp. = experiment; deg = degrees.

In angular error, only the effect of imagined heading was statistically reliable, $F(2, 18) = 25.48, p < .01, MSE = 44.90$. Pairwise comparisons showed that the difference between 0° and 90° was marginally significant, $t(18) = 1.96, p < .10$; 0° differed from 225°, $t(18) = 6.79, p < .01$; and 90° differed from 225°, $t(18) = 4.83, p < .01$. Pointing latency showed the same pattern as pointing error, although the effect of imagined heading was only marginally significant, $F(2, 18) = 3.04, p < .10, MSE = 1.14$. None of the other effects was significant.

The results of Experiment 3 indicated that the effect of imagined heading in Experiment 1 was not caused by misalignment with the walls of the room. These findings provide strong evidence that reference directions were not updated as participants locomoted. As predicted, performance for 90° was worse than performance for 0°, although the relatively small sample size precluded unambiguous statistical confirmation of this prediction.

Experiment 4

Experiment 4 replicated the A-I = 0° condition of Experiment 2 in the cylindrical room; in particular, participants were tested with egocentric pointing judgments.

Method

Participants. Participants were 12 students and staff members in the Department of Psychology at Vanderbilt University.

Materials, design, and procedure. Materials, design, and procedure were the same as those in Experiment 2, except that only the A-I = 0° condition was included, and the entire experiment was conducted in the cylindrical room.

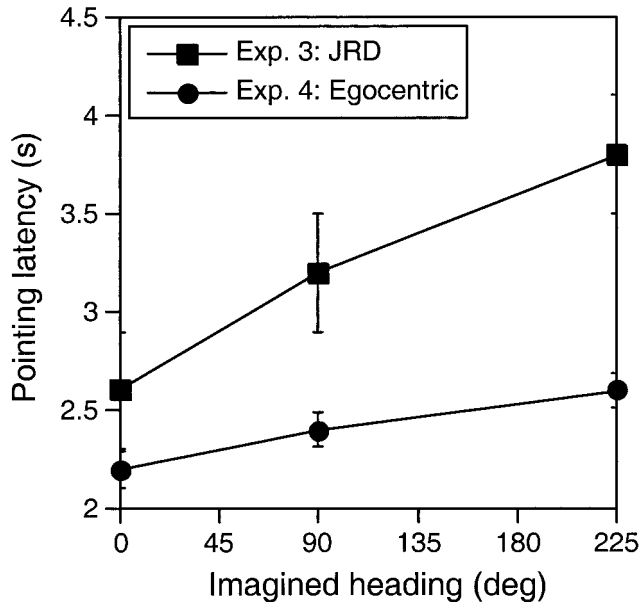


Figure 14. Latency of judgments of relative direction (JRD, Experiment 3) and egocentric pointing judgments (Egocentric, Experiment 4) as a function of imagined heading in the cylindrical room experiments. Exp. = experiment; deg = degrees.

Results and Discussion

Absolute angular error and latency of egocentric pointing judgments are plotted in Figures 13 and 14 as a function of imagined heading. Means for each participant and each condition were analyzed in mixed-model ANOVAs with terms for gender and imagined heading (0°, 90°, and 225°).

In angular error, only the effect of imagined heading was significant, $F(2, 20) = 4.48, p < .05, MSE = 32.20$. Pairwise comparisons showed that 0° and 90° did not differ ($t < 1$); 0° differed from 225°, $t(20) = 2.89, p < .01$; and 90° differed from 225°, $t(20) = 2.20, p < .05$. In pointing latency, the only significant effect was also imagined heading, $F(2, 20) = 4.65, p < .05, MSE = .09$. Pairwise comparisons showed that the difference between 0° and 225° was significant, $t(20) = 3.04, p < .01$, but none of the other comparisons was significant ($ts < 1.5$).

The most important finding in Experiment 2 was also replicated in the cylindrical room: Participants pointed to objects more efficiently from the original learning heading of 0° than from the heading of 225°, even though all locomotion was visually guided. This result indicates that participants had to use spatial information in the intrinsic-reference-system-based representation to point directly to objects surrounding them. The magnitude of the effect of imagined heading was again large according to an objective criterion; in angular error, $f = .44$ (Cohen, 1988).

