

# The Role of Self-to-Object Updating in Orientation-Free Performance on Spatial-Memory Tasks

Over the past 20 years, the orientation specificity of human spatial memory has been an active topic of scientific inquiry. At issue is whether a room-sized spatial array observed from a single vantage point is stored in memory in the same orientation in which it was perceived, or whether the visual system constructs an orientation-free representation from orientation-specific input. This issue relates more broadly to the organizational structure of human memory for spaces large enough to navigate. At one end of the theoretical continuum, human spatial memory is characterized as a collection of orientation-specific descriptions of spatial relations observed from discrete viewpoints (Diwadkar & McNamara, 1997; Shelton & McNamara, 1997); whereas, the other end of the continuum proposes a single, unified description of spatial relations that is not tied to any specific viewpoint (Easton & Sholl, 1995; Sholl, 2000; Sholl & Nolin, 1997).

Recent research has provided compelling evidence for the orientation specificity of memories for room-sized spatial arrays viewed from single vantage points (Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Sholl & Nolin, 1997). An orientation-specific representation is defined as having a single preferred orientation, such that the most distant interobject relations in the observer's forward field of view are stored at the "top" of the representation. Orientation-specific representations are inferred from alignment effects, which are easier judgments of relative location when a person's orientation with respect to the spatial array at test (either in reality or in imagination) is aligned with his or her orientation at learning than when it is misaligned.

Findings that a single view of a test space produces an orientation-specific representation are consistent with the characterization of spatial memory as a collection of discrete orientation-specific descriptions of spatial relations (Diwadkar & McNamara, 1997; Shelton & McNamara, 1997). However, this account is complicated by other findings showing that under some conditions participants who have viewed a room-sized spatial array from a single perspective performed as if they had access to an orientation-free representation (Presson, DeLange, & Hazelrigg, 1989; Presson & Hazelrigg, 1984; Sholl & Nolin, 1997). Orientation-free representations have no preferred orientation. They are inferred from the absence of alignment effects; that is, retrieval of relative location is just as easy from a perspective that is misaligned with the learning perspective as from an aligned perspective. The purpose of the research reported in this article is to study the cognitive mechanisms that contribute to orientation-free performance, to understand better how representations of room-sized spaces are created.

## Spatial-Memory Task

The standard spatial-memory task used to study orientation specificity was first introduced by Presson and Hazelrigg (1984) as a variation of a procedure developed by Levine, Jankovic, and Palij (1982). In this paradigm, people study simple four-point paths laid out on the floor in front of them for about 30 s from a single, stationary observation point, which we call the *study site*. The points (i.e., the two end points and the two turning points) are numbered to create four sequentially numbered locations on each path. After study, the participant is blindfolded and transported by wheelchair to a *test site*, which is the person's actual location and facing direction at test. At the test site, participants are told the location on the path and the facing direction from which they are to judge the relative direction of the target, which is another location on the path. We use the term *reference location* to refer to the location and facing direction on the path from which relative direction is judged. For ease of description, we refer to the testing condition in which the test site and reference location are identical

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as *on-path testing* and the testing condition in which the test site and reference location differ as *off-path testing*.

The present article focuses exclusively on spatial memory for large paths or arrays (around 140 sq. ft [about 13.4 m<sup>2</sup>]) viewed from a ground-level plane. Under these learning conditions, on-path testing produces orientation-free performance (Presson et al., 1989; Presson & Hazelrigg, 1984; Sholl & Nolin, 1997); whereas, off-path testing produces orientation-specific performance (Roskos-Ewoldsen et al., 1998; Sholl & Nolin, 1997). Both testing conditions were designed to force participants to retrieve relative direction from the spatial memory created at study; however, there is reason to believe, as outlined below, that off-path testing successfully achieves this objective, whereas on-path testing does not.

One factor that differentiates on-path from off-path testing is the trajectory along which participants are transported to the test site. In on-path testing, participants are transported within the study space (the room containing the path) along a convoluted trajectory that is intended to disorient them by the time they reach the test site. In off-path testing, typically but not always, participants are wheeled directly out of the study space to a remote location. The hypotheses tested here attribute the performance differences between on-path and off-path test conditions to the opportunity for updating the body's location relative to the path in the former but not the latter condition.

### The Updating Hypothesis and the Virtual-Views Hypothesis

Sholl and colleagues (Sholl & Friedman, 1997; Sholl & Nolin, 1997) have proposed two alternative hypotheses to explain orientation-free performance: an updating hypothesis and a virtual-views hypothesis. Central to both hypotheses is the premise that blindfolded participants automatically update their location relative to the path while being transported from the study site to the on-path test site. The updating hypothesis asserts that in past studies passive transport did not disorient the participant as expected and that orientation-free performance was attributable to retrieval from a working memory (WM) representation of the location of the target relative to the body. In contrast, the virtual-views hypothesis asserts that passive transport did disorient the participant by the time the test site was reached. However, while the participant was still oriented to the study space, a new memory representation was formed from multiple virtual views of the path. In the following sections, we review behavioral evidence for a self-to-object updating process and discuss the updating and virtual-views hypotheses more fully.

#### *Self-to-Object Updating*

Behavioral evidence suggests that when walking in the absence of vision, people update their location relative to nearby, stationary landmarks continuously (Farrell & Thomson, 1999; Rieser, 1989; Rieser, Guth, & Hill, 1986; Simons & Wang, 1998; Wang & Simons, 1999) and automatically (Farrell & Robertson, 1998; Farrell & Thomson, 1998). Consider a person walking with eyes open through a large-scale space containing a number of stationary objects on either side. Each forward step laterally displaces the objects relative to the body in the direction opposite the direction

of movement. Rieser (1989) proposed that the mechanism underlying self-to-object updating is the overlearned visual-motor association between each forward step and the resultant gradient of visual displacements in the forward field of view. When walking with eyes closed, visual displacements are anticipated in response to the biomechanical cues produced by walking, so that throughout the trajectory the person has in WM continuously updated knowledge of the location of the objects relative to the body.

Although there is strong evidence that self-to-object updating is automatically engaged when walking without vision, self-to-object updating has not been systematically studied under conditions of nonsighted passive transport, which is the mode of transport used in the orientation-specificity paradigm. In passive transport, the primary signals for body movement are vestibular cues, which register linear and angular body acceleration and when doubly integrated with respect to time produce estimates of linear and angular body displacement (e.g., Potegal, 1982). Behavioral evidence suggests that blindfolded people are not very good at these kinds of estimates when passively transported in a dead-reckoning task (Sholl, 1989). However, passive transport in a dead-reckoning task differs from passive transport in an orientation-specificity study on at least one dimension that may be behaviorally relevant. In the dead-reckoning task, participants have no visual preview of the large-scale space through which they are to be transported; whereas, in orientation-specificity studies participants visually preview the path, and the room that contains it, during the study interval. Under some conditions, a visual preview of the environment facilitates dead reckoning during nonsighted walking (Philbeck, Loomis, & Beall, 1997), and it may be similarly beneficial during nonsighted, passive transport.

#### *The Updating Hypothesis*

According to the updating hypothesis, a moment-to-moment representation of the body's location relative to the path locations is maintained in WM during passive transport. The hypothesis does not specify the precise nature of this representation. One possibility is that a set of four homing vectors, each specifying the straight-line distance and direction connecting the body to one of the four path locations, is continuously updated as the body moves through space. As a result, when participants reach the on-path test site they have in WM an updated representation of the location of the path's four numbered points relative to the body.

How accurately the updated body position approximates the actual body position is a function of the computational sensitivity of the updating process. At the test site, the participant is instructed, "you are at Location [x] with Location [y] in [front/back] of you. Point to Location [z]," with x and y describing the participants' actual location and facing direction. The verbal information provided by the instruction could be used to adjust minor discrepancies between the updated and the actual body position. The participant then retrieves the target location directly from the WM representation.

In off-path testing, self-to-object updating cannot benefit performance because the test site differs from the reference location. As a consequence, the location of the target relative to the reference location is not directly specified in WM. Under these test

conditions, the updating hypothesis predicts that the direction of the target relative to the reference location is retrieved from the orientation-specific long-term memory (LTM) representation formed during the study interval.

