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Sensorimotor Alignment Effects in the Learning Environment and in Novel Environments

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Four experiments investigated the conditions contributing to sensorimotor alignment effects (i.e., the advantage for spatial judgments from imagined perspectives aligned with the body). Through virtual reality technology, participants learned object locations around a room (learning room) and made spatial judgments from imagined perspectives aligned or misaligned with their actual facing direction. Sensorimotor alignment effects were found when testing occurred in the learning room but not after walking 3 m into a neighboring (novel) room. Sensorimotor alignment effects returned after returning to the learning room or after providing participants with egocentric imagery instructions in the novel room. Additionally, visual and spatial similarities between the test and learning environments were independently sufficient to cause sensorimotor alignment effects. Memory alignment effects, independent from sensorimotor alignment effects, occurred in all testing conditions. Results are interpreted in the context of two-system spatial memory theories positing separate representations to account for sensorimotor and memory alignment effects.

Keywords: spatial memory, spatial updating, sensorimotor interference, perspective taking, alignment effect

An everyday task such as providing a friend with directions to one's home can entail imagining the friend's perspective and telling him or her whether to turn left or right at intersections. The ease with which a person can reason from a perspective and/or location other than one's own has been shown to depend on at least three factors: the perspectives one experienced when learning the imagined space (Diwadkar & McNamara, 1997; Shelton & McNamara, 1997), the structure of the space itself (McNamara, Rump & Werner, 2003; Mou & McNamara, 2002; Shelton & McNamara, 2001; Werner & Schmidt, 1999), and the position and orientation of the person's body during recall (May, 2004; Mou, McNamara, Valiquette, & Rump, 2004; Presson & Montello, 1994; Rieser, 1989). Reasoning about space is often easier from perspectives aligned rather than misaligned with salient reference frames (e.g., environmental reference frames or the body's reference frame). This empirical result is termed an alignment effect. Herein, we distinguish between two kinds of alignment effects. We refer to the advantage of responding from imagined perspectives that are aligned rather than misaligned with the body during retrieval as a *sensorimotor alignment effect*. As an example, the reader is invited to close his or her eyes and imagine the immediate surrounds from his or her current location and orientation in the environment. The reader is then asked to try to imagine how things would look if he or she were to rotate in place 180°. The increased difficulty after imagined rotation is an example of a sensorimotor alignment effect. Additionally, we refer to the advantage of reasoning from a perspective aligned rather than misaligned with the reference frames used to encode an environment in long-term memory as a *memory alignment effect*. For example, imagining the layout of buildings downtown is often easier when the imagined perspective is aligned compared with misaligned with major city streets (see Werner & Schmidt, 1999).

These sensorimotor and memory alignment effects have typically been studied separately (but see Mou, McNamara, et al., 2004). Whereas the sensorimotor alignment effect has been documented in spatial updating experiments, the memory alignment effect has been reported in experiments investigating the organizational structure of spatial memory. In fact, studies have often confounded the two effects by asking participants to report locations from perspectives aligned with both their physical perspective and a preferred orientation of long-term spatial memory. The goal of the present study is to examine these two effects by dissociating the physical perspective from the perspective that we believe determines the primary orientation of spatial memory. We present our findings in the context of recent models positing the presence of two systems of spatial memory.

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To preview, we begin with a review of the evidence supporting prominent two-system accounts of spatial memory. These theories explain results from perspective-taking tasks and related phenomena by proposing separate systems for representing egocentric (self-centered) and allocentric (environment-centered) spatial relations. Following this overview is a summary of four experiments aimed at further specifying the role of body location and orientation in the retrieval process. In particular, these studies focus on differences in spatial memory retrieval when recall takes place in either the learning environment or in a neighboring environment. In all four experiments, alignment effects are interpreted as evidence for specific types of reference frames used to store and retrieve spatial memories.

Spatial Updating and Retrieval/Response Effects

In typical spatial updating tasks, participants are asked to indicate the egocentric locations of previously viewed objects after movement to a novel standpoint. In many such experiments, movement to the novel standpoint requires rotation and/or translation, is achieved through physical or imaginal motion, and includes one or many cues to self-motion. This research has revealed that people are quite capable of updating egocentric locations of objects as they physically rotate and translate through space, even without vision (Philbeck, Loomis & Beall, 1997; Rieser, 1989). In stark contrast, egocentric updating after imagined self-motion (especially rotation) can be quite error-prone. Rieser instructed participants to learn the locations of 9 objects spaced evenly in a circle around them. In later testing (after perceptual access to the targets was removed), participants rotated either physically or imaginally and then, after rotation, pointed to the updated object locations. Errors and response latencies increased with increasing imagined, but not physical, rotation. In another experiment, Rieser showed that this cost of imagined rotation does not exist for imagined translation. When participants imaginally translated to the object locations (i.e., imagined changing their position but not their orientation), performance was overall quite good. However, there was a fundamental difference between the translation and rotation tasks in this experiment: Rotations resulted in larger object-bearing changes than did translations. Even when the object-bearing changes for the two movement types are equated, however, imagined rotations are still more difficult than are imagined translations (May, 2004; Presson & Montello, 1994).

Presson and Montello (1994; also see Easton & Sholl, 1995) proposed that the difficulty associated with imagined rotations could be due to a reference frame conflict between the imagined perspective and the participant's actual perspective. Based in part on this theory, May (2004) suggested that sensorimotor interference could explain why performance is worse when pointing to remembered object locations after imagined compared with physical movements. His theory is founded, in part, on the idea that the object bearings relative to the observer's actual position and orientation in the environment (stored in the form of sensorimotor location codes) interfere with the object bearings relative to the observer's imagined position and orientation in the environment (stored in the form of cognitive location codes) after imagined self-motion. May (2004) defined *object direction disparity* as the discrepancy between sensorimotor and cognitive object location codes after imagined movement (the difference between β_1 and β_2 in Figure 1) and suggests that increased object direction disparity results in increased task difficulty, regardless of the movement type (translation or rotation). To test this theory, May independently manipulated object direction disparity in a task similar to those used by Rieser (1989) and Presson and Montello (1994), where participants pointed to objects after imagined rotations or translations. As hypothesized, May found that increased object direction disparity resulted in increased errors and response latencies for both imagined translations and rotations. In addition, imagined rotations were more difficult than imagined translations by a roughly constant amount. May hypothesized that this constant performance difference between imagined translation and rotation was due to a second factor: head direction disparity, or the angular difference between one's actual and imagined perspectives. May claims that this is the primary reason for previously reported performance differences between imagined rotations and translations. Head direction disparity becomes problematic when the participant has selected the correct response from the imagined perspective (e.g., standing at A, facing B, point to C) but then must execute the response using the body in its actual location in the environment. This is similar to the theory based on reference frame conflict presented by Presson and Montello.

Allocentric Spatial Memory and Encoding Effects

During the encoding of a layout, there are at least two factors that can influence the subsequent recall of the layout from long-term memory: egocentric experience and environmental structure. Specifically, these two factors provide reference frames that can be used during the encoding of a spatial scene and are by no means mutually exclusive. Their presence is often detected by the result-

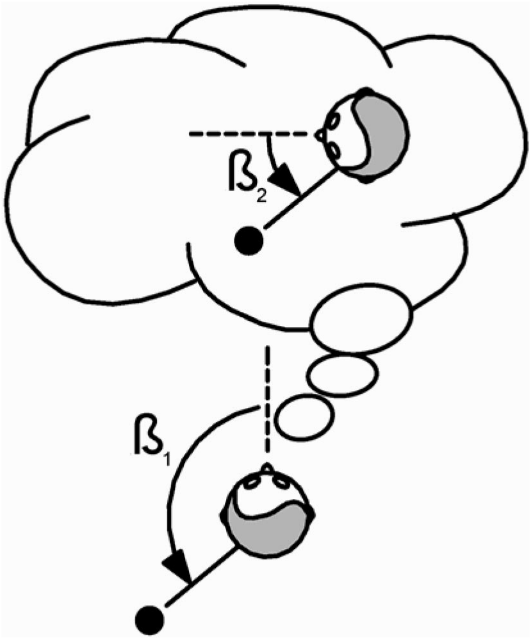

Figure 1. Illustration of object direction disparity (May, 2004). β_1 represents the object bearing from the observer's actual facing direction, and β_2 represents the same object's bearing from the observer's imagined perspective. Object direction disparity is defined as β_1 minus β_2.

ant alignment effects, whereby offline memory retrieval (i.e., when recalling a distant environment that one is not currently occupying) is facilitated (inhibited) when the recalled perspective is aligned (misaligned) with the reference frame used during encoding. A popular method for testing retrieval is to use judgments of relative direction (JRDs), in which participants are asked to imagine a specific location and orientation and then point to another object from that perspective (e.g., "Imagine standing at the library, facing the psychology building. Point to the chemistry building.").

Early evidence suggested that spatial memories are egocentric in nature, where views experienced during learning are used to structure the locations of objects within the scene. Shelton and McNamara (1997; see also Diwadkar & McNamara, 1997) found that accessing spatial memories was easiest from the perspective(s) experienced during learning, suggesting that egocentric experience served to establish a preferred orientation in memory and that object locations were defined with respect to that preferred orientation. However, it is now recognized that the structure of the scene itself plays a critical role in reference frame selection, and that the reference frames selected through egocentric experience alone persist only when the environmental structure does not provide a stronger reference frame.