A potentially important factor for which even the cylindrical room does not control is the perceptual organization of the layout of objects. To some eyes, for example, the layout in Figure 7 may seem to be better organized into rows and columns from the headings of 0° and 90° than from the heading of 225°. Perhaps the poorer perceptual organization of the layout from 225° interfered with spatial updating. Even if this conjecture is valid, the difference between 225° and the other headings may simply be an

example of another environmental factor that influences how spatial layout is mentally represented and processed. For instance, Shelton and McNamara's (2001) aligned–misaligned view experiment already provides one example of a situation in which updating of the dominant reference direction seems to depend on features of the surrounding environment. However, we doubt that the headings in Figure 7 differ sufficiently to produce such an effect.

First, to our eyes, the perceptual organization is at least as good from 225° as it is from 0° or 90°; in particular, the salient columnar organization from 225° would seem to facilitate updating of the dominant reference direction. One must bear in mind that the perceptual organization of the layout as shown in Figure 7 is affected by its orientation with respect to the paper and the figure border and by the orientation of the object names. Orientations of 0° and 90° are aligned with the edges of the paper and the border, whereas the 225° orientation is not. Furthermore, the print is extended along the 90°–270° axis and is in its canonical orientation from 0°; from 225°, the orientation of the print conflicts with the perceptual organization into rows and columns. In the experiments, real objects were used, and they were placed at random orientations on the bare floor of a room.

Second, in a line of research that now includes 13 published experiments (Mou & McNamara, 2002; Shelton & McNamara, 2001; Valiquette et al., 2003), we have not obtained any evidence that some intrinsic organizations are better than others. The patterns of performance across imagined headings are sometimes affected by which intrinsic organization is selected, but within a given experiment, the best performance is the same regardless of which direction is emphasized during learning (as in Figure 4).⁵ Given that all intrinsic organizations seem to be equivalent in terms of representing the spatial layout of the arrays of objects we have used as stimuli, there is no reason to believe that certain intrinsic directions should be privileged in spatial updating.

Third, and finally, two additional layouts of objects were used in three pilot studies. One layout was the same as the one depicted in Figure 1. Procedures were very similar to those used in Experiments 1 and 2, except that participants were blindfolded during locomotion. The same results were obtained in those pilot studies as in the present experiments, and there was no indication that the pattern of results interacted with the particular layout learned. In particular, for the layout in Figure 1, mean angular errors in judgments of relative direction in the A–I = 0° condition were 20°, 19°, and 30° for imagined headings of 0°, 90°, and 225°. We cannot see any basis for claiming that the layout in Figure 1 has

⁵ We caution against comparing absolute levels of performance in pointing tasks across studies. Not only were the participant samples different, but different apparatus and procedures were often used. For instance, Shelton and McNamara (2001) used a simulated pointer displayed on the computer monitor. The pointer was manipulated with the mouse. The response was not recorded until the participant clicked the mouse button, and participants typically considered alternative pointing directions before responding. This apparatus produces very high levels of accuracy. By contrast, Mou and McNamara's (2002) experiments used an analog joystick mounted on the desk in front of the monitor. The pointing response was recorded automatically as soon as the joystick reached its terminus. There was therefore no opportunity for participants to fine-tune their responses. The present experiments also used an analog joystick, but participants held it in their hands at waist level.

better intrinsic organization from 0° or 90° than from 225°; in fact, the opposite seems to be true.

General Discussion

The results of these experiments indicated that the reference system used to represent the layout of several objects in a room was not updated during locomotion. Participants were better able to recover interobject spatial relations from the original learning heading than from other headings, even when their body orientation was the same as the imagined heading. This effect of the difference between the learning heading and the imagined heading occurred in judgments of relative direction, which depend on object-to-object spatial relations, and egocentric pointing judgments, which depend on self-to-object spatial relations. Experiments 3 and 4 showed that these findings did not depend on the room geometry. The effect of imagined heading in egocentric pointing judgments is especially important because it suggests that the location and the orientation of the body were specified in the same reference system used to represent the layout of the objects.