### *The Virtual-Views Hypothesis*

According to the virtual-views hypothesis, self-to-object updating is engaged during transport, but at some point prior to reaching the test site the self-to-object updating process breaks down and the participant becomes disoriented. As a consequence, when the participant reaches the test site WM contains no updated representation of the body's location relative to the path, and retrieval must be from LTM. Central to the virtual-views hypothesis is the idea that LTM is affected by a stream of virtual views of the path experienced while the updating process is still engaged. *Virtual views* are defined here as images of the path as it would appear if the person were to open his or her eyes and look at it, and they are assumed to have an effect on spatial memory similar to the effect of actual views.<sup>1</sup>

Evidence shows that when a spatial array is studied from two or three different facing directions, each studied view forms a separate orientation-specific representation in LTM (Diwadkar & McNamara, 1997; Shelton & McNamara, 1997). In past studies, the trajectories connecting the study and test sites typically contained many twists and turns (Presson et al., 1989; Roskos-Ewoldsen et al., 1998; Sholl & Nolin, 1997). In principle, each change in the direction of the trajectory afforded a different virtual view of the path. So, if virtual views function like actual views, each virtual view experienced from a different facing direction prior to disorientation may produce an additional orientation-specific representation in LTM, and the resultant collection of orientation-specific representations could function together to produce orientation-free performance. Alternatively, a single orientation-free representation may be computed from the multiple orientation-specific representations created by the multiple virtual views.<sup>2</sup> The experiments reported here cannot distinguish between these alternatives, and the term *orientation-free* will be used to refer to either type of representational structure.

The virtual-views hypothesis attributes orientation-specific performance in off-path testing to the fact that in most cases, the trajectory leading to the off-path test site does not afford an opportunity to mentally view the path from multiple facing directions. That is, mostly the participant is wheeled either directly out of the room to a remote location or directly to an off-path location in the room, therefore the trajectory does not circuitously cross over and around the path itself.

### *Summary*

In Table 1 we summarize the similarities and differences between the updating and the virtual-views hypotheses. As shown in Table 1, both hypotheses allow that an orientation-specific representation of the path is formed from a single static view during study. They both propose that a self-to-object updating mechanism operates during transport from the study to the test site. The hypotheses differ in two respects. First, the virtual-views hypothesis but not the updating hypothesis asserts that the orientation-

specific memory formed at study is transformed by the updating process. Second, although both hypotheses allow that the self-to-object updating process will break down at some point along a convoluted trajectory, they differ in their claims regarding whether testing occurred before or after disorientation in past studies. The updating hypothesis claims that testing occurred prior to disorientation and that orientation-free performance resulted from retrieval from an updated WM representation ( $\text{Test}_{\text{pre}}$  in Table 1). Whereas, the virtual-views hypothesis claims that testing occurred after disorientation with retrieval from an orientation-free LTM representation ( $\text{Test}_{\text{post}}$  in Table 1). The shaded portions of Table 1 show the retrieval process predicted by each hypothesis if testing occurs at the time predicted by the other hypothesis.

Sholl and Nolin (1997) reported orientation-free performance when spatial memory was tested from two different locations on the path (i.e., there were two trials for each studied path), and a similar procedure was followed in the present experiments. In Table 1, we describe the phases of the first trial. The second trial does not include a study phase, and transport is from the first test site to a second test site. It is assumed here that the cognitive processes engaged at the end of transport on the first trial were reengaged when transport was continued on the second trial. That is, if test was predisorientation in Trial 1, then self-to-object updating would resume during transport to the second test site and test would be predisorientation in Trial 2. In contrast, if test was postdisorientation in Trial 1, then participants would remain disoriented during transport to the Trial 2 test site.

Although the two hypotheses were developed to explain orientation-free on-path performance, they can also account for the alignment effects observed in off-path testing. In formulating these accounts, we assumed that off-path testing was mediated by retrieval from LTM, as has been previously demonstrated (Roskos-Ewoldsen et al., 1998; Sholl & Nolin, 1997).<sup>3</sup> The updating hypothesis predicts retrieval from an orientation-specific LTM representation because the representation is not altered during

<sup>1</sup> Visual imagery may characterize all nonsighted self-to-object updating when a test space has been visually previewed. If so, the updating hypothesis differs from the virtual-views hypothesis by claiming that the images do not alter the representation of the path formed at study.

<sup>2</sup> The number of orientation-free representations necessary to produce orientation-free performance is unknown. Existing evidence suggests that it is more than three (Shelton & McNamara, in press). It is also possible that an orientation-free representation is not assembled from discrete images but is constructed instead from a continuously unfolding dynamic image of the path. Unfortunately, there has been little systematic study of how people process the invariant structure of fixed spatial layouts that emerges from dynamic visual flow (e.g., Gibson, 1979). Nevertheless, imagining the path from a moving point of observation may reveal the path's invariant geometric structure, which is then stored in a single orientation-free representation.

<sup>3</sup> If an alignment effect is observed in the standard spatial-memory paradigm used here, it cannot be determined with certainty whether the orientation-specific representation resides in WM or LTM. However, prior studies have included an intervening task between study and test (e.g., reading verbal instructions, pointing to numbers on the face of a clock), ensuring that spatial memories were retrieved from LTM (Roskos-Ewoldsen et al., 1998; Sholl & Nolin, 1997). Alignment effects were consistently observed, indicating orientation specificity is a characteristic of long-term spatial memory.

Table 1  
*A Schematic of the Working Memory (WM) and Long-Term Memory (LTM) Processes Engaged in the On-Path Version of the Spatial-Memory Task, According to the Virtual-Views and Updating Hypotheses*

Trial phase	Virtual-views hypothesis		Updating hypothesis	
	WM	LTM	WM	LTM
Study	Perceive actual view of the path	Store O-S rep.	Perceive actual view of the path	Store O-S rep.
Transport	S-T-O updating	Rep. modified by virtual views	S-T-O updating	Rep. unaltered during updating
Test <sub>pre</sub> <sup>a</sup>	Retrieve updated S-T-O rep. Disorientation		Retrieve updated S-T-O rep. Disorientation	
Test <sub>post</sub> <sup>a</sup>		Retrieve O-F rep.		Retrieve O-S rep.

*Note.* The time course of a typical trial is divided into a study phase, transport, and test phase. Skip the test<sub>pre</sub> row when following the time course for a test<sub>post</sub> trial. The shaded portions represent the retrieval process predicted by each hypothesis if test occurs at the time predicted by the other hypothesis. O-S = orientation-specific; S-T-O = self-to-object; O-F = orientation-free; rep. = representation.

<sup>a</sup> Test<sub>pre</sub> and test<sub>post</sub> refer to testing pre- and postdisorientation, respectively.

transport.<sup>4</sup> The virtual-views hypothesis makes the same prediction, because the typical off-site trajectory affords an insufficient number of virtual views from different facing directions to create an orientation-free LTM representation.

### Preview

The updating and the virtual-views hypotheses were tested in three experiments. The first two experiments used the standard spatial-memory task, and the third experiment modified the instructions to transform the spatial-memory task into an updating task. In all three experiments, the test arrays were four-point paths that covered around 144 sq. ft (13.4 m<sup>2</sup>) of floor space, and the paths were always viewed from a perspective close to the ground. As mentioned earlier, these are two of the study conditions that have produced orientation-free performance in the past. Experiment 1 combined off-path testing with a trajectory from the study site to the test site that was designed to permit self-to-object updating with respect to the to-be-remembered path. Experiment 2 manipulated the complexity of the trajectory between the study site and an on-path test site, and Experiment 3 tested participants' orientation to the study space after transport on the Experiment 2 trajectories.

### General Method

#### Participants

Participants were primarily Boston College undergraduates who participated in the experiments either in partial fulfillment of a research participation requirement or for pay. Examination of the data from Experiments 1 and 2 revealed that in each experiment a few participants showed extreme alignment effects. Relatedly but conversely, in a map-learning task expected to produce strong orientation specificity, Rossano, Warren, and Kenan (1995) identified a subgroup who showed unexpected orientation-free performance and whose performance was masked by another subgroup who showed strong orientation-specific performance. These authors cau-

tioned against overgeneralization from group averages in research on orientation specificity.