Environmental structures, such as the rectangular walls of a room (Hintzman, O'Dell, & Arndt, 1981; Shelton & McNamara, 2001), the rectilinear grid of city streets (Montello, 1991; Werner & Schmidt, 1999), and nearby buildings and lakes (McNamara et al., 2003) can all provide salient environmental reference frames used to structure spatial memories. Shelton and McNamara (2001) proposed that reference frames are chosen on the basis of a combination of egocentric experience and environmental structure such that experienced views aligned with salient environmental features are more likely to be used as reference frames in memory than views misaligned with the environment. Other findings, however, have qualified this theory by showing that even nonexperienced orientations can be represented under the appropriate conditions. Mou and McNamara (2002) instructed participants to learn a set of objects arranged in rows and columns, viewed from a single perspective that was misaligned with the intrinsic structure of the objects. The experimenter encouraged participants, through verbal instruction, to learn the objects along these rows and columns rather than from their actual perspective. Subsequent recall showed that spatial memories for the objects were structured around the object-defined columns, even though participants never experienced this perspective. This does not refute Shelton and McNamara's (2001) theory of the interaction between egocentric experience and environmental structure but instead modifies it to include a role for other, nonspatial cues that can influence the selection of environmental reference frames.

Taken together, these results show that egocentric experience, environmental structure, and task demands can all combine to create reference frames used to store spatial memories. The resulting alignment effects are readily observed in offline testing and are referred to as memory alignment effects, as they appear to depend primarily on the structure of long-term memory.

Multiple Systems of Spatial Memory

Many prominent theories of spatial memory have proposed separate systems to account for findings from long-term spatial memory research and spatial updating research. These separate systems generally provide for (a) a working memory system (sometimes referred to as a sensorimotor system), which represents objects egocentrically and requires attention to maintain and (b) a long-term memory system which represents objects relative to one another or relative to some external reference frame. On the basis of the empirical findings reviewed above, we now evaluate the merits of two such models. One popular model proposed by Sholl (2001; Easton & Sholl, 1995) proposes an egocentric (self-reference) system, in which self-to-object locations are defined with respect to the front–back and left–right body axes, with privileged access to objects in front of the body (much empirical evidence supports this idea; Franklin & Tversky, 1990; Sholl, 1987; Werner & Schmidt, 1999). This self-reference system can operate as either a sensorimotor self-reference system, as when reasoning about the immediate environment, or a representational self-reference system, as when reasoning about a remote environment. This model also proposes an environment-defined allocentric system, where object locations are represented relative to other nearby objects in an orientation-free manner in long-term memory. When immersed within an environment, the body's reference frame is imposed on this allocentric representation, providing access to object locations from the allocentric system by way of the sensorimotor self-reference system. When imagining a nonimmediate environment, the observer is able to access the allocentric system through the representational self-reference system, which functions similarly to the sensorimotor system but with equal access to all orientations. Importantly, the concept of an orientation-free allocentric system does not fit well with more recent findings indicating that allocentric memories are structured according to reference frames, with preferred access to specific orientations (e.g., Mou & McNamara, 2002).

Similar to Sholl's (2001) model, Mou, McNamara, et al. (2004) also proposed separate systems to represent egocentric and allocentric object locations. The proposed egocentric system can account for sensorimotor interference and facilitation, but the model also predicts that the egocentric representation is transient and fades quickly in the absence of perceptual support. Their proposed allocentric system represents object locations relative to the primary reference frame used in long-term memory, and fits well with the recent offline spatial memory literature. These researchers proposed that moving observers update their location relative to both systems, with egocentric updating allowing for online control of movement and allocentric updating allowing for maintenance of orientation within the remembered environment.

The four experiments that follow test the predictions of Sholl's (2001) and Mou, McNamara, et al.'s (2004) models of spatial memory regarding the presence of memory and sensorimotor alignment effects when reasoning about immediate and nonimmediate environments.

Experiment 1

In order to avoid sensorimotor effects altogether, many researchers interested in exploring the allocentric memory system choose to test participants' memories offline, after transport to an environment remote from the learning environment (Avraamides & Kelly, 2005; Brockmole & Wang, 2002; Diwadkar & McNamara, 1997; Mou & McNamara, 2002; Shelton & McNamara, 1997; Sholl, 1999; Sholl & Bartels, 2002; Werner & Schmidt, 1999). According to Mou, McNamara, et al.'s (2004) theory, movement to a remote location should result in deactivation of the egocentric object locations, which were acquired during learning. Sholl's (1999) theory makes a similar prediction, where the sensorimotor self-reference system is replaced with the representational self-reference system. It is therefore often assumed that testing in the remote environment is free from sensorimotor interference. It is reasonable to think that object direction disparity can be eliminated in this way, given that the sensorimotor codes of the actual object locations relative to the body are probably deactivated after transport to a remote environment. Indeed, work by Wang and Brockmole (2003) suggests that people actively maintain representations in working memory only for locations contained within their current environment and that a new set of objects and locations are activated on moving to a new environment. However, if people are able to maintain a representation of their heading during transport, then we might expect subsequent testing to still be affected by head direction disparity.

Experiment 1 was designed to test this hypothesis using immersive virtual reality technology. Participants learned a layout of eight virtual objects and were later asked to imagine different perspectives while standing in either the virtual learning environment or a neighboring, but novel, virtual environment. Participants actively walked, with vision, to this novel environment by walking 3 m forward (passing through a virtual wall dividing the two rooms) and turning 90°. Thus, the updating requirement was minimal, allowing participants to maintain an awareness of their own heading relative to both the learning and novel environments. Separate from the sensorimotor alignment effects, care was taken to minimize any salient reference frames that might result in memory alignment effects. However, egocentric experience has been shown to result in the selection of a reference frame based simply on the initially viewed perspective under learning procedures similar to those of Experiment 1 (Avraamides & Kelly, 2005). It was expected that any memory alignment effects would be present regardless of whether testing occurred in the learning or the novel environment, given that memory alignment effects should occur regardless of body orientation and position during recall. This prediction is based on work by Mou, McNamara, et al. (2004), which showed the separate contributions of memory and sensorimotor alignment effects.

Although the experiments described up to this point have all used real-world environments, there is growing evidence that virtual environment technology is a viable tool for understanding real-world spatial cognition. In the spatial updating realm, Williams, Narasimham, Westerman, Rieser, and Bodenheimer (in press) have demonstrated an equivalent sensorimotor alignment effect for real and virtual scenes. Other evidence suggests that spatial updating can occur naturally in a virtual environment so long as body-based cues (i.e., proprioceptive and vestibular) are present (Chance, 2000; Chance, Gaunet, Beall & Loomis, 1998; Kearns, Warren, Duchon & Tarr, 2002; Ruddle & Lessels, 2006), as was the case in the current experiments. Other work on long-term spatial memory has shown that the reference frames used to structure memories for virtual environments are affected by the interaction between egocentric experience and environmental structure (Kelly & McNamara, 2007), supporting similar conclusions from real-world environments (Mou & McNamara, 2002; Shelton & McNamara, 2001). Finally, the interaction between memory and sensorimotor alignment effects previously found with real-world scenes (Mou, McNamara, et al., 2004; Waller, Montello, Richardson, & Hegarty, 2002) has also been demonstrated with virtual environments (Mou, Biocca, et al., 2004), further supporting the use of virtual environments in the present experiments.

Method

Participants. Thirty-two undergraduate students (16 male) at the University of California, Santa Barbara, participated in exchange for course credit.

Stimuli. All experimental stimuli were displayed using a Virtual Research V8 head-mounted display (HMD) which presented stereoscopic images with 680 × 480 resolution and refreshed at 60 Hz. The HMD field of view was 50° horizontal by 38° vertical. Images were rendered by a 2.2 GHz Pentium 4 processor with a GeForce 4 graphics card, using Vizard software (from WorldViz, Santa Barbara, CA). The simulated viewpoint was updated based on head movements, produced by physical rotations and translations of the participant. Thus, participants walked through the virtual environment with full physical movement, just like they would when exploring a real environment. Head orientation was tracked by a three axis orientation sensing system (IS300 from InterSense Inc., Bedford, MA), and head location was tracked three-dimensionally by a passive optical position sensing system (Precision Position Tracker, PT X4 from WorldViz, Santa Barbara, CA). The total system latency did not exceed 100 ms.

The virtual environment consisted of two octagonal (three meter radius) rooms: a learning room and a novel room, depicted in Figure 2. The two rooms were adjacent to one another, but neither room could be seen while standing in the other room. The learning room contained eight objects placed on pillars which were evenly spaced around the room (each pillar stood centered against one of the eight walls). The pillars were 1.5 meters tall, and displayed the

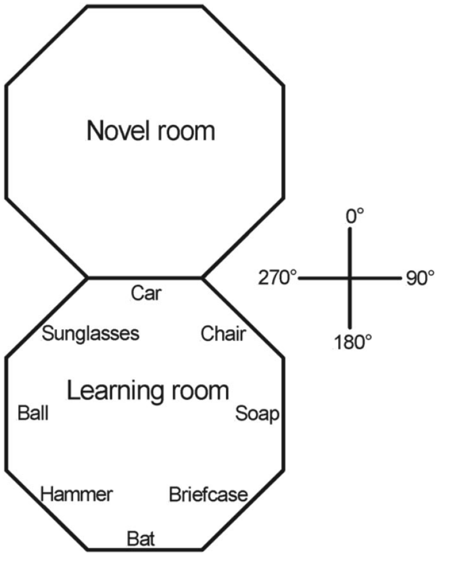

Figure 2. Room layouts used in Experiments 1 through 4.

object name in bright green text on the front of the pillar (Figure 3 displays the participant's view of one object). The first set of objects consisted of a hat, guitar, bug, plant, train, trumpet, boat, and chair. The second object set included a car, sunglasses, ball, hammer, bat, briefcase, soap, and pot. All objects were scaled to fit within a 30 cm cube. The walls of the learning room were covered with a wood texture and the walls of the novel room were covered with a brick texture to make them visually distinct, even after the objects were removed.