The results of these experiments are difficult to explain in existing models of spatial memory and updating. Models that rely on orientation- or viewpoint-dependent representations of familiar views (e.g., Diwadkar & McNamara, 1997; Schölkopf & Mallot, 1995; Shelton & McNamara, 1997) can account for the difference between imagined headings of 0° and 225° because the former was studied but the latter was not. These models, however, have difficulty explaining equivalent levels of performance for imagined headings of 0° and 90° in the $A-I = 0^\circ$ conditions of Experiments 1 and 2, as the heading of 90° was not studied. It could be argued that views from 90° were represented during the testing phase. However, these models then do not have a principled account of why performance was poor for 225°, as this heading was experienced just as often as 90° during testing. In our opinion, this class of models is no longer tenable in light of the findings reported by Shelton and McNamara (2001) and Mou and McNamara (2002). These egocentric representation models predict better performance on familiar than on unfamiliar headings, and this prediction has been repeatedly disconfirmed.

Our findings also pose problems for Sholl's model (e.g., Easton & Sholl, 1995; Sholl, 2001; Sholl & Nolin, 1997). Sholl's model contains two subsystems: The 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 allocentric object-to-object system codes the spatial relations among objects in environmental coordinates 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 (Sholl & Nolin, 1997, p. 1497). In the present experiments, participants locomoted with vision and were oriented at all times. This model therefore predicts that egocentric pointing judgments and judgments of relative direction should be unaffected by imagined heading (i.e., the difference between the learning heading and the imagined heading). The results of the present experiments are not consistent with this prediction.

Wang and Spelke (2000, 2002) recently proposed another model of spatial memory and updating. According to this model, humans navigate by computing and dynamically updating spatial relations between their bodies and significant objects in the surrounding environment. This system supports path integration, the primary mode of navigation according to the model. The appearances of familiar landmarks and scenes are represented in viewpoint-dependent representations. 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).

Wang and Spelke's (2000, 2002) model is challenged by two sets of findings. Previous experiments in our laboratory have required participants to use long-term memories of spatial relations among objects to generate actions (e.g., Mou & McNamara, 2002; Shelton & McNamara, 1997, 2001). Pointing error was often under 10° in the best conditions, indicating that participants had highly accurate knowledge of the spatial layout of the objects (albeit from learned headings). It is not clear how such accurate spatial actions could be generated given the types of spatial relations stored in each subsystem of the model. Presumably, the spatial relations needed to make the pointing judgments were not inferred from information in the dynamic egocentric system, as participants were taken to a different room on a different floor of the building to be tested, and testing itself lasted 20–30 min. If judgments were based on remembered views, they should have been accurate and fast for all familiar views; this pattern was not observed (e.g., the aligned-misaligned view and cylindrical room experiments discussed in the introduction). Finally, the allocentric system in Wang and Spelke's (2000, 2002) model contains information only about the geometric shape of the environment, not about spatial relations among objects. Wang and Spelke's model also has difficulty accounting for the present results on spatial updating, especially in egocentric pointing judgments, as participants locomoted with vision and were oriented at all times. These are precisely the conditions under which the dynamic egocentric system operates most efficiently.

We have little doubt that each of these models could be augmented with additional mechanisms that might enable them to explain the present findings. The challenge for these augmented models will be to account for the results of all four of the present updating experiments, as well as previous findings on the spatial reference systems used in memory (such as those reviewed in the introduction to this article).

Our explanation of these findings builds on the pioneering models proposed by Sholl (e.g., Easton & Sholl, 1995; Sholl, 2001; Sholl & Nolin, 1997) and by Wang and Spelke (2000, 2002). This theoretical framework was inspired by recent theories of the relationship between visually guided action and visual perception (Creem & Proffitt, 1998, 2001; Milner & Goodale, 1995; Rossetti, 1998; Rossetti, Pisella, & Pélisson, 2000). We propose that 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 (any of several types of egocentric frames of reference may be used in this subsystem). The environmental

subsystem is responsible for representing the spatial layout of familiar environments. This subsystem is governed by the theory of spatial memory proposed by Shelton and McNamara (2001) and by Mou and McNamara (2002), as discussed in the introduction to this article. Small- and large-scale environments are represented in this subsystem.