In the present experiments, to eliminate the bias introduced by extreme outliers, we developed a method for objectively identifying them. For each participant the difference between the contraaligned and aligned conditions was found for both accuracy and latency, and the differences were converted into standard scores. Any participant with a standard score more extreme than  $\pm 2.5$  was removed and replaced. One male and 1 female were thus identified as outliers in Experiment 1, and 2 males were identified as outliers in Experiment 2. This result suggests that for undetermined reasons a very small proportion of the population (about 6.5%) show extreme alignment effects regardless of test conditions. Thus, the findings reported for Experiments 1 and 2 apply to the other 93.5% of the population.

#### Stimulus Materials

Paths similar to the ones used by Presson et al. (1989, Arrays 1–8) were used in this experiment. Each path had three linear segments, and the first and last segments were parallel. There were two path sets: Paths 1–4, the segments of which were connected with two 90° angles, and Paths 5–8, the segments of which were connected with one 70° and one 110° angle. (The connecting angles in Presson et al.'s, 1989, Paths 5–8 were 45° and 135°). The longest path segment equaled 12.4 ft (3.8 m) and the shortest segment

<sup>4</sup> When off-path testing occurs in the study space (e.g., the Roskos-Ewoldsen et al. [1998] locative condition), WM may contain an updated representation of the body's location relative to the path. However, the target location is not directly recoverable from the WM representation, because target location has been updated relative to the body's location at the test site, not at the reference location. Under these test conditions, retrieval from an updated WM representation would produce orientation-specific performance if the body's orientation at test was aligned with its orientation at learning. This is because aligned trials require a translation transformation of the WM representation; whereas, contraaligned trials require both a rotation and a translation transformation (Rieser, 1989; Easton & Sholl, 1995).

equaled 1.0 ft. (0.3 m). The paths covered approximately 144 sq. ft (13.4 m<sup>2</sup>) of the floor space in the test room, which measured about 13 ft × 16 ft. Aside from slight discrepancies caused by the different angles in Paths 5–8, the paths preserved the relative segment lengths of the Presson et al. paths.

Paths were constructed from heavy green twine strung between heavy-duty suction cups fitted with hooks. The location numbers were attached to the suction cups. All paths were viewed from a study site from which the entire path was visible in the participant's forward field and that roughly bisected the middle segment of each path.

### Procedure

Each participant was tested individually and was given instructions either in the hallway outside of the test room or in the test room itself. Afterward participants were seated in a wheelchair, blindfolded, and fitted with earphones attached to an auditory device that masked the source of ambient noise in the environment (see Rieser et al., 1986). A rectangular plywood board was attached like a tray table (with a hook and loop fastener) to the arms of a wheelchair. A 360° protractor was mounted on the plywood board. Participants made their pointing responses with a freely rotating metal pointer attached to the center of the protractor. The pointer overlapped the degree marks on the protractor, and pointing responses were measured to the nearest degree.

Participants then made a couple of pointing responses to demonstrate that they understood how to use the pointer (e.g., they were asked to “point to the door” or “point to me”). They were told to lift their hand from the pointer when they had completed their response and that in the experiment their pointing responses should be made as quickly as possible without sacrificing accuracy. Pointing responses were always made from the straight ahead position. Because the target angles were matched across the aligned and contraaligned conditions to within an average of 10°, any latency differences between the two conditions cannot be attributed to the length of time it took to physically move the pointer from the straight ahead position.

A typical experimental trial proceeded as follows. After wheeling the participant to the study site, the experimenter constructed the next to-be-learned path. Then on a cue from the experimenter, the participant lifted the blindfold, studied the path for 30 s, and then replaced the blindfold. The experimenter then wheeled the participant along a trajectory to the test site. At the test site, the participant was told, “You are at Location [x] with Location [y] in [front/back] of you. Point to Location [z]”. The x, y, and z variables were filled in with the retrieval cues and the target location for that particular trial. A stopwatch was started at the completion of the retrieval instruction and stopped when the participant lifted his or her hand from the pointer. The pointing latency and angle were recorded, and the pointer was returned to the straight-ahead position. The participant was wheeled back to the study site and then wheeled along a second trajectory to a second test site for the path (for off-path testing, the two test sites were the same; for on-path testing, they were different locations on the same path). At the end of that trial, the participant was wheeled back to the study site, and the experimenter constructed the next to-be-learned path. The study–test sequence was then repeated.

Testing started with two trials on a practice path. Each participant then learned four different paths and was tested twice on each path for a total of eight trials: four aligned and four contraaligned. The four paths were tested in a randomly determined order for each participant, and the two trials nested within each path were always given in the same order. The direction of the target location relative to the body (in front/behind) and the direction of Location y relative to the body (in front or behind) were counterbalanced across the aligned and contraaligned trials.

### Design and Analysis

The general experimental design was a 2 (sex [male, female]) × 2 (path set [Paths 1–4, Paths 5–8]) × 2 (alignment [aligned, contraaligned])

factorial design, with repeated measures on the last factor. In Experiments 2 and 3 there was one additional between-subjects factor (trajectory [0 turn, 3 turn]). Within each sex, participants were randomly assigned to the levels of the between-subjects factors. Pointing errors were computed by finding the absolute difference between the observed and the correct pointing angles.

In all experiments, the alpha level was set at .05, but theoretically significant effects are reported at a .10 alpha level. Also, the effect size (*r*) is reported for each alignment effect to facilitate comparisons across experiments and in an attempt to characterize the size of the observed alignment effects. The latter was done in accordance with Cohen's (1988) scheme in which *r*s of .10, .24, and .37 are characterized as small, medium, and large effect sizes, respectively. A number of the observed alignment effects fell between a .05 and .10 alpha level; however, they all had effect sizes in the medium to large range and are discussed as if significant. In addition, type of path was included in the analyses as a control variable, but no effects of path type are reported.

## Experiment 1

Experiment 1 tested the updating and the virtual-views hypotheses as follows. After viewing the test array, blindfolded participants were wheeled in a cloverleaf trajectory inside the test room and then outside the room and into the hallway, as illustrated in Figure 1. Half of the participants were tested in the hallway and the other half in a room adjacent to the test room.<sup>5</sup> In both cases, participants' facing direction at test was misaligned with the direction they faced at study by a 90° clockwise rotation.

The benefit of testing participants outside the room was that it ensured that participants could not rely on an updated WM representation of target location. We are confident of this for two reasons. First, and most important, the results of Experiment 3 show that participants are completely disoriented by more than three 180° turns. The trajectory to the off-path test site contained three 180° turns, two (Figure 1A) or three (Figure 1B) 90° turns, and one 360° turn. Second, there is evidence suggesting that self-to-object updating is restricted to objects within the bounded space occupied by the body and does not extend to objects beyond these boundaries (Wang, Brockmole, & Stewart, 2000). Therefore, even in the unlikely event that participants were still oriented when wheeled out of the study space, it is doubtful they would have continued to update their location relative to the path once in the hallway. The updating hypothesis predicts an alignment effect, because retrieval is from the orientation-specific representation formed during the study interval. In contrast, the virtual-views hypothesis predicts orientation-free performance, because the memory representation of the path formed at study has been altered by the multiple virtual views from the different facing directions afforded by the cloverleaf trajectory.

The use of off-path testing in Experiment 1 made the present procedure similar to other procedures that have shown orientation-specific performance (Roskos-Ewoldsen et al., 1998; Sholl & Nolin, 1997). With the possible exception of Roskos-Ewoldsen et al.'s procedure in one condition (i.e., the Experiment 1, nonlocative condition), the present procedure differed from these earlier procedures in that the trajectory from the study site to the test site

<sup>5</sup> The reason that we used first the hallway and then the adjacent room as remote test sites is that the adjacent room was not available to us when we began the experiment.