Design. In a 2 × 2 × 8, mixed factorial design, there were two levels of test environment (learning room or novel room), two levels of participant-facing direction at test (90° or 270°), and eight levels of imagined perspective (every 45° from 0° to 315°). Test environment was manipulated between participants, whereas physical facing direction and imagined perspective were manipulated within participants.

Procedure. Participants were first placed in the center of the learning room facing 0°. During the learning phase of the experiment, participants were given unlimited time to learn the locations of all eight objects. No more than two objects were visible simultaneously because of the limited horizontal field of view of the HMD. Thus, participants had to turn in place to study each object.

A sequence of 16 practice trials began once participants felt they had memorized all of the objects. All objects remained visible throughout the practice. Participants were presented with statements of the form: "Face: *x,* Find: *y,*" where *x* and *y* were different objects from the set they had just learned. During practice, participants physically turned to face the first object, and then used a joystick to point to the second object. They performed two practice trials while facing each object. Although the joystick measured angles continuously from 0 to 360°, the responses were quantized in 45° increments. This was done because the object locations themselves were spaced every 45°, and this spatial regularity was made clear to participants during learning. Any errors during practice were verbally corrected by the experimenter. After completion of the 16 practice trials, participants were given another opportunity to inspect the objects. Most participants chose to do so for an additional 10 to 30 seconds. When participants decided they were ready for the test trials, they turned to face 0° and the objects were subsequently removed from the scene.

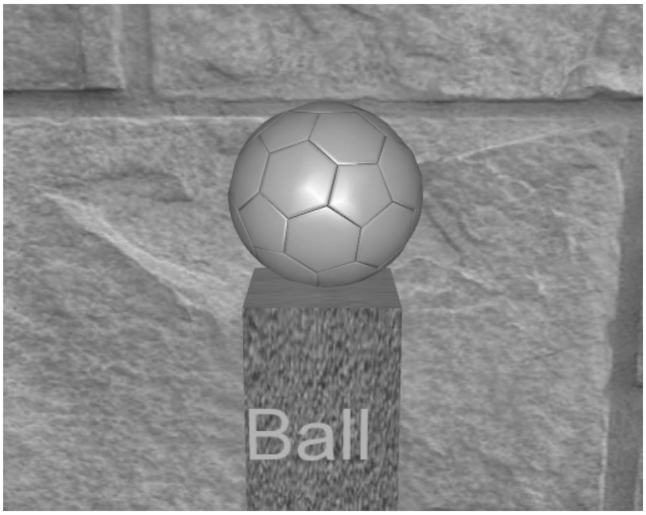

Figure 3. The participant's view of one of the eight objects in the learning room.

If participants were to be tested in the novel room, they walked straight forward through the virtual wall they were facing (0°) and walked to the center of the novel room. At this point, regardless of the test room condition, participants turned 90° to their right or left to assume facing directions of either 90° or 270°. After turning, participants in the novel environment were asked to point back toward the learning room to ensure that they had updated their change in location and orientation. All participants were able to do this successfully.

Once participants were repositioned, the joystick was placed on a stand in front of them and they were provided with instructions. They were told that the test trials were essentially the same as the practice trials, except now they were to imaginally (rather than physically, as during practice) assume the indicated facing direction as though they were standing in the center of the learned objects. Once they imagined the new perspective, they were to indicate the location of the second object from the imagined perspective by pointing with the joystick. All participants were instructed to respond as quickly as possible to each trial without sacrificing accuracy. Any pointing response deviating more than ± 22.5° from the correct response direction was considered an error.

After each response the next trial immediately appeared. Participants completed 56 trials, consisting of eight imagined perspectives crossed with seven possible object locations (participants were never asked to face and find the same object on a single trial). Trial order was pseudo-randomized, with the constraint that the same object would never appear in consecutive trials (neither as an orienting nor a pointing target). Thus, the imagined perspective changed on every trial. After completion of the 56 trials, participants removed the HMD and took a two to five minute break before starting the second session. During the second session, participants learned a new object set in the learning room and faced the opposite direction at test (e.g., if they faced 90° in the first session, they turned to face 270° in the second session).

Results

Response latency. Figures 4 and 5 show mean response latency[1] as a function of imagined perspective when testing occurred in the learning room and the novel room, respectively. The response latency data were analyzed with a 2 (test room: learning or novel) × 2 (physical facing direction: 90° or 270°) × 8 (allocentric imagined perspective: 0° to 315° in 45° increments) mixed-model analysis of variance (ANOVA). For response time, the main effect of imagined perspective was significant, $F(7, 210) = 20.38$, $p < .001$, $\eta_p^2 = .41$, qualified by significant interactions between physical facing direction and imagined perspective, $F(7, 210) = 5.37$, $p < .001$, $\eta_p^2 = .15$, and between physical facing direction, imagined perspective, and test room, $F(7, 210) = 3.18$, $p = .003$, $\eta_p^2 = .10$.

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[1] In these experiments, response times represent all trials, both correct and incorrect. When incorrect trials are removed, the response time patterns are very similar for all four experiments. However, this results in a loss of approximately 20% of the data in each experiment. All analyses reported include both correct and incorrect trials.

In light of this three-way interaction, we conducted separate 2 (physical facing direction) × 8 (imagined perspective) ANOVAs to assess the interaction between physical and imagined perspectives within each environment. Analysis of the response time data when testing occurred in the learning room showed a significant main effect of imagined perspective, $F(7, 105) = 12.34$, $p < .001$, $\eta_p^2 = .45$, and a significant interaction between physical and imagined perspective, $F(7, 105) = 9.54$, $p < .001$, $\eta_p^2 = .39$. Driving this interaction is the finding that trials aligned with the body (e.g., an imagined perspective of 90° when physically facing 90°) were faster than trials misaligned with the body ($ps<.05$), with the exception of the 0° imagined perspective. Similar analysis of the response time data when testing occurred in the novel room showed a significant main effect of imagined perspective, $F(7, 105) = 9.38$, $p < .001$, $\eta_p^2 = .39$, and no interaction between physical and imagined perspective, $F(7, 105) = 0.34$, *ns*, $\eta_p^2 = .02$.

To more directly assess the presence of memory and sensorimotor alignment effects, the response latency data were grouped into three trial types: original (when imagined perspective was equal to the original view of 0°), sensorimotor aligned (when imagined and actual perspectives were the same), and misaligned (when the imagined perspective was diametrically opposite from the actual perspective).[2] For each participant, responses to trials in each category were averaged. The reorganized data are shown in Figure 6. Response times were then reanalyzed in a 2 (test room) × 3 (perspective) ANOVA, showing a main effect of perspective, $F(2, 60) = 37.37$, $p < .001$, $\eta_p^2 = .56$, and an interaction between perspective and test room, $F(2, 60) = 5.05$, $p = .009$, $\eta_p^2 = .14$. Within-subject contrasts revealed a sensorimotor alignment effect (i.e., better performance on sensorimotor aligned compared with misaligned trials) when testing occurred in the learning environment, $F(1, 15) = 33.88$, $p < .001$, $\eta_p^2 = .69$, but not in the novel environment, $F(1, 15) = 0.03$, *ns*, $\eta_p^2 = .002$. Memory alignment effects (i.e., better performance on the original compared with the misaligned trials) occurred in both the learning, $F(1, 15) = 35.98$, $p < .001$, $\eta_p^2 = .71$, and novel, $F(1, 15) = 29.67$, $p < .001$, $\eta_p^2 = .66$, environments.

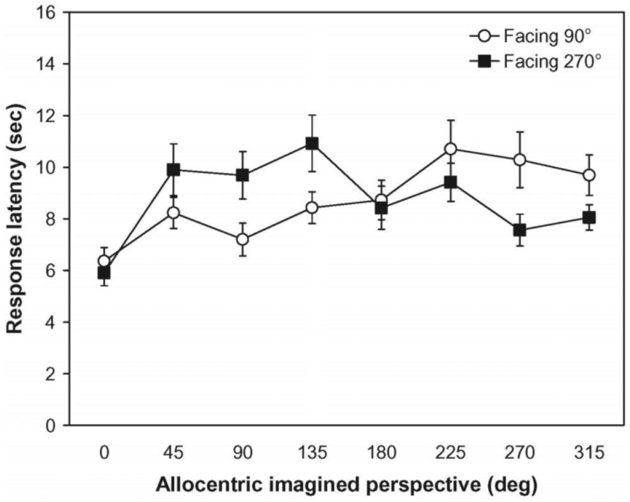

Figure 4. Mean response latency in Experiment 1 when testing occurred in the learning environment. Latency is plotted as a function of allocentric imagined perspective for physical facing directions of 90° and 270°. Error bars are standard errors that include between-participants variation.

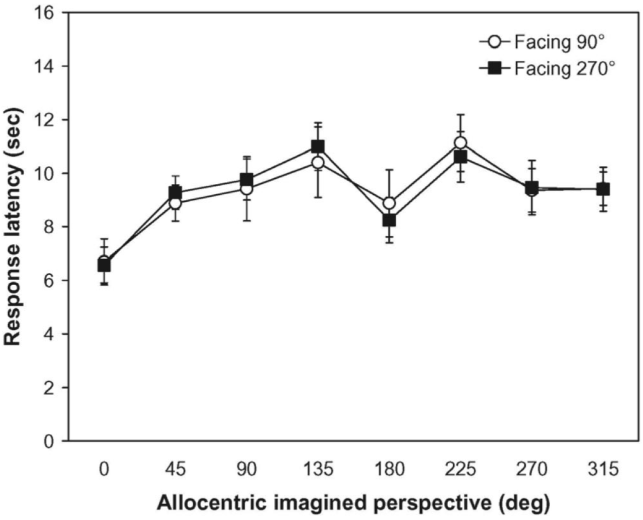

Figure 5. Mean response latency in Experiment 1 as a function of allocentric imagined perspective when testing occurred in the novel environment. Error bars are standard errors that include between-participants variation.