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 (although there must be limits on the number of objects monitored and on the self-to-object distance over which updating takes place). 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 is capacity limited (e.g., Rieser, Hill, Talor, Bradfield, & Rosen, 1992).

Egocentric updating allows an observer to avoid obstacles, walk through doorways, stay on the sidewalk, and so on, 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. We assume that environmental updating requires more attentional control than egocentric updating. A driver chatting on a cell phone, for instance, is more likely to miss the correct turn than to drive off the road. Although self-to-object spatial relations are represented in both subsystems, the egocentric subsystem is still needed for efficient locomotion. This proposed distinction between egocentric and environmental updating is similar to Sholl's (2001) distinction between updating at perceptual-motor and representational levels.

We assume that egocentric pointing judgments depend primarily on spatial relations computed and represented in the egocentric subsystem, as long as those judgments are made online or nearly online. Performance in online egocentric pointing judgments may be affected by various egocentric reference systems (e.g., pointing to front is more efficient than pointing to back), but it should not be affected by the participant's heading or the layout of the objects. However, if perceptual support is diminished (e.g., standing still with eyes closed), and a sufficiently long delay is interposed between movement and testing, spatial relations represented by the egocentric subsystem will lose fidelity. This process does not result in disorientation, as the person's location and orientation are still defined in the environmental subsystem. But if the person is required to point to objects in the surrounding environment, he or she may be forced to rely on spatial information in the environmental subsystem. Patterns of performance will therefore be affected by the intrinsic reference system used to represent the layout of the space and the location of the observer; in particular, performance will be orientation dependent. It may be possible to maintain self-to-object spatial relations in the egocentric subsystem during periods of reduced perceptual support, but our conjecture is

that such processes are limited to small numbers of objects. For example, one can monitor the location of a single object with little difficulty as one turns away from it; however, monitoring the locations of even three or four objects is substantially more challenging.

The delay between locomotion and pointing was not precisely controlled in Experiments 2 and 4 but was on the order of 10 s. (Participants reviewed the layout, closed their eyes, and informed the experimenter, who then initiated presentation of instructions.) In the context of the theory, our findings indicate that self-to-object spatial relations in the egocentric subsystem had begun to decay even at such short retention intervals. The presence of residual spatial relations in the egocentric subsystem may place an upper bound on the magnitude of the effect of imagined heading in egocentric pointing judgments and explain why imagined heading had smaller effects in egocentric pointing judgments than it did in judgments of relative direction.

We assume that judgments of relative direction are based primarily on spatial relations represented in the environmental subsystem, regardless of the delay between locomotion and testing. This task requires participants to retrieve or infer spatial relations among three objects in the environment. The intrinsic reference systems used in the environmental subsystem are not typically updated during locomotion. Hence, judgments of relative direction should produce similar patterns of performance regardless of whether the observer has locomoted between learning and testing; in particular, performance should be best for imagined headings parallel to the reference directions selected at the time of learning. Such findings were observed in Experiments 1 and 3. Our theoretical framework can readily explain Shelton and McNamara's (2001) and Mou and McNamara's (2002) challenging findings because the environmental subsystem is governed by their theory of spatial memory.

Like Sholl's model (Easton & Sholl, 1995; Sholl, 2001; Sholl & Nolin, 1997), our theoretical framework also divides memory-based navigation into egocentric and allocentric systems. However, properties and functions of these systems are quite different in the two models. In Sholl's model, both the self-reference and the object-to-object systems form enduring representations, the object-to-object system is orientation independent, and spatial updating only occurs in the self-reference system.