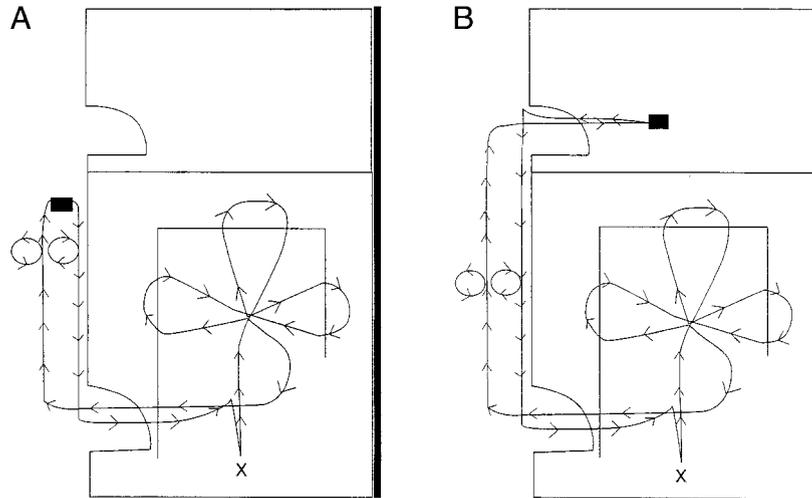


Figure 1. A schematic illustration of the 3-turn cloverleaf trajectory used in Experiment 1 and of the trajectories followed in Procedures 1 (Panel A) and 2 (Panel B) to and from the test site. The study site is illustrated with an X, the test site is indicated with a small filled rectangle, and the cloverleaf trajectory is overlaid on a sample path within the test space.

had the potential to provide multiple virtual views of the test array. The present trajectory and the Roskos-Ewoldsen et al. nonlocative trajectory were similar in that they both occurred within the test space. However, the two trajectories may have differed, if the “many twists and turns” (p. 218) in the Roskos-Ewoldsen et al. (1998) trajectory disoriented people early enough to prevent the experience of multiple virtual views.

Method

Participants. Fifteen males and 15 females ranging in age from 18 to 50 participated in this experiment. Two outliers were discarded, one male, who had a large alignment effect for latency, and one female, who had a large alignment effect for error.

Procedure and design. The hallway was the test site for the first 14 participants (7 males and 7 females), who were told they would be tested

on the path itself (Procedure 1). The next 14 participants were tested in an adjacent room (7 males and 7 females) and were so instructed (Procedure 2). The trajectories linking the study site to the test site in each procedure are shown in Figure 1.

Results

Procedure 1 versus Procedure 2. The two procedures used in this experiment did not differentially affect either accuracy,  $F(1, 18) = 0.18, p = .678, MSE = 189.92$ , or latency,  $F(1, 18) = 0.04, p = .841, MSE = 2.383$ , nor did they interact with any other variables. Therefore the data from the two procedures were combined.

Pointing errors and latencies. Mean pointing errors and latencies as a function of sex and alignment, respectively, are shown in Figure 2. For error, there was a main effect of alignment,  $F(1,$

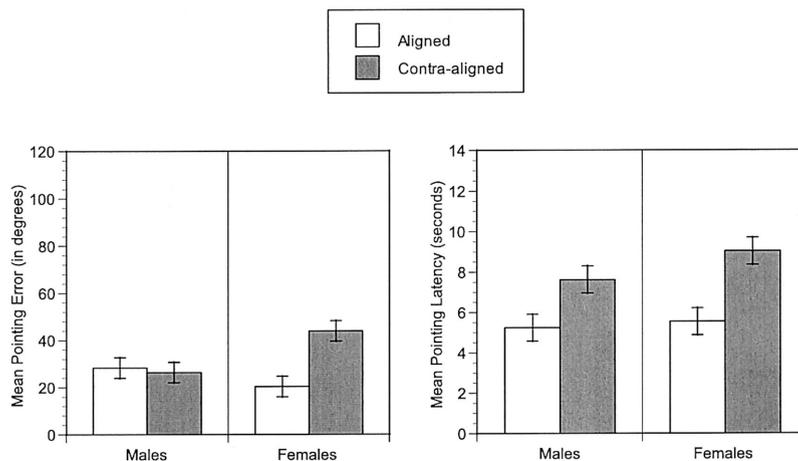


Figure 2. Mean pointing errors and latencies as a function of sex and alignment in Experiment 1. Error bars represent the standard error of the mean.

24) = 6.17,  $p = .020$ ,  $MSE = 266.37$ , which was qualified by an Alignment  $\times$  Sex interaction,  $F(1, 24) = 8.56$ ,  $p = .007$ ,  $MSE = 266.37$ . A one-tailed test of the simple effect of alignment showed a significant effect for females,  $t(24) = 3.83$ ,  $p = .05$ ,  $r = .62$ , but not males,  $t(24) < 1.0$ ,  $r = -.06$ . For pointing latencies, there was an alignment effect,  $F(1, 24) = 19.18$ ,  $p < .001$ ,  $MSE = 6.29$ , for both males ( $r = .46$ ) and females ( $r = .60$ ).

### Discussion

To facilitate comparisons within and between experiments, we summarize in Table 2 the results of all three experiments by organizing the observed effect sizes by test-site location, type of task, and trajectory complexity. The reader may find it helpful to refer to Table 2 when reading the discussion of each experiment.

In Experiment 1, females showed large alignment effects for accuracy ( $r = .62$ ) and latency ( $r = .60$ ) suggesting that they formed an orientation-specific representation of the path, despite having had the opportunity to experience multiple virtual views of it. This finding suggests that if females show orientation-free performance with on-path testing, it is likely due to retrieval from an updated working-memory representation of the path.

The male results were less clear. Their pointing latencies showed a large alignment effect ( $r = .46$ ), whereas pointing errors showed no significant alignment effect ( $r = -.06$ ). Together the accuracy and latency results show that the contraaligned trials required more processing than aligned trials, but with the additional processing time males were able to compute response angles that were as accurate in the contraaligned as in the aligned trials. Male performance is atypical of orientation specificity, because alignment effects, when present, are strong enough to show up in error data. In fact, early studies inferred orientation specificity from error data alone (Levine et al., 1982; Presson et al., 1989; Presson & Hazelrigg, 1984). Indeed, because the alignment effect they observed was so dramatic, Levine et al. (1982; Experiment 4)

did not even report quantitative errors, choosing instead to categorize errors as greater or less than  $90^\circ$ .

The atypicality of male performance deserves further comment. The prior studies demonstrating orientation-specific performance for large arrays with off-path testing have most typically shown large, statistically significant alignment effects for error and latency. In the Roskos-Ewoldsen et al. (1998) study, participants either were wheeled directly to a test site at the center of the test space (locative condition) or were wheeled to the same test site after a circuitous trajectory within the test space (nonlocative condition). Under these testing conditions, estimated effect sizes for large spatial arrays (Experiment 1) were .34 for pointing error and .39 for pointing latency. In Sholl and Nolin's (1997) procedure, participants were either tested directly at the study site (Experiment 4, learning-site condition) or were immediately removed from the test space and tested in a remote location (Experiment 4, remote-site condition; and Experiment 5). Large effect sizes were observed with study-site testing: .37 for error and .44 for latency. With remote-location testing, effect sizes were .20 and .57 for error and .16 and .63 for latency, in Experiment 4 and Experiment 5, respectively.

To summarize, in prior experiments using procedures similar to the present procedure (i.e., large paths initially viewed from a horizontal perspective and tested off-path), the average effect size for error was .38 and for latency it was .42. Thus, prior studies suggest that the mental transformation of an orientation-specific representation in contraaligned trials not only takes extra time but also degrades the representation, decreasing the precision with which relative direction is computed. With the possible exception of the Roskos-Ewoldsen et al.'s (1998) nonlocative condition, the factor that differentiates the present procedure from earlier procedures is the opportunity for self-to-object updating during the trajectory from the study site to the test site.

The male results in the present Experiment 1 show a roughly "average" latency effect size ( $r = .46$ ), but no effect size for error ( $r = -.06$ ). The additional processing time, without the usual increase in error signifying orientation specificity, suggests that orientation specificity may not be an all-or-none property of spatial representations and that it may be an oversimplification to dichotomize performance as either orientation specific or orientation free. In correlational analyses of psychometric and chronometric measures of spatial ability, it has been suggested that the quality of spatial representations (e.g., resolution, fidelity), as measured by accuracy, is dissociable from the efficiency of the transformations performed on those representations, as measured by latency (Pellegriano & Kail, 1982; Poltrock & Brown, 1984). If this interpretation is correct, then males have formed a partially orientation-free representation that maintains its quality on contraaligned trials, even though used less efficiently.