Error rate. The accuracy data (presented in Table 1) were also analyzed with a 2 (test room: learning or novel) × 2 (physical facing direction: 90° or 270°) × 8 (imagined perspective: 0° to 315° in 45° increments) mixed-model ANOVA. The main effect of imagined perspective was significant, $F(7, 210) = 7.82$, $p < .001$, $\eta_p^2 = .21$ but was qualified by a significant interaction between physical and imagined perspective, $F(7, 210) = 4.00$, $p < .001$, $\eta_p^2 = .12$.

After reorganizing the accuracy data by imagined perspective (either original, sensorimotor aligned, or misaligned), we conducted a 2 (test room) × 3 (alignment) ANOVA. The main effect of imagined perspective, $F(2, 60) = 21.46$, $p < .001$, $\eta_p^2 = .42$, was qualified by an interaction between perspective alignment and test environment, $F(2, 60) = 3.64$, $p = .03$, $\eta_p^2 = .11$. Within-subject contrasts revealed a sensorimotor alignment effect when testing occurred in the learning environment, $F(1, 15) = 13.74$, $p = .002$, $\eta_p^2 = .48$, but not when testing occurred in the novel environment, $F(1, 15) = 2.05$, *ns*, $\eta_p^2 = .12$. Memory alignment effects occurred in both the learning, $F(1, 15) = 26.95$, $p < .001$, $\eta_p^2 = .64$, and novel, $F(1, 15) = 10.37$, $p = .006$, $\eta_p^2 = .41$, environments.

There was no evidence of a speed–accuracy tradeoff, indicated by the positive correlations between response latency and error rate for both same room testing, $r(46) = .51$, $p < .01$, and the novel room testing, $r(46) = .51$, $p < .01$.

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[2] The sensorimotor aligned and misaligned perspectives were chosen because they were equidistant from the learning perspective, and therefore any difference between those two would reflect only the sensorimotor influence.

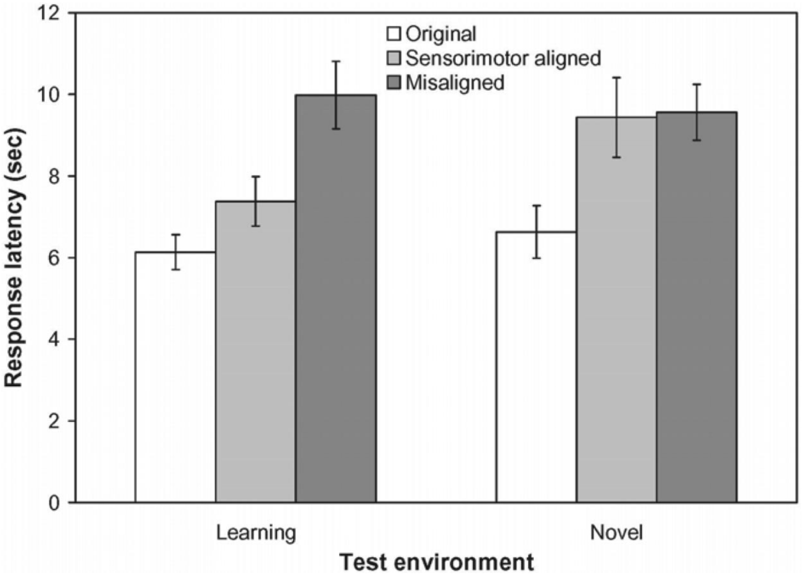

Figure 6. Mean response latency in Experiment 1, grouped by perspective type and test environment. Error bars are standard errors that include between-participants variation.

Discussion

Replicating previous findings (May, 2004; Rieser, 1989), participants in Experiment 1 showed clear evidence of a sensorimotor alignment effect when tested in the learning room. Responses were faster and more accurate for imagined perspectives aligned with the body than for perspectives misaligned with the body. In contrast to the learning room data, the distinction between trials aligned and misaligned with the body disappeared when testing occurred in the novel room, similar to what would be expected after disorientation (May, 1996).

This pattern of results supports the predictions made by both the models of Sholl (2001) and Mou, McNamara, et al. (2004). According to Sholl's model, when participants are tested in the learning room, the egocentric self-reference system operates at a perceptual–motor level. Therefore, it not surprising that its orientation affects performance. However, when participants are tested away from the learning environment the egocentric system operates at the representational rather than the perceptual–motor level. As a result, no sensorimotor influence should be expected in that condition. The Mou, McNamara, et al. model includes a sensorimotor system that represents egocentric object locations of the immediate environment. Therefore, this model predicts that the orientation of the egocentric system should affect performance when participants are tested within the learning room. Furthermore, Mou, McNamara, et al. described the egocentric system as transient, decaying quickly without perceptual support. Therefore, their model suggests that when participants walked into the novel room, the egocentric representation had faded. This could explain the lack of sensorimotor interference with testing in the novel room.

Despite these accounts, we consider the implications if participants actually did maintain an egocentric representation of the learned objects after walking into the novel room. In this case, following May's sensorimotor interference theory, the sensorimotor aligned and misaligned perspectives would both incur the cost of object direction disparity. This cost would occur because the imagined object bearings are different from the actual bearings of the objects in the room next door, for both the sensorimotor aligned and misaligned perspectives. However, only the misaligned perspective would incur the cost of head direction disparity, and we would therefore still expect to find a sensorimotor alignment effect in the novel room, which did not occur. There-

Table 1
Mean Error Rates (and Standard Errors) in Experiment 1

	Imagined perspective							
Condition	0°	45°	90°	135°	180°	225°	270°	315°
Learning room								
Facing 90°	.16 (.04)	.21 (.05)	.15 (.04)	.25 (.06)	.19 (.05)	.34 (.06)	.35 (.06)	.24 (.04)
Facing 270°	.09 (.03)	.25 (.05)	.24 (.05)	.27 (.06)	.25 (.06)	.24 (.06)	.16 (.04)	.22 (.06)
Novel room								
Facing 90°	.09 (.04)	.15 (.05)	.10 (.04)	.16 (.06)	.06 (.05)	.21 (.06)	.14 (.06)	.18 (.04)
Facing 270°	.07 (.03)	.21 (.05)	.19 (.05)	.23 (.06)	.16 (.06)	.21 (.06)	.14 (.04)	.26 (.06)

fore, we maintain that the sensorimotor representation of the learned objects was no longer active upon testing in the novel room.

Of additional interest is the presence of memory alignment effects when testing occurred in either room. This is seen in the faster and more accurate responses when imagined perspectives were aligned with the original view experienced during learning (0°). As expected, this memory alignment effect appeared regardless of the test location, suggesting that it truly is due to encoding of the scene and is not specific to body orientation or position at retrieval. Again, this result supports predictions made by Mou, McNamara, et al.'s (2004) theory, which posits that allocentric memory is organized around reference frames defined by experience within the environment and the structure of the environment itself. The finding that allocentric memories were organized with respect to the 0°–180° axis defined by the initial view replicates work by Avraamides and Kelly (2005) who also found that this reference frame persisted even after participants had extensive experience with other views of the environment.

The Mou, McNamara, et al. (2004) theory presents at least two possible explanations for the changing sensorimotor effect after movement to the novel environment. The first possibility is that the egocentric representation simply decays with time and that more time elapsed when testing occurred in the novel as compared with the learning environment as a result of the physical movement required when walking there. However, the distance between the two rooms was only 3 m, and the added time required to walk to the novel room did not cause a substantial increase in the delay between learning and testing. The second possibility offered by Mou, McNamara et al.'s theory is that perceptual support for the egocentric system, perhaps provided by the familiar texture on the room walls, was removed after walking to the novel room, which had a distinct room texture. To further investigate these two alternatives, participants in Experiment 2 underwent the same learning as in the previous experiment. After learning, participants were tested in the novel environment and then, without viewing the objects again, returned to the learning environment for further testing. If the perceptual support provided by the learning environment was responsible for the activation and deactivation of the egocentric system in Experiment 1, then the sensorimotor alignment effect could, in principle, return upon walking back into the learning environment. Experiment 2 tested this hypothesis. On the basis of Experiment 1, we expected that memory alignment effects would occur regardless of the test environment.

Experiment 2

The same stimuli and learning procedures from Experiment 1 were used again in Experiment 2. The primary change in Experiment 2 was that participants were tested over two blocks of trials, without viewing the objects again between blocks. In one condition, the first trial block was performed in the novel environment, and the second block was performed after walking back into the learning environment. A second condition was added as a control to determine whether any potential differences between Blocks 1 and 2 were due to the test environment and not just to practice. In this control condition, participants completed both trial blocks in the learning environment.

Method

Participants. Sixteen (8 male) undergraduate psychology students participated in exchange for course credit.