Our framework is even more similar to Wang and Spelke's (2000, 2002): The egocentric subsystem is analogous to their dynamic egocentric system, although temporal aspects of the egocentric subsystem receive more emphasis in our framework. We are agnostic on whether viewpoint-dependent representations of landmarks and scenes are needed in addition to the intrinsic-reference-system-based representation (but see Franz, Schölkopf, Mallot, & Bühlhoff, 1998). The primary point of divergence between these models is in the allocentric system: In our model, it represents the spatial structure of the environment, including spatial relations among objects, using an intrinsic reference system. In Wang and Spelke's (2000, 2002) model, it only represents the shape of the environment, and the reference system is unspecified. As discussed previously, we believe that an allocentric system must contain enduring representations of spatial relations among objects. However, it is possible that the geometry of surrounding surfaces has a special role in the environmental subsystem, as suggested by Wang and Spelke's (2000) findings.

An important question that remains unanswered is why efficient updating has been obtained in previous experiments. In the following paragraphs, we consider several possible explanations of those findings.

The efficiency of spatial updating may depend on the geometric complexity of the layout. The layouts used in our experiments contained more objects or were more complex than those used in most spatial updating experiments: Rieser (1989) used circular arrays of evenly spaced objects; Presson and Montello (1994) only used three objects; and Waller et al. (2002) used four-point paths like the one in Figure 6. Participants in Rieser's experiment, for example, might have been able to use, in a top-down manner, their knowledge that the objects were spaced in regular intervals to facilitate pointing after turning. Knowledge of the serial ordering of the objects and that they were spaced in equal intervals would support accurate estimates of direction. Additional research is needed in which the number of objects and the complexity of the layout are manipulated parametrically.

It is also possible that at least some demonstrations of efficient spatial updating were tapping spatial relations in the egocentric subsystem. A potentially important feature of Rieser's (1989) locomotion condition is that the target object was spoken to the participant as he or she was turned to the new heading. There was therefore no delay between locomotion and testing (this procedure also would have enabled participants to monitor a single object as they turned).

Similar reasoning may apply to Simons and Wang's (1998; Wang & Simons, 1999) findings. They showed that detection of changes to a recently viewed layout of objects was disrupted when the layout was rotated to a new view and the observer remained stationary but not when the layout remained stationary and the observer moved to the new viewpoint. Put another way, updating was efficient when the observer moved around the layout but not when the layout rotated in front of the observer (see Wraga, Creem, & Proffitt, 2000, for analogous results in imagined updating). Change detection is not a motor task, but the delays between locomotion and testing were sufficiently brief (< 7 s) that these findings may provide evidence of efficient updating in the egocentric subsystem.⁶ The difference between observer movement and layout rotation demonstrates the essential role of locomotion in spatial updating.

A third possible explanation of demonstrations of efficient spatial updating relies on the experimental design developed in the present experiments. Consider, for example, Waller et al.'s (2002) direct-walk condition. Participants learned the path (e.g., Figure 6) and then walked directly to the viewpoint they were asked to adopt in imagination before making their pointing judgments. Performance in judgments of relative direction was equally good for aligned ("At 4, facing 3") and misaligned ("At 3, facing 4") trials. Recast in terms of the independent variables manipulated in the present experiments, the direct walk condition corresponds to A-I heading = 0° . The aligned and misaligned pointing conditions correspond to imagined headings of 0° and 180° , respectively (or more precisely, to disparities between the learning heading and the imagined heading of 0° and 180°). One possible explanation of the equally good performance in these two conditions is that participants represented the layout at the time of learning in both the 0° and the 180° directions (as illustrated in Figure 5B). This is the same mechanism that we used to explain equivalent performance for imagined headings of 0° and 90° in the A-I = 0° condition of

Experiments 1 and 2 (see also Mou & McNamara, 2002). The use of imagined headings of 0° and 180° is typical in many investigations of spatial memory and updating (e.g., Sholl & Bartels, 2002).