According to this line of thinking, it may be most appropriate to think of representations of large-scale space as varying along a continuum from orientation-specific to orientation-free. Along these lines, an orientation-free representation may be built up as a continuous function of the number of different environmental perspectives experienced from a moving point of observation. As the number of observed (or virtual) perspectives increases, the orientation specificity of the developing representation decreases, until it is accessible equally quickly and accurately from any perspective. If this account is correct, orientation-free representa-

Table 2  
Effect Sizes for Pointing Errors and Latencies as a Function of Test-Site Location (Off-Path, On-Path), Type of Test (Spatial Memory, Updating), the Complexity of the Trajectory (0 Turn, 3 Turn), and Sex, Across Experiments 1–3

Sex	Off-path		On-path			
	Spatial memory (Experiment 1)		Spatial memory (Experiment 2)		Updating (Experiment 3)	
	RT	Error	RT	Error	RT	Error
3 turn						
Males	.46 <sup>a</sup>	-.06	-.05	-.18	-.67 <sup>a</sup>	-.30 <sup>a</sup>
Females	.60 <sup>a</sup>	.62 <sup>a</sup>	.34 <sup>a</sup>	.30 <sup>a</sup>	.20	-.38 <sup>a</sup>
0 turn						
Males			.21	.33 <sup>a</sup>	.13	-.13
Females			.25	.06	.17	.19

Note. RT = response time.

<sup>a</sup> Alignment effects that are significant at an alpha level of .05 or less.

tions may be built up from multiple discrete views of the test space (e.g., Shelton & McNamara, 1997), from dynamic visual flow patterns (e.g., Gibson, 1979), or both. Thus the virtual-views hypothesis could explain male performance, if the spatial memory formed by males fell at some midpoint on the continuum, allowing orientation-free performance for error but not latency.

Sex differences in the orientation specificity of spatial memory have not been previously reported and hence were unanticipated. We tested for sex differences in the next two experiments, and we take up the issue of sex differences in the formation of spatial memories in the General Discussion.

## Experiment 2

Experiment 2 used on-path testing and manipulated the trajectory from the study site to the test site. Sample trajectories are illustrated in Figure 3. The labels *0 turn* and *3 turn* describe the minimum number of 180° turns between the study and test sites. In the 0-turn condition participants were wheeled directly to the test site, but on contraaligned trials a 180° turn was needed to align the wheelchair properly. In the 3-turn condition, participants were wheeled along the same cloverleaf trajectory used in Experiment 1. At the end of the 3-turn trajectory, the wheelchair was 180° misaligned with the facing direction at study, necessitating one additional 180° turn in the aligned trials. The 3-turn condition most closely duplicates the earlier studies that have produced orientation-free performance using on-path testing, because it includes a circuitous trajectory connecting the study to the test site

within the test space (Presson et al., 1989; Presson & Hazelrigg, 1984; Sholl & Nolin, 1997).

To predict the results of Experiment 2, we assumed that participants would be oriented to the path at the end of the 0-turn trajectory but would be disoriented at the end of the 3-turn trajectory. The predictions, which are described next, are diagrammatically summarized in Table 3 and motivated by the hypothesized processes outlined in Table 1.

We predicted that if the updating hypothesis correctly accounts for female orientation-free performance with on-path testing as suggested by the outcome of Experiment 1, then females should show no alignment effect in the 0-turn condition, because retrieval would be from an updated WM representation of the path locations relative to the body. However, they should show an alignment effect in the 3-turn condition, because retrieval would be from LTM.

We further predicted that if the virtual-views hypothesis accounts for male performance in Experiment 1, then males should show either no alignment effect or a partial alignment effect (by which we mean a replication of the effect for latency but not error observed in Experiment 1) in the 3-turn condition, because the 3-turn trajectory affords multiple virtual views of the path. In the 0-turn condition, we predicted that males would show no alignment effect, because retrieval is from an updated WM representation. As shown in Table 1, if the test occurs prior to disorientation, the virtual views and updating hypotheses are behaviorally indistinguishable. Directional planned comparisons tested for the presence of alignment effects in each sex by number-of-turns condition.

## Method

**Participants.** Sixteen males and 16 females, ranging in age from 18 to 23, originally participated in the experiment. Two male outliers were replaced: one in the 3-turn condition who showed an extreme alignment effect for accuracy and another in the 0-turn condition who showed a reverse alignment effect for latency, likely because of a speed-accuracy trade-off.

**Procedure.** In this experiment, participants were transported along either the 0-turn or 3-turn trajectory to a test site that was in actuality the reference location described at retrieval.

## Results

A 2 (sex)  $\times$  2 (trajectory)  $\times$  2 (path)  $\times$  2 (alignment) analysis of variance (ANOVA), with repeated measures on the last factor, was conducted to compute an error term for the planned comparisons. Both the results of the omnibus *F* tests and the one-tailed planned comparisons are reported.

**Pointing error.** Mean pointing errors are shown in Figure 4. The only effect to approach significance by the omnibus *F* test was the Sex  $\times$  Trajectory  $\times$  Alignment interaction,  $F(1, 24) = 3.70$ ,  $MSE = 479.59$ ,  $p = .067$ . Planned comparisons ( $MSE = 479.59$ ) showed an alignment effect for males in the 0-turn condition,  $t(24) = 1.71$ ,  $p = .05$ ,  $r = .33$ , but no alignment effect in the 3-turn condition,  $t(24) < -1.0$ ,  $r = -.18$ . For females, there was no alignment effect in the 0-turn condition,  $t(24) < 1.0$ ,  $r = .06$ , and an alignment effect that approached significance in the 3-turn condition,  $t(24) = 1.54$ ,  $p = .07$ ,  $r = .30$ .

**Pointing latencies.** Mean pointing latencies are shown in Figure 5. By omnibus *F* test, the only effect to approach significance

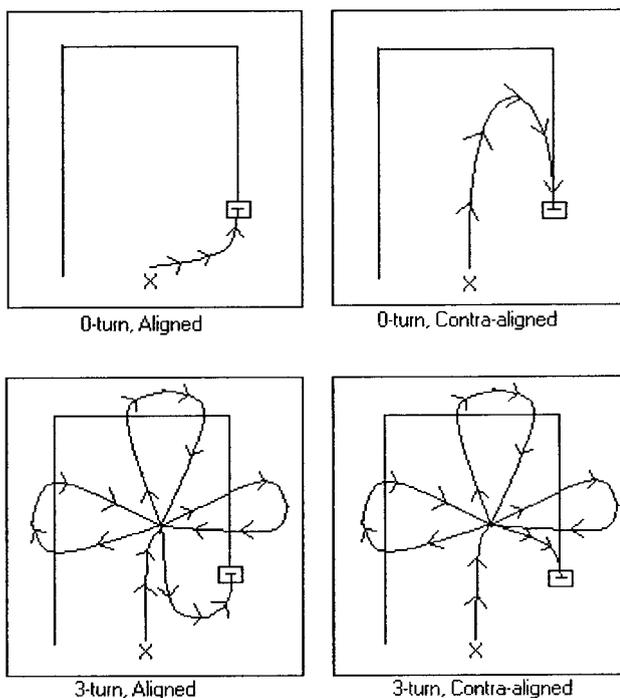


Figure 3. Schematic illustrations of sample 0-turn and 3-turn trajectories from the study site (marked with an X) to a test site (marked by an unfilled rectangle) in the aligned and contraaligned conditions of Experiments 2 and 3.

Table 3  
Predictions of the Updating and Virtual-Views Hypotheses as a Function of the Trajectory Condition in Experiment 2

Predictions	Alignment effect	No alignment effect
Updating hypothesis		
0-turn trajectory		✓
3-turn trajectory	✓	
Virtual-views hypothesis		
0-turn trajectory		✓
3-turn trajectory		✓

Note. The predictions are based on the assumption that the 0-turn trajectory does not disorient participants and the 3-turn trajectory does.

was a main effect of alignment,  $F(1, 24) = 3.66, MSE = 2.83, p = .067$ . Planned comparisons ( $MSE = 2.83$ ) showed no significant alignment effect for males in either the 0-turn,  $t(24) = 1.06, p = .15, r = .21$ , or 3-turn condition,  $t(24) < -1.0, r = -.05$ . For females, there was no significant alignment effect in the 0-turn condition,  $t(24) = 1.24, p = .11, r = .25$ , but a significant alignment effect in the 3-turn condition,  $t(24) = 1.71, p = .05, r = .34$ .