Design. Using a within-participant design, all participants learned the locations of two sets of objects over the course of the experiment, one for each room order condition. After learning and practice were complete, participants completed two blocks of test trials in each condition. The location of the participant during these two test blocks varied depending on their room order condition. In one room order (switch), participants walked into the novel room to perform the first block of trials and then walked back into the learning room to complete the second block of trials. In the other room order (stay) participants completed both blocks of trials in the learning room. The stay condition was included as a control for any practice effects. Participant facing direction was counterbalanced, such that participants who faced 90° during the first trial block faced 270° during the second trial block, and vice versa. Within each trial block, participants were asked to imagine perspectives that were (a) parallel with the original study view, (b) aligned with their physical facing direction at test, or (c) completely (180°) misaligned with their facing direction at test (and also misaligned with the original study view by an amount equivalent to the view aligned with their facing direction at test). As an example, a participant who turned to face 90° at test would be asked to imagine perspectives of 0° (original view), 90° (sensorimotor aligned view), and 270° (misaligned view). Thus, the design was a 2 (room order) × 2 (test block) × 3 (imagined perspective) factorial design.

Procedure. Learning and practice procedures were identical to Experiment 1. Like before, participants first experienced the learning room while facing 0°. After learning and practice were complete, participants in the switch condition walked into the novel room and turned to face either 90° or 270°, just as they did in Experiment 1. The joystick was then placed in front of them and they began the test. Participants completed the first block of 21 trials, consisting of three imagined perspectives (original, sensorimotor aligned, or misaligned) crossed with seven possible object locations. Trials were pseudo-randomized as before. Upon completion of the first block of trials, participants in the switch condition were led back into the learning room. They were then instructed to turn and face either 90° or 270°, and the second block of 21 trials began. Participants in the stay condition remained in the learning room and turned to face 90° or 270° before completing the first block of 21 trials. Upon completion of the first block, they turned around 180° and completed the second trial block, remaining in the learning room for both testing blocks.

Results

Response latency. Figure 7 shows mean response times in each condition of Experiment 2. A 2 (switch or stay) × 2 (test block) × 3 (imagined perspective: original, sensorimotor aligned, or misaligned) repeated measures ANOVA was conducted with the response time data. There was a significant main effect of test block, $F(1, 15) = 19.32$, $p = .001$, $\eta_p^2 = .56$, and perspective, $F(2, 30) = 16.75$, $p < .001$, $\eta_p^2 = .53$, qualified by significant interactions between room order and imagined perspective, $F(2, 30) = 4.22$, $p = .02$, $\eta_p^2 = .22$, as well as room order, test block, and imagined perspective, $F(2, 30) = 3.54$, $p = .042$, $\eta_p^2 = .19$.

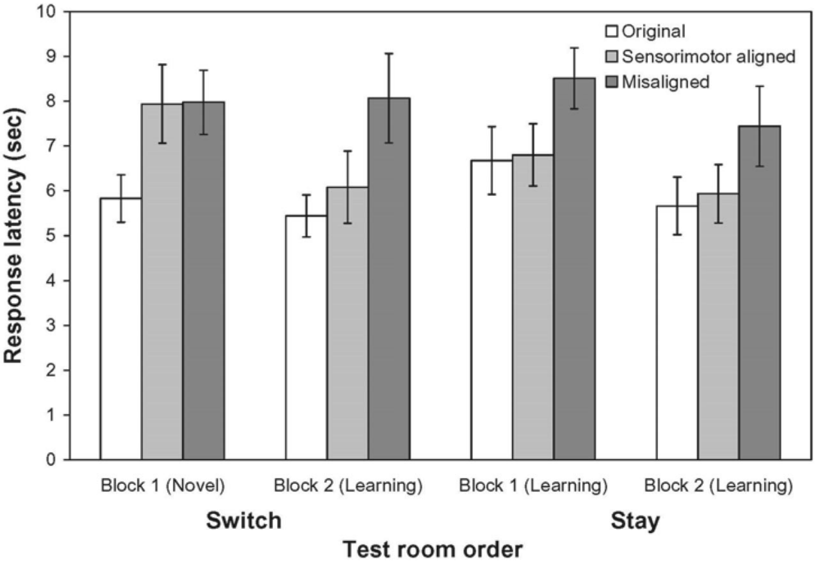

Figure 7. Mean response latency in Experiment 2 for Blocks 1 and 2 of the switch and stay conditions. Error bars are standard errors that include between-participants variation.

As seen in Figure 7, both of these interactions were driven by the increased response times in sensorimotor aligned trials when testing occurred in the novel as compared with the learning environment. No other interactions were significant.

Given the significant three-way interaction between room order, test block, and imagined perspective, separate 2 (test block) × 3 (imagined perspective) ANOVAs were conducted for the switch and stay conditions. In the switch condition, there were significant main effects of test block, *F*(1, 15) = 9.14, *p* = .009, η_p^2 = .38, and imagined perspective, *F*(2, 30) = 12.29, *p* < .001, η_p^2 = .45, and a marginal interaction between test block and imagined perspective, *F*(2, 30) = 2.91, *p* = .07, η_p^2 = .16. Within-subject contrasts revealed memory alignment effects in the first, *F*(1, 15) = 23.18, *p* < .001, η_p^2 = .61, and second, *F*(1, 15) = 13.29, *p* = .002, η_p^2 = .47, blocks of the switch condition. Sensorimotor alignment effects did not occur in the first block of the switch condition, *F*(1, 15) = 0.003, *ns*, η_p^2 = .00, but returned in the second block, *F*(1, 15) = 5.93, *p* = .03, η_p^2 = .28. In the stay condition, there were significant main effects of block, *F*(1, 15) = 5.73, *p* = .03, η_p^2 = .28, and imagined perspective, *F*(2, 30) = 16.86, *p* < .001, η_p^2 = .53, but no interaction between block and imagined perspective. Memory and sensorimotor alignment effects occurred in both the first [memory: *F*(1, 15) = 17.07, *p* = .001, η_p^2 = .53; sensorimotor: *F*(1, 15) = 32.28, *p* < .001, η_p^2 = .70] and second [memory: *F*(1, 15) = 13.41, *p* = .002, η_p^2 = .47; sensorimotor: *F*(1, 15) = 15.77, *p* = .001, η_p^2 = .51] test blocks of the stay condition.

Error rate. A 2 (switch or stay) × 2 (test block) × 3 (imagined perspective: original, sensorimotor aligned or misaligned) repeated measures ANOVA with the accuracy data (Table 2) showed main effects of room order, *F*(1, 15) = 6.36, *p* = .023, η_p^2 = .30; test block, *F*(1, 15) = 6.98, *p* = .018, η_p^2 = .32; and imagined perspective, *F*(2, 30) = 9.38, *p* = .001, η_p^2 = .39. Interactions between test block and imagined perspective, as well as between room order, test block, and imagined perspective were both significant, *F*(2, 30) = 3.32, *p* = .05, η_p^2 = .18, and *F*(2, 30) = 3.86, *p* = .032, η_p^2 = .21, respectively. Again, both interactions were driven by the poorer performance on sensorimotor aligned trials when testing occurred in the novel as compared with the learning environment. No other interactions were significant.

In light of the significant three-way interaction, we conducted separate 2 (test block) × 3 (imagined perspective) ANOVAs for the switch and stay conditions. In the switch condition, there was a significant main effect of imagined perspective, *F*(2, 30) = 6.54, *p* = .004, η_p^2 = .30, and a significant block by imagined perspective interaction, *F*(2, 30) = 6.05, *p* = .006, η_p^2 = .29. Within-subject contrasts revealed memory alignment effects in the first,

Table 2
Mean Error Rates (and Standard Errors) in Experiments 2–4

	Imagined perspective		
Condition	Original	Sensorimotor aligned	Misaligned
Experiment 2			
Switch			
Block 1	.16 (.04)	.35 (.07)	.29 (.06)
Block 2	.16 (.05)	.18 (.05)	.30 (.07)
Stay			
Block 1	.17 (.05)	.18 (.04)	.25 (.08)
Block 2	.11 (.03)	.16 (.06)	.22 (.06)
Experiment 3			
Learning room	.11 (.02)	.13 (.02)	.27 (.05)
Novel room	.15 (.04)	.18 (.04)	.27 (.05)
Experiment 4			
Visual-novel/Updated-novel	.09 (.02)	.17 (.07)	.25 (.07)
Visual-novel/Updated-same	.08 (.04)	.23 (.04)	.30 (.07)
Visual-same/Updated-novel	.06 (.02)	.21 (.07)	.22 (.07)
Visual-same/Updated-same	.15 (.04)	.08 (.04)	.20 (.07)

$F(1, 15) = 10.06$, $p = .006$, $\eta_p^2 = .40$, and second, $F(1, 15) = 10.06$, $p = .006$, $\eta_p^2 = .40$, blocks of the switch condition. Sensorimotor alignment effects did not occur in the first block of the switch condition, $F(1, 15) = 1.25$, *ns*, $\eta_p^2 = .08$, but returned in the second block, $F(1, 15) = 8.46$, $p = .01$, $\eta_p^2 = .36$. In the stay condition, there was only a marginal main effect of imagined perspective, $F(2, 30) = 3.01$, $p = .06$, $\eta_p^2 = .17$, and no interaction. Memory alignment effects were marginally significant in the first block, $F(1, 15) = 3.95$, $p = .07$, $\eta_p^2 = .21$, and significant in the second block, $F(1, 15) = 9.30$, $p = .008$, $\eta_p^2 = .38$, of the stay condition. Sensorimotor alignment effects did not occur in either the first, $F(1, 15) = 1.12$, *ns*, $\eta_p^2 = .07$, or the second, $F(1, 15) = 1.67$, *ns*, $\eta_p^2 = .10$, blocks of the stay condition.

There was no evidence of speed–accuracy tradeoff, as response latency and error rate were uncorrelated for both test blocks of the switch [Block 1: $r(46) = .10$, *ns*; Block 2: $r(46) = .15$, *ns*] and stay [Block 1: $r(46)=.27$, $p = .06$; Block 2: $r(46) = .06$, *ns*] conditions.