Continuing the analysis, Waller et al.'s (2002) rotate-update/aligned condition is equivalent to A-I = 180° /imagined heading = 0° , and their rotate-update/misaligned condition is equivalent to A-I = 0° /imagined heading = 180° . Framed in this way, one can see that the effect of alignment in Waller et al.'s rotate-update condition might have been produced by the difference between the actual heading and the imagined heading, not by the difference between the learning heading and the imagined heading.

The natural question at this point is whether these explanations are consistent with other results reported by Waller et al. (2002). We believe that they are, although they depend on three assumptions: First, participants represented the four-point paths along the 0° - 180° axis and therefore could retrieve views in the 180° direction as efficiently, or nearly as efficiently, as views in the 0° direction; second, an angular disparity of 180° between the actual heading and the imagined heading caused a decrement in performance because of the need to align egocentric front with the X \rightarrow Y direction; and third, when participants were disoriented, they adopted a subjective heading as their presumed actual heading (see Footnote 2).

Consider, for example, the stay condition, in which participants learned the paths and made judgments of relative direction from the learning position. According to the interpretation being advanced, the difference between the aligned and the misaligned conditions was produced by the angular disparity between the actual and the imagined headings, not by the angular disparity between the learning heading and the imagined heading. The same reasoning could explain other demonstrations of "alignment" effects (e.g., Levine et al., 1982).

The results of the wheel and deceptive wheel conditions are explained in the same way, although one must assume that after disorientation, participants adopted a subjective heading as their presumed actual heading. The original headings of 0° and 180° are natural candidates. In other words, participants made their pointing judgments as if they were facing 0° or 180° . An inspection of individual participants' data in Figures 3 and 4 of Waller et al.'s (2002) article indicates that the majority of participants used 0° , such that the imagined heading of 180° was difficult; several participants used 180° , such that the imagined heading of 0° was difficult; and a few participants alternated across trials, producing average performance of about the same level for headings of 0° and 180° (and intermediate between the average best performance for either heading). According to this conceptual analysis, performance was worse, on average, in the disoriented (i.e., wheel and deceptive wheel conditions)/aligned condition than in the stay/aligned condition and better, on average, in the disoriented/misaligned condition than in the stay/misaligned condition (this is the facilitation-inhibition pattern discussed by Waller et al., 2002)

⁶ An alternative interpretation is that as participants moved to the new viewpoint, they updated their location and orientation with respect to a representation of the layout of objects in the environmental subsystem. Updated self-to-object representations in this subsystem might have facilitated change detection. Either interpretation is consistent with our theoretical framework.

because there was more variability across participants in the disoriented than in the stay conditions in which heading was adopted as the actual heading. The results in Figures 3 and 4 of Waller et al.'s article are completely consistent with this interpretation.

In summary, in the context of the theory we are proposing, there are several possible reasons why efficient updating might have been observed in previous experiments. Different explanations may apply to different experimental methods. Only systematic investigations will allow us to determine which, if any, are valid.

In closing, the most important conclusions from the present experiments are these: First, future investigations of spatial updating must account for the separate contributions of spatial processes and alignment processes to performance in spatial memory tasks. Judgments of relative direction and egocentric pointing judgments, in particular, require people to retrieve or infer interobject spatial relations and to align those spatial relations with an egocentric frame of reference for the purpose of making the pointing judgment. The contributions of these two sets of processes to performance need to be distinguished. In the present experiments, this goal was achieved by manipulating the angular difference between the learning heading and the imagined heading and the angular difference between the actual heading and the imagined heading.

Second, our current and previous findings (Mou & McNamara, 2002; Shelton & McNamara, 2001) are consistent with a model of spatial memory and updating with the following properties:

1. Interobject spatial relations are specified in an intrinsic reference system using a small number (one or two) of reference directions.
2. The initially selected reference system is not typically updated during locomotion. Updating appears to occur only when subsequent learning experiences are aligned with salient axes in the environment.
3. To the extent that self-to-object spatial relations are represented separately from the intrinsic-reference-system-based representation, they do not seem to be maintained for moderately large numbers of objects under conditions of reduced perceptual support.
4. The location and orientation of the observer are specified and updated in the same reference system used to represent the spatial structure of the environment.

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