Discussion

In the 0-turn condition, males showed a moderately strong alignment effect for accuracy ( $r = .33$ ) and a medium effect size for latency ( $r = .21$ ), which did not reach significance. When compared with earlier findings (Roskos-Ewoldsen et al., 1998; Sholl & Nolin, 1997), the alignment effect for error is of about average size and the effect size for latency falls within the range of previously reported effect sizes for orientation-specific performance. This profile is consistent with retrieval from an orientation-specific representation and inconsistent with retrieval from an updated WM representation. In the 3-turn condition, there were no alignment effects for either accuracy ( $r = -.18$ ) or latency ( $r = -.05$ ), which is consistent with retrieval from an orientation-free

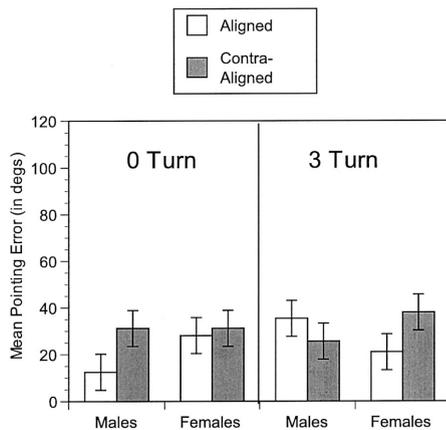


Figure 4. Mean pointing error as a function of type of trajectory, sex, and alignment in Experiment 2. Error bars represent the standard error of the mean. degs = degrees.

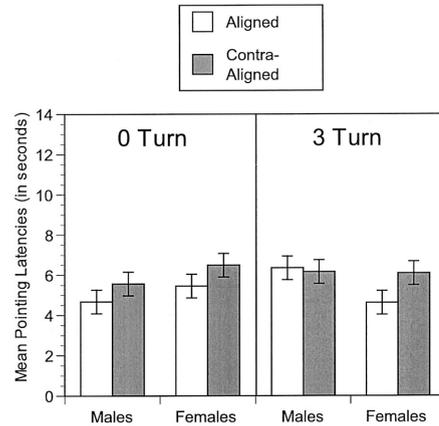


Figure 5. Mean pointing latency as a function of type of trajectory, sex, and alignment in Experiment 2. Error bars represent the standard error of the mean.

LTM representation as predicted by the virtual-views hypothesis. The pattern of findings across the 0-turn and 3-turn conditions raises the following questions: If self-to-object updating is engaged long enough to create an orientation-free LTM representation, why don't males use the updated WM representation of self-to-object relations in the 0-turn condition? and What combination of representation and process produced orientation-specific performance? We return to this issue in the discussion of Experiment 3.

In contrast to the males, females showed a moderately strong alignment effect in the 3-turn condition for both accuracy ( $r = .30$ ) and latency ( $r = .34$ ). In the 0-turn condition, there was no alignment effect for accuracy ( $r = .06$ ) and a medium effect for latency ( $r = .25$ ), which did not reach significance. This pattern is consistent with the updating hypothesis and can be explained as follows. In the 3-turn condition, an alignment effect was observed because self-to-object updating has become disengaged, and to solve the problem females must retrieve an orientation-specific spatial memory of the path. However, in the 0-turn condition the self-to-object updating mechanism was still engaged, which was indicated by the failure to find an alignment effect for accuracy.

But what about the medium effect size for latency ( $r = .25$ )? Although it was nonsignificant, we have suggested that a similar 0-turn effect size for males ( $r = .21$ ) is consistent with orientation-specific performance. If the .25 effect size shown by females is indeed reliable, why not interpret the female 0-turn profile (a medium effect size for latency; no effect for accuracy) as retrieval from a partially orientation-free LTM representation, as we did in the case of males for a similar performance profile (a large effect size for latency; no effect for accuracy) in Experiment 1? First, it is logically inconsistent to suggest that females retrieve a partially orientation-free LTM representation in the 0-turn condition but retrieve a fully orientation-specific LTM representation in the 3-turn condition. Moreover, within sampling error, a similar response profile is observed for females in the 0-turn condition of the Experiment 3 updating task, providing empirical support for an updating explanation for the Experiment 2 results.

### Experiment 3

The Experiment 2 predictions were predicated on the assumption that participants would be oriented to the path at the end of the 0-turn trajectory and disoriented to the path at the end of the 3-turn trajectory. These assumptions were tested with an updating task in Experiment 3.

Experiment 3 tested male and female orientation to the test space at the same test sites and following the same trajectories used in Experiment 2. The primary difference between Experiments 2 and 3 lay in the verbal prompts given at retrieval. In Experiment 2, at the end of the trajectory participants were told, "You are at Location [x] with Location [y] in [front/back] of you. Point to Location [z]". The variables x, y, and z were filled in with numbered path locations, therefore participants were told their location and facing direction on the path. In Experiment 3, participants were simply told, "Point to Location [z]". Therefore, in Experiment 3 participants were not told their position on the path. Thus, to judge the relative location of the target, they needed to use an updated WM representation of their location relative to the path. On each trial, participants first pointed to a numbered location on the path, to test their orientation relative to the path itself. Then they pointed to the door of the test room, to test their orientation to the stable, global reference frame provided by the four walls of the room.

Alignment was manipulated in this experiment, but it was difficult to predict its effect with certainty. Updating based on vestibular cues is subject to cumulative error (McNaughton, Chen, & Markus, 1991), thus we hypothesized that within the 0- and 3-turn conditions, the trajectory with the extra 180° turn may produce larger pointing errors: In the 0-turn condition, this is the contra-aligned trajectory, and in the 3-turn condition, the aligned trajectory. However, we believed that if participants were disoriented in the 3-turn condition as we expected, then pointing should have been random in both the aligned and contraaligned conditions.

### Method

**Participants.** Twelve males and 12 females, ranging in age from 18 to 22, participated in the experiment.

**Procedure.** The procedure was the same as in Experiment 2 with a few exceptions. First, only one reference location was tested per path. Second, after their first pointing response to a target location on the path, participants were asked to point to the door through which they had entered the room. Therefore, there were two trials for each of the four paths tested, for a total of eight trials (four aligned and four contraaligned, across paths). Third, confidence ratings were collected at the end of the experiment. Participants were asked to rate their confidence in the overall accuracy of their pointing responses on a scale of 1 (*not at all confident*) to 7 (*very confident*).

### Results

A 2 (sex) × 2 (trajectory) × 2 (path) × 2 (target [path location, door]) × 2 (alignment) ANOVA, with repeated measures on the last two factors, was conducted on the error and latency data. Alignment effect sizes are reported in Table 2. Confidence ratings were analyzed without the alignment factor.

**Pointing error.** Mean pointing errors are shown in Figure 6. There was a main effect of trajectory,  $F(1, 16) = 15.21$ ,

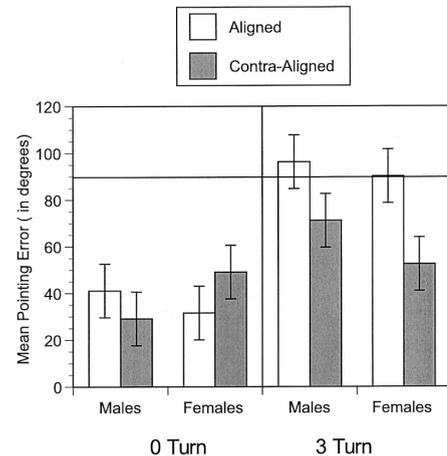


Figure 6. Mean pointing error as a function of type of trajectory, sex, and alignment in Experiment 3. The horizontal line represents random performance, and error bars represent the standard error of the mean.