Discussion

Results from Experiment 2 showed that the deactivation of the learned egocentric object locations when testing occurred in the novel environment (evidenced by the lack of a sensorimotor alignment effect) was not due to elapsed time but rather to the lack of perceptual support afforded by the novel environment. This conclusion is based on the finding that sensorimotor interference returned when participants returned to the learning environment, suggesting that the egocentric representation of object locations is dependent on perceptual information indicating the observer's location. This is seen in the switch condition in Figure 7 by comparing Block 1 (where testing occurred in the novel room) and Block 2 (where testing occurred in the original room). The stay condition served as a control to verify that any changes between Blocks 1 and 2 in the switch condition were not due to practice effects or elapsed time. To that end, the responses were faster in the second block of trials in the stay condition, but this clearly does not account for the changing data pattern across Blocks 1 and 2 of the switch condition.

In addition to the sensorimotor alignment effects, results again showed evidence of a memory alignment effect, where memories were structured around the initially experienced perspective during learning. This memory alignment effect is evident in the improved performance for trials aligned with the original study view, regardless of test environment or test block.

In contrast to Experiments 1 and 2, recent work by May (2007; see also Rieser, Garing, & Young, 1994) suggests that the cognitive costs of imagining perspectives misaligned with the body might be comparable regardless of whether testing occurs in the learning environment or in a remote location. May (2007) instructed participants to learn a set of 14 objects and then tested them in either the learning room or a remote room (on a different floor of the building). Prior to testing, participants in both locations were blindfolded and told what direction they were currently facing (e.g., "You are now at object A, facing object B"). They were then asked to imagine what the environment would look like and where all of the objects should be located from this perspective, effectively anchoring them to a specific perspective prior to testing. For testing in the learning room, this anchoring perspective was consistent with the participants' actual perspective. In the remote room, this relationship was arbitrarily chosen. Participants then performed JRDs, which required them to imagine perspectives that were either aligned or misaligned with the anchoring perspective. Results were similar between the two testing environments: Responses were slower and more error prone on trials that were misaligned with the anchoring perspective.

The results obtained here in Experiments 1 and 2 differ from May's (2007) findings, but differences in methodology could account for this. Perhaps most importantly, May asked participants to imaginally immerse themselves in the learning environment prior to testing, even after they had been transported to the remote test site. In the current experiments, participants were given no such instructions. The other notable difference is that May's participants were blindfolded at test, which could have allowed them to cognitively immerse themselves in the learning environment. In contrast, participants in Experiments 1 and 2 had perceptual input from the novel environment, which could have made it more difficult to imagine the learning environment. Experiment 3 attempts to reconcile the seemingly opposing data by using instructions similar to those used by May.

Experiment 3

Stimuli and learning procedures were identical to those in Experiments 1 and 2. Participants were subsequently tested in the novel and learning environments, but the instructions prior to test (in both test environments) were modified to reflect those used by May (2007).

Method

Participants. Sixteen (8 male) undergraduate psychology students participated in exchange for course credit.

Design. In a 2 × 3 factorial design, there were two levels of test location (learning room and novel room) and three levels of imagined perspective (original, aligned, and misaligned). Both variables were manipulated within participants. Order of participant-facing direction at test (90° or 270°) was counterbalanced, and imagined perspective was pseudo-randomized as in the previous experiments.

Procedure. After completion of learning and practice, participants either stayed in the learning room or walked into the novel room and subsequently turned 90° to either the right or the left to assume facing directions of 90° or 270°. Regardless of the test environment, participants were instructed to imagine the objects surrounding them as though they were standing in the middle of the learning environment. Specifically, they were instructed to imagine a particular object in front of them (the object that was located at either 90° or 270° during learning, depending on whether the participant was actually facing 90° or 270° during testing). They were then told to imagine where the remaining objects would be located around them if they were actually facing the first object and were given unlimited time to imagine all of these egocentric object locations. Once participants were ready, they began 42 test trials consisting of three imagined perspectives (original, sensorimotor aligned, or misaligned) crossed with seven pointing directions and two repetitions. After completion, participants took a short break before learning a new object set. During the second test session, participants who completed Session 1 in the novel environment stayed in the learning environment for Session 2 and vice versa and faced the opposite direction (90° or 270°) at test.

Results

Response latency. Figure 8 shows mean response times in Experiment 3. We conducted a 2 (test environment) × 3 (imagined perspective: original, aligned, or misaligned) repeated measures ANOVA using the response time data. The only significant result was the main effect of imagined perspective, $F(2, 30) = 22.55$, $p < .001$, $\eta_p^2 = .60$. Within-subject contrasts showed significant memory alignment effects in the learning environment, $F(1, 15) = 25.35$, $p < .001$, $\eta_p^2 = .63$, and the novel environment, $F(1, 15) = 20.52$, $p < .001$, $\eta_p^2 = .58$, as well as significant sensorimotor alignment effects in the learning environment, $F(1, 15) = 21.80$, $p < .001$, $\eta_p^2 = .59$, and the novel environment, $F(1, 15) = 9.19$, $p = .008$, $\eta_p^2 = .38$.

Error rate. Similar analysis conducted with the accuracy data (Table 2) revealed only a significant main effect of imagined perspective, $F(2, 30) = 17.03$, $p < .001$, $\eta_p^2 = .53$. Contrasts showed significant memory alignment effects in the learning environment, $F(1, 15) = 12.00$, $p = .003$, $\eta_p^2 = .45$, and the novel environment, $F(1, 15) = 9.56$, $p = .007$, $\eta_p^2 = .39$, as well as significant sensorimotor alignment effects in the learning environment, $F(1, 15) = 14.35$, $p = .002$, $\eta_p^2 = .49$, and the novel environment, $F(1, 15) = 16.25$, $p = .001$, $\eta_p^2 = .52$.

There was no evidence of speed–accuracy tradeoff, as response latency and error rate were positively correlated for learning room testing, $r(46) = .55$, $p < .01$, and uncorrelated for novel room testing, $r(46) = .15$, *ns*.

Discussion

When given explicit instructions to imagine themselves surrounded by the test objects, participants in Experiment 3 showed a similar sensorimotor alignment effect (in both accuracy and reaction time) regardless of whether testing occurred in the learning or the novel environment. This is in contrast to Experiments 1 and 2, where there was no benefit of imagined perspectives aligned with the body when testing took place in the novel environment. As before, the predicted memory alignment effect was found in both environments and was unaffected by the changed instruction set.

Experiment 3 helps to reconcile Experiments 1 and 2 with the results reported by May (2007). In the context of the Mou, McNamara, et al. (2004) model, it appears that the egocentric representation of the learned objects is not naturally activated after movement to a novel environment. However, observers can willfully imagine the object locations from the learning environment in an egocentric manner that does invoke sensorimotor interference. It is impressive that they can do this, given the concurrent perceptual information telling them they were no longer in the learning environment. Mou, McNamara, et al. allowed for the possibility of deliberate rehearsal as a method of maintaining the egocentric representation, but they make no mention of how this rehearsal strategy might be applied to a non-immediate environment.

Similar to Experiment 3, Waller et al. (2002, Experiment 3) also showed that the egocentric system could be manipulated through experimenter instruction. After learning a four-point path from a single vantage point, participants were blindfolded and turned 180° prior to performing a perspective taking task. Half of the participants were told to imagine the path rotating with them as they turned so that they maintained the same perspective of the path even though they had rotated (essentially, they were told to ignore the effects of their rotation on the egocentric object locations). The other half were told to imagine the path staying fixed

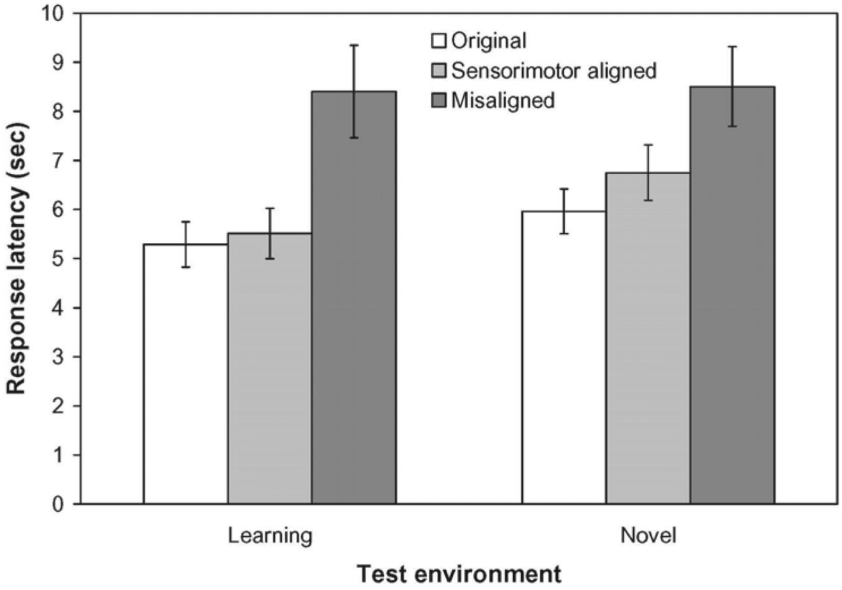

Figure 8. Mean response latency in Experiment 3 for the learning and novel environments. Error bars are standard errors that include between-participants variation.

to the physical world as they turned. The results indicated that participants who ignored the effects of their rotations showed a benefit for trials aligned with the initial viewing perspective, even though their bodies were 180° misaligned with this perspective. On the other hand, participants who were told to update relative to a fixed path during rotation showed the reverse effect, where trials aligned with the body (and therefore misaligned with the learning perspective) were easier than trials aligned with the learning perspective. Using a similar manipulation in virtual reality, Mou, Biocca, et al. (2004) demonstrated the same basic finding after showing participants that the virtual objects they had learned were actually yoked to their head movements. In this way, the objects always occupied the same egocentric locations, regardless of where the participant moved. Visual access to the objects was then removed, and the participants turned 90° before performing a sequence of JRDs. Performance indicated that participants continued to imagine the objects as though yoked to their own movements.