$MSE = 2,501.79$ ,  $p = .001$ , and an Alignment × Trajectory interaction,  $F(1, 16) = 4.39$ ,  $MSE = 1,591.54$ ,  $p = .05$ . As expected, pointing errors in the 3-turn condition were significantly greater than in the 0-turn condition in both the aligned,  $t(30) = 4.36$ ,  $p < .001$ , and contraaligned conditions,  $t(30) = 1.75$ ,  $p = .04$ . A two-tailed test of the simple effect of alignment indicated no effect in the 0-turn condition,  $t(16) < 1.0$ , but a significant reverse effect in the 3-turn condition,  $t(16) = -2.73$ ,  $p = .02$ .

Inspection of the 3-turn results depicted in Figure 6 indicates that males and females in the aligned condition but not the contraaligned condition were performing at chance. Chance performance equals 90°, because pointing errors can vary from 0° to 180°, and a uniform distribution of pointing errors, which would characterize random performance, has a mean equal to 90°.

**Pointing latencies.** Mean pointing latencies are shown in Figure 7. There was a main effect of target,  $F(1, 16) = 12.81$ ,  $MSE = 1.64$ ,  $p = .003$ , indicating that it took participants longer to point to locations on the path ( $M = 4.8$  s) than to the door of the room ( $M = 3.9$  s). This is likely to be a practice effect, because participants always pointed to a path location first and the door second. Moreover, the door was a constant target across trials, so as soon as participants finished pointing to the path location, they could prepare to point to the door, even before the trial onset.

There was a Sex × Alignment interaction,  $F(1, 16) = 6.98$ ,  $MSE = 1.64$ ,  $p = .018$ , and a Trajectory × Alignment interaction,  $F(1, 16) = 5.09$ ,  $MSE = 1.64$ ,  $p = .038$ , both of which were qualified by a Sex × Trajectory × Alignment interaction,  $F(1, 16) = 5.78$ ,  $MSE = 1.64$ ,  $p = .028$ . A two-tailed test of the simple effects of alignment showed that the interaction is attributable to a significant reverse effect of alignment on the response latencies of males in the 3-turn condition,  $t(16) = -3.89$ ,  $p = .001$ , but no significant effect of alignment in any of the other conditions.

**Confidence.** There was a main effect of trajectory,  $F(1, 16) = 24.05$ ,  $MSE = 0.92$ ,  $p < .001$ , qualified by a Sex × Trajectory interaction,  $F(1, 16) = 10.23$ ,  $p = .006$ . Males were significantly more confident in the 0-turn ( $M = 5.33$ ) than the 3-turn ( $M = 2.17$ ) condition, but females were not ( $M = 4.00$

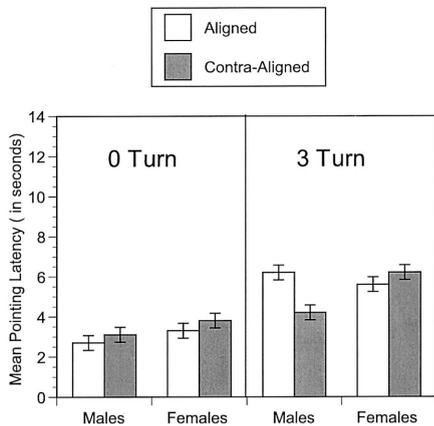


Figure 7. Mean pointing latency as a function of type of trajectory, sex, and alignment in Experiment 3. Error bars represent the standard error of the mean.

and 3.33, respectively). Also, males were significantly more confident than females in the 0-turn condition but significantly less confident in the 3-turn condition.

### Discussion

Males and females performed similarly on the updating task: They were oriented to the study space in the 0-turn conditions ( $M = 36.3^\circ$  and  $39.1^\circ$  in the aligned and contraaligned conditions, respectively) and in the 3-turn contraaligned condition ( $M = 61.9^\circ$ ) but not the 3-turn aligned condition ( $M = 93.3^\circ$ ). But even though performance was nonrandom at the end of the 3-turn contraaligned trajectory, orientation coding was fairly coarse, and with the additional  $180^\circ$  turn in the aligned 3-turn condition, orientation broke down completely. Thus, under the present test conditions, the capacity of the self-to-object updating mechanism may be limited to three  $180^\circ$  turns. We next discuss how the Experiment 3 updating results inform the Experiment 2 spatial-memory results.

**Zero-turn condition.** First we consider the findings for females and then those for males. Females' performance in the 0-turn condition of Experiment 3 largely mirrored their performance in the 0-turn condition of Experiment 2, and it is consistent with the idea that if reasonably well oriented to the study space, females will retrieve relative direction (regardless of whether in the context of a spatial-memory task or an updating task) directly from an updated self-to-object WM representation. Notably, even though the effect of alignment on pointing latency was nonsignificant in both cases, the effect size in Experiment 3 ( $r = .17$ ) approached the effect size in Experiment 2 ( $r = .25$ ), which is consistent with our interpretation that the Experiment 2 findings indicate retrieval from an updated self-to-object representation. The tendency for less efficient retrieval in the contraaligned condition may be attributable to less certainty about orientation following the  $180^\circ$  turn.

Male performance in the 0-turn condition of Experiment 3 suggests males were relatively well oriented to the test space at the end of both the aligned and contraaligned 0-turn trajectories. This finding needs to be reconciled with male orientation-specific per-

formance observed in the 0-turn condition of Experiment 2. That is, if males were oriented to the study space at the end of the aligned and contraaligned trajectories in the 0-turn condition of Experiment 2, why didn't they retrieve target location directly from their updated WM representation?

The virtual-views hypothesis can explain orientation-specific performance in the 0-turn condition if retrieval is from LTM. This is because the 0-turn trajectories have either no change in direction (the aligned condition) or only one major change in direction (the contraaligned condition), affording an insufficient number of virtual views from different facing directions to form an orientation-free LTM representation. Thus, at test an orientation-specific representation would be retrieved. However, this account is problematic because it requires that males discard pertinent information in WM in favor of retrieving partial information<sup>6</sup> from LTM.

There is another, as yet unconsidered, explanation that, although ad hoc, seems more plausible than retrieval from LTM. This explanation rests on the between-subjects manipulation of number of turns and the fact that the spatial-memory task can be solved by a variety of strategies but the updating task cannot. To explain, in Experiment 3 relative direction must be computed on the basis of self-to-object updating, regardless of whether the participant is assigned to the 0-turn or the 3-turn condition. In contrast, in the spatial-memory task of Experiment 2, males in the 0-turn condition may have adopted a different strategy than did males in the 3-turn condition. We have taken the position that the spatial-memory task can be solved either by retrieving an updated self-to-object representation from WM or by retrieving a representation of the path from LTM. A third strategy is suggested by the alignment effect for error shown by males in the 0-turn condition. This strategy, which we call a *visuospatial imagery* strategy, entails holding in WM an image of the path as it appeared from the study site, while traversing the trajectory to the test site.

As reviewed earlier, existing evidence suggests that self-to-object updating is automatically engaged during nonsighted locomotion (Farrell & Robertson, 1998; Farrell & Thomson, 1998). Although automatic processes are often characterized as both (a) occurring outside of volitional control and (b) requiring minimal attentional resources, Farrell and Robertson (1998) emphasized that their results support automaticity only in its former sense. Indeed, because it is inhibited under cognitive load (Smyth & Kennedy, 1982), self-to-object updating is likely to demand attentional resources. Thus, if males in the 0-turn condition adopted an imagery strategy, and if holding a static, orientation-specific image of the path in WM is resource demanding, then updating may have been inhibited because of a lack of sufficient resources.

If males did indeed adopt an imagery strategy, they may have done so to optimize their overall accuracy. They were notably more accurate in the 0-turn aligned trials of Experiment 2 ( $M = 12.5^\circ$ ) than in the comparable updating trials of Experiment 3 ( $M = 41.2^\circ$ ), and they were similarly accurate on the contraaligned trials of Experiments 2 ( $M = 31.2^\circ$ ) and 3

<sup>6</sup> By partial information we mean that the direction of the target can be computed directly from the orientation-specific representation in the case of aligned trials, but in the case of contraaligned trials the LTM representation must be transformed prior to computing target direction.

( $M = 29.1^\circ$ ). So for males, relative direction may be recovered with greater precision from an orientation-specific WM image of the path than from an updated self-to-object representation. Moreover, the geometric transformation required for WM to compute relative direction on contraaligned trials is done at no cost to accuracy relative to that incurred by updating, which may be attributable to male mental-rotation skills (e.g., Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995).

Clearly, additional research will be needed to test the visuospatial imagery explanation for male performance when short trajectories link the study and test sites in the spatial-memory task. Most important to the purpose of the present experiments is the Experiment 3 finding that males remain oriented to the test space over extended trajectories, providing ample opportunity for multiple virtual views of the path to form an orientation-free LTM representation.

*Three-turn condition.* The accuracy results observed in Experiment 3 differed substantially from those observed in the same condition in Experiment 2, suggesting that in the 3-turn condition neither males nor females used an updated self-to-object representation to solve the spatial-memory task. Together, the male findings from Experiments 2 and 3 provide strong support for the virtual-views hypothesis. The results from the 3-turn condition of Experiment 3 show that males stay oriented to the study space long enough to experience multiple virtual views of the path. The results from the 3-turn condition of Experiment 2 suggest that males are able to integrate those virtual views of the path into an orientation-free representation.

Like males, females were oriented to the study space long enough to experience multiple virtual views, but unlike males, females showed an alignment effect in the 3-turn condition of Experiment 2. Experiment 3 demonstrated that females were disoriented on about 50% of the trials (i.e., the aligned trials) in the 3-turn condition. Thus, as predicted by the updating hypothesis, when not reliably oriented to the study space, females rely on an orientation-specific representation of the path to guide relative direction judgments.

There are two ways to interpret the finding of orientation specificity. According to the updating hypothesis, females retrieve an orientation-specific LTM representation of the path formed at study, which has been unaltered by updating. A second interpretation is that once females realize they are unable to maintain their orientation until the end of the 3-turn trajectory, they adopt a visuospatial imagery strategy. The distinction between the two interpretations is theoretically important, because the former implies that females are unable to integrate virtual views, whereas the latter suggests that females adopt a strategy that prevents virtual views.

## General Discussion

Table 2 helps to summarize the results of the three experiments. If we take pointing error as our primary measure of orientation specificity, then the male results are consistent with the virtual-views hypothesis. Males showed no alignment effect following a cloverleaf trajectory in the study space, when spatial memory was tested either on the path ( $r = -.18$ ) or off the path ( $r = -.06$ ). When wheeled directly to the test site, males showed an alignment effect in an on-path test of spatial memory ( $r = .33$ ). These

findings are consistent with retrieval from an orientation-free representation following an extended trajectory within the study space but not after a limited trajectory. Experiment 3 showed that males were oriented to the study space during most of the extended trajectory, and hence had an opportunity to experience multiple virtual views. Moreover, when comparing the effect sizes for males in the 3-turn updating task with those in the 3-turn spatial-memory task of Experiment 2, it is clear that males did not rely on an updated self-to-object representation to produce their orientation-free performance.

The male results are somewhat less consistent when response latency in the off-path spatial-memory task is taken into account. Because of the relatively strong alignment effect for latency ( $r = .46$ ), we have argued that males in this condition formed a partially orientation-free representation. Thus, a more comprehensive account of the findings suggests that multiple virtual views modify the orientation-specific representation formed at study into either a partially or a fully orientation-free representation by the time the test site is reached. The alignment effect found in the 0-turn spatial-memory task is consistent with the idea that if males are immediately disoriented with respect to test space or if the transport trajectory does not afford multiple views of the test space, males will solve the task using an orientation-specific representation. Unresolved is whether the orientation-specific representation resided in WM, LTM, or both, during the 0-turn trajectory.

For females, prior findings of orientation-free performance with on-path testing are likely to be attributable to an updated self-to-object representation in WM. When females were tested off path, so that an updated self-to-object representation did not directly specify the direction of the target, they showed orientation-specific performance ( $r = .60$  and  $.62$  for response time [RT] and error, respectively). Similar performance was observed when females were tested on the path following a cloverleaf trajectory that was disorienting about 50% of the time ( $r = .34$  and  $.30$  for RT and error, respectively). Females showed orientation-free performance in the spatial-memory task only when reliably oriented to the path, which in the present study was after a simple, limited trajectory ( $r = .25$  and  $.06$  for RT and error, respectively).

Unresolved is why females fail to develop an orientation-free representation over the course of an extended trajectory in the study space. Is this because they cannot integrate multiple virtual views experienced while updating, as proposed in the updating hypothesis? Or is it because they hold an orientation-specific image of the path in WM that inhibits updating?

Together, the male and female findings reported here can explain earlier reports of orientation-free performance with on-path testing, if the trajectories used in those earlier studies were complex enough to provide multiple views of the path but not complex enough to be disorienting. There has been some difficulty replicating Presson and colleagues' (Presson et al., 1989; Presson & Hazelrigg, 1984) initial reports of orientation-free performance (Roskos-Ewoldsen et al., 1998; Sholl & Nolin, 1997), which may be attributable to the fact that there are likely to be a small set of trajectories that meet the aforementioned requirements. Moreover, with a few exceptions, in prior studies the trajectories linking the study and test sites have been largely uncontrolled. Yet another reason orientation-free performance may have been difficult to replicate is that there appear to be a small number of both male and

female outliers who show extreme alignment effects, which could mask the orientation-free performance of the majority.

### *Sex Differences*

Prior orientation-specificity studies have sometimes shown an overall male advantage in pointing accuracy (Presson et al., 1989; Roskos-Ewoldsen et al., 1998), but there have been no prior reports of Sex  $\times$  Alignment interactions. Thus, the present findings suggesting that different cognitive mechanisms may contribute to male and female orientation-free performance were unexpected. Relatedly, there have been other reports of surface similarities in male and female navigational performance that are attributable to different underlying competencies, but these have been for sighted navigational tasks (Bever, 1992; Lawton, Charleston, & Zieles, 1996; Sandstrom, Kaufman, & Huettel, 1997). The extent to which the competencies that underlie sighted, active navigation overlap the competencies engaged during nonsighted, passive transport is unknown. That said, it is of interest to review the different competencies males and females use when solving sighted, navigational problems.

For the most part, both self-report measures and behavioral evidence are consistent with the idea that males are more likely than females to rely on orientation strategies and geometric cues in sighted navigation, whereas females are more likely than males to rely on route strategies and landmark cues (Bryant, 1982; Holding & Holding, 1989; Lawton, 1994; Lawton et al., 1996; Lawton & Morrin, 1999; Moffat, Hampson, & Hatzipantelis, 1998; Sandstrom et al., 1997; Sholl, Acacio, Makar, & Leon, 2000; Waller, 2000; but see also Montello & Pick, 1993; O'Laughlin & Brubaker, 1998).<sup>7</sup> Orientation strategies involve maintaining updated knowledge of one's location and facing direction relative to a global reference frame (e.g., compass directions, nonvisible landmarks, and printed maps); whereas, route strategies involve anticipating egocentric responses to local landmarks. It is interesting to note that in the nonsighted updating task of Experiment 3, both males and females showed the same level of proficiency when using an orientation (or updating) strategy; however, only males integrated their updated virtual views of the space into an orientation-free representation.

A primary question raised by the present findings is why do males but not females integrate virtual views of the study space to form an orientation-free representation. The answer to this question may come from taking a closer look at how visuospatial WM is deployed during the trajectory linking the study and test sites. Recent behavioral and neuroscientific evidence suggests a spatial WM that is separable from a visual-object WM (e.g., Baddeley & Logie, 1999; Postle & D'Esposito, 1999), and we have identified three different visuospatial WM processes that may be engaged during the trajectory to the test site: self-to-object updating, integration of multiple virtual views, and rehearsal of a visuospatial image of the path. Therefore, in addition to the unresolved issues we have already identified, the potential involvement of multiple WM systems and processes in the formation of spatial memories raises a host of additional questions, which include the following: How are the aforementioned processes distributed across visual-object and spatial WM? What are their resource requirements and do those differ for males and females? and Do they compete for a common pool of attentional resources?

Perhaps of some relevance to the integration of virtual views is the finding that males are more proficient than females on desktop measures of the ability to integrate the Euclidean interrelations between landmarks appearing in nonoverlapping views of a test space (Galea & Kimura, 1992; Holding & Holding, 1989; Muehl & Sholl, 2001). Additionally