The results of Experiment 3 are also consistent with work by Avraamides (2003, Experiment 3), who instructed participants to learn a scene from descriptions in text. After learning, they performed an egocentric direction task after physically or imaginally turning to face a new perspective. Responses were faster after participants physically assumed the tested perspective, showing that they had recalled the objects in a sensorimotor framework, even though they never directly perceived the objects during learning. Similarly, participants in Experiment 3 learned a configuration of objects and, after moving to the novel room, were instructed to imagine those objects surrounding them, without ever receiving perceptual input that those objects existed in the novel room. In both Experiment 3 and Avraamides (2003), participants showed sensorimotor alignment effects for purely imaginary object locations.

Whereas Experiments 1–3 have identified some of the situations under which the online egocentric system is activated, the necessary conditions for this activation are not yet clear. For example, Experiments 1 and 2 suggest that the participant must be in the learning location in order for sensorimotor alignment effects to naturally occur (i.e., without special instructions like those used in Experiment 3). However, there were multiple sources of information that could have led participants to feel as though they were located in the learning or novel environments. In particular, Experiments 1 and 2 provided redundant information about the test location through vision and spatial updating. Not only was the novel environment visually distinct from the learning environment (i.e., the wall textures on the two environments were visually distinct), but the participants also walked 3 m to arrive in the novel room. One or both of these sources could be responsible for the findings of Experiments 1 and 2. Therefore, Experiment 4 was conducted to identify the importance of the visual and spatial similarities between the learning and test environments in activating the online egocentric system.

Experiment 4

By independently manipulating the updated location as well as the visual environment, Experiment 4 sought to identify the requisite components for sensorimotor interference to naturally occur. Specifically, by changing the wall texture of the test environment to be either identical to the wall texture of the learning environment or unique, the visual environment at test could be either the same as it was during learning or novel. Similarly, the updated environment, which was manipulated by having participants walk to one of two locations, could be either the same as the learning environment or different from the learning environment (i.e., 3 m away from the learning location). This was achieved by having the participant physically walk either into a neighboring room and stay there for testing or into the neighboring room and immediately turn around and walk back into the learning room.

Method

Participants. Thirty-two (16 male, 16 female) undergraduate psychology students participated in exchange for course credit. One participant was replaced after reporting simulator sickness and failing to complete the experiment.

Design. In a 2 × 2 × 3 mixed factorial design, there were two levels of the visual environment at test (“visual–novel” or “visual–same,” where the wall texture of the test environment was either unique or identical to the learning environment), two levels of the updated location at test (“updated–novel” or “updated–same,” where the participant walked to a new location 3 m away and either stayed there or walked back to the original location for testing), and three levels of imagined perspective (original, sensorimotor aligned, or sensorimotor misaligned). Figure 9 presents an illustration of the different combinations of visual and updated environments. The visual environment was manipulated by changing the visual texture of the room walls. The walls could either be textured to appear identical to the learning room or textured to appear unique. The visual environment was manipulated between participants, whereas the updated location and imagined perspective were both manipulated within participants. In both updating conditions (updated–same and updated–novel), participants walked 3 m out of the learning room prior to repositioning in their respective test environments so that both conditions had some updating requirement. The visual–novel/updated–novel condition

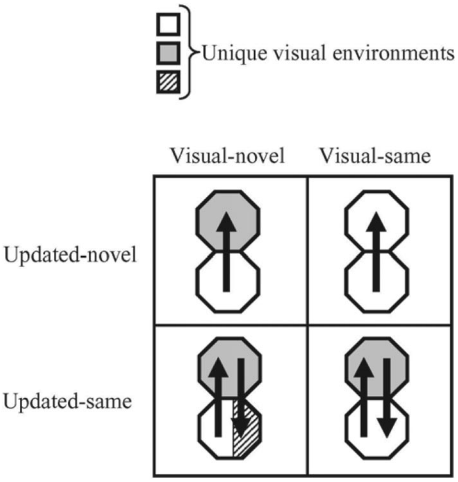

Figure 9. Illustration of the four combinations of visual environment (same or novel) and updated environment (same or novel) used in Experiment 4.

was the same as the novel room condition of Experiment 1, where participants physically moved to a novel location and the walls of the test room were visually distinct from the walls of the learning room. In the visual–novel/updated–same condition, participants walked out of the learning room, then immediately turned around and returned to the learning location to find that the wall texture had changed. In the visual–same/updated–novel condition, participants walked to a novel location where the test room was visually identical to the learning room. In the visual–same/updated–novel location, participants walked out of the learning room and turned around and walked back into the learning room, which was left unchanged in their absence. In all conditions, the learning and test rooms both had the same octagonal geometric structure used in Experiments 1–3.

Procedures. Learning and practice procedures were identical to those of Experiments 1–3. Upon completion of practice, the objects were removed and the participant was repositioned prior to testing. Participants in the updated–novel conditions walked forward 3 m into the neighboring room and turned 90° to the left or right prior to testing. The visual environment was either the same as the learning environment (visual–same) or unique (visual–novel). In both cases, the procedure was the same. Participants in the updated–same condition also walked forward 3 m into the neighboring room, but then immediately turned around 180° and returned to the learning room and turned 90° to the left or right. The visual environment (i.e., the wall texture) upon return to the learning room was either unchanged (visual–same) or changed (visual–novel). Task instructions were the same as in Experiments 1 and 2. Participants completed 21 trials and took a short break in between conditions before learning a new object set.

Results

Response latency. Mean response times in Experiment 4 are plotted in Figure 10. A 2 (visual environment: same or novel) × 2 (updated environment: same or novel) × 3 (imagined perspective: original, sensorimotor aligned, or misaligned) mixed-model ANOVA was conducted with the response time data. The main effect of imagined perspective was significant, $F(2, 60) = 56.50$, $p < .001$, $\eta_p^2 = .65$. Of greater interest was the significant interaction between imagined perspective and visual environment, $F(2, 60) = 3.64$, $p = .032$, $\eta_p^2 = .11$, resulting from the larger sensorimotor alignment effect for the visual–same compared with the visual novel conditions, $F(1, 30) = 6.69$, $p = .015$, $\eta_p^2 = .18$. No other interactions were significant. Memory alignment effects occurred in all four conditions, visual–novel/updated–novel: $F(1, 15) = 33.35$, $p < .001$, $\eta_p^2 = .69$; visual–novel/updated–same: $F(1, 15) = 45.03$, $p < .001$, $\eta_p^2 = .75$; visual–same/updated–novel: $F(1, 15) = 21.48$, $p < .001$, $\eta_p^2 = .59$; visual–same/updated–same: $F(1, 15) = 24.95$, $p < .001$, $\eta_p^2 = .63$. Sensorimotor alignment effects did not occur in the visual–novel/updated–novel condition, $F(1, 15) = 1.52$, *ns*, $\eta_p^2 = .09$, but did occur in the other three conditions, visual–novel/updated–same, $F(1, 15) = 39.50$, $p < .001$, $\eta_p^2 = .73$; visual–same/updated–novel, $F(1, 15) = 12.93$, $p = .003$, $\eta_p^2 = .46$; visual–same/updated–same, $F(1, 15) = 14.12$, $p < .001$, $\eta_p^2 = .49$.

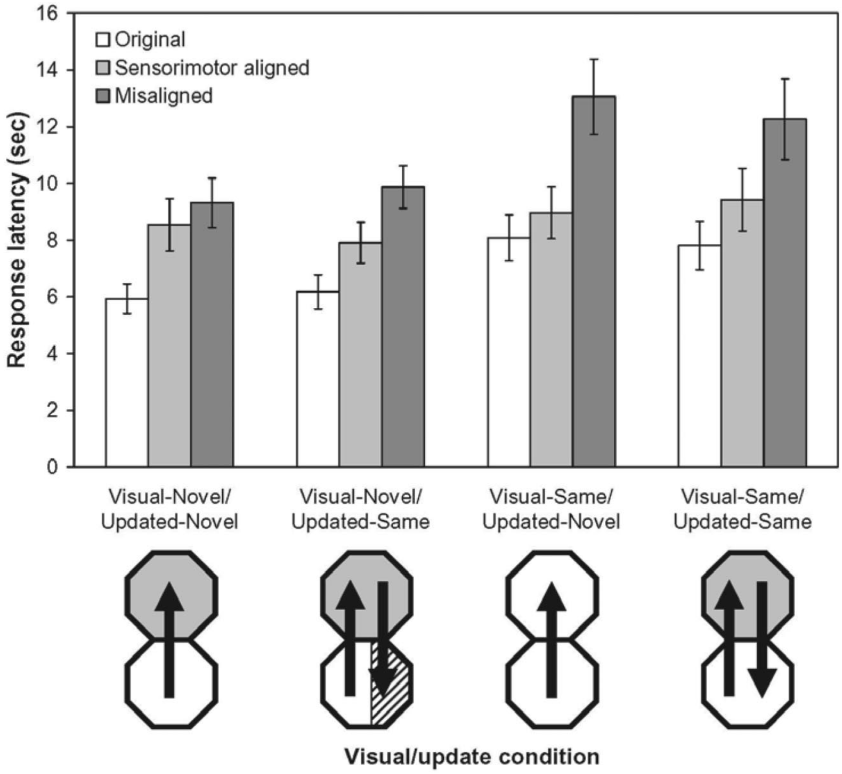

Figure 10. Mean response latency in Experiment 4. Error bars are standard errors that include between-participants variation.

Error rate. The accuracy data (Table 2) were analyzed in the same fashion. The mixed-model ANOVA revealed a main effect of imagined perspective, $F(2, 60) = 12.02$, $p < .001$, $\eta_p^2 = .29$, and a significant three-way interaction between imagined perspective, visual environment, and updated environment, $F(2, 60) = 4.09$, $p = .022$, $\eta_p^2 = .12$. As a result of the latter finding, separate 2 (updated environment: same or novel) × 3 (imagined perspective: original, sensorimotor aligned, or misaligned) repeated measures ANOVAs were conducted for both visual environment conditions. For the visual–novel condition, there was only a main effect of imagined perspective, $F(2, 30) = 9.57$, $p < .001$, $\eta_p^2 = .39$. For the visual–same condition, there was a main effect of imagined perspective, $F(2, 30) = 3.28$, $p = .05$, $\eta_p^2 = .18$, and also a significant interaction between imagined perspective and updated environment, $F(2, 30) = 6.47$, $p = .005$, $\eta_p^2 = .30$, due primarily to the superior performance on the sensorimotor aligned perspective compared with the initial perspective in the visual–same/updated–same condition. Memory alignment effects occurred in the visual–novel/updated–novel, $F(1, 15) = 4.99$, $p = .041$, $\eta_p^2 = .25$, visual–novel/updated–same, $F(1, 15) = 10.67$, $p = .005$, $\eta_p^2 = .42$, and visual–same/updated–same, $F(1, 15) = 10.21$, $p = .006$, $\eta_p^2 = .41$, conditions but not in the visual–same/updated–novel condition, $F(1, 15) = 0.96$, *ns*, $\eta_p^2 = .06$. Sensorimotor alignment effects did not occur in the visual–novel/updated–same, $F(1, 15) = 1.22$, *ns*, $\eta_p^2 = .08$, or the visual–same/updated–novel, $F(1, 15) = 0.04$, *ns*, $\eta_p^2 = .002$, conditions; were marginally significant in the visual–novel/updated–novel condition, $F(1, 15) = 3.57$, $p = .079$, $\eta_p^2 = .19$; and were significant in the visual–same/updated–same condition, $F(1, 15) = 5.21$, $p = .038$, $\eta_p^2 = .26$.

There was no evidence of speed–accuracy tradeoff, as response latency and error rate was either positively correlated or uncorrelated for visual–novel/updated–novel, $r(46) = .22$, *ns,* visual–novel/updated–same, $r(46) = .03$, *ns,* visual–same/updated–novel, $r(46) = .41$, $p = .004$, and visual–same/updated–same, $r(46) = .10$, *ns,* conditions.

Discussion

Experiment 4 replicated key results from Experiments 1 and 2, showing a sensorimotor alignment effect in the visual–same/updated–same condition and not in the visual–novel/updated–novel condition. In addition, the sensorimotor alignment effect was also found in the visual–same/updated–novel condition (in response latencies but not errors), where the participant walked into a new room that was visually identical to the learning room. This suggests that visual similarity to the learning environment was sufficient to activate the egocentric system, even though spatial updating provided conflicting location information. The sensorimotor alignment effect was also found in the visual–novel/updated–same condition (again, in response latencies but not errors), where participants exited the learning room and then immediately returned to find that the wall textures had been changed. Taken together, the results of Experiment 4 suggest that the visual environment and the spatially updated location can both be independently sufficient to activate the egocentric representation of objects from the learning room. Similar to Experiments 1–3, a memory alignment effect existed in the response time data for all conditions.

Whereas others have shown the importance of visual landmarks and environmental geometry as cues for reorientation (Hermer & Spelke, 1994), the visual information in Experiments 1–4 never contained landmark information that could help the participant maintain orientation, and even the geometric information was limited. Instead, participants in the current experiments relied heavily on spatial updating to maintain their orientation. Experiment 4 established that the visual texture of the environment was sufficient to activate an egocentric representation, but the role of environmental geometry in this task is unknown and could also play an important role in spatial memory retrieval.

General Discussion

The four experiments presented here help to further evaluate the models of spatial memory and spatial updating described previously. Although our findings are overall compatible with accounts providing for both egocentric and allocentric representations, certain aspects of our findings are not predicted by Sholl's (2001) and Mou, McNamara, et al.'s (2004) models. Before proceeding, we review the primary findings from all four experiments:

1. Memory alignment effects occurred in all test environments, regardless of the presence or absence of sensorimotor alignment effects.
2. Sensorimotor alignment effects were present when testing occurred in the learning room, but not when testing occurred in the novel neighboring room.
3. Sensorimotor alignment effects returned when participants returned to the learning room after having previously visited the novel room.
4. Sensorimotor alignment effects occurred even in the novel room after participants were cognitively anchored within the learning room through imagery instructions.
5. Sensorimotor alignment effects occurred in a test room that was visually identical to the learning room but in a different spatial location.
6. Sensorimotor alignment effects occurred in a test room that was visually novel but in the same spatial location as the learning room.

In light of this evidence, we are now in a position to further evaluate Sholl's (2001) and Mou, McNamara, et al.'s (2004) models. First, Sholl's (2001) model cannot account for Finding 1, that allocentric memories of object locations were represented with respect to a specific orientation. According to Sholl's model, spatial memories are encoded using an orientation-independent allocentric system. In our experiments, participants learned the layouts from multiple perspectives. Still, spatial memories were maintained in an orientation-dependent manner. Mou, McNamara, et al.'s (2004) model, however, does allow for such orientation specific allocentric representations. It seems that participants used the first perspective experienced during learning to organize the remaining objects in long-term memory. The impact of this reference frame was found regardless of the test location, and was reliable across all four experiments. Whereas others have previously demonstrated that egocentric experience is used to select the primary reference frame (Diwadkar & McNamara, 1997; Shelton & McNamara, 1997, 2001; but see Mou & McNamara, 2002), those experiments only allowed participants to view the objects from a limited number of perspectives during learning. In contrast, participants in the current experiments viewed all perspectives multiple times during learning. Despite this extensive experience with all perspectives, performance was superior when the initial view was tested. This replicates a similar finding by Avraamides and Kelly (2005) and underscores the salience of the initially viewed perspective in reference frame selection. The perspective 180° opposite from the original perspective (which was only tested in Experiment 1) was also facilitated relative to neighboring perspectives. This suggests that participants encoded the layout relative to the 0°–180° axis, and not just the 0° perspective. Other work is equivocal with regard to the 180° perspective, where some have found a benefit (Diwadkar & McNamara, 1997; Hintzman et al., 1981) and others have not (Avraamides & Kelly, 2005; Shelton & McNamara, 1997).

Finding 2 is readily explained by both Sholl's (2001) and Mou, McNamara, et al.'s (2004) models, albeit through separate mechanisms. Both models posit egocentrically organized sensorimotor representations of the immediate environment, which account for the sensorimotor alignment effects that occurred in the learning room. Using Sholl's model to explain the novel room data, we observe that object locations were recalled via the representational system, oriented with respect to the initially viewed perspective rather than the current facing direction. Using Mou, McNamara, et al.'s model to explain the novel room data, we observe that the object locations were recalled from long-term memory, which was organized around the initially viewed perspective.

Findings 3 and 4 are challenging for Mou, McNamara, et al.'s (2004) model. According to Mou, McNamara, et al.'s model, egocentric representations are transient, and depend heavily on perceptual support. When participants re-entered the learning room in Experiment 2, none of the objects were visually available. In contrast to Mou, McNamara, et al.'s predictions, our findings suggest that egocentric representation can be reinstated after a long delay and with minimal perceptual support, consisting only of the surrounding environment and not the objects themselves. Furthermore, our results from Experiment 3 show that visualization can be sufficient to reinstate egocentric representations. Sholl's (2001) proposed sensorimotor system is not transient, and therefore seems to handle Finding 3 well. Additionally, the representational system can be flexibly oriented when reasoning about a remote environment and therefore can also account for Finding 4.

Findings 5 and 6 add to our understanding of the sensorimotor representation that is present in both models. It further qualifies Mou, McNamara, et al.'s (2004) claim regarding the transient nature of the sensorimotor representation by showing that this representation fades only in cases where the retrieval environment is both visually and spatially distinct from the learning environment.

The goal of these experiments was to further investigate the allocentric and egocentric memory systems proposed by two-system accounts of navigation. To that end, many of our findings are compatible with both Sholl's (2001) model and with Mou, McNamara, et al.'s (2004) model, especially the evidence for separate egocentric and allocentric representations to support spatial judgments about the immediate environment and nonimmediate environments, respectively. We also believe that incompatible findings can be reconciled in both models with only minor modifications. A viable model should include (a) an egocentrically organized sensorimotor representation and (b) an orientation-dependent allocentric representation. The sensorimotor representation is analogous to a working memory representation with limited capacity, and it supports online actions such as reaching for objects and avoiding obstacles. Its inputs typically come from perception in a bottom-up manner but can also come from imagery in a top-down manner. The allocentric representation is analogous to a long-term memory representation, and its preferred orientation depends on a variety of factors during learning, such as the environment itself and one's experience during learning. Collectively, these two systems can readily explain a wide array of results in spatial cognition, including each of the primary findings from the current experiments.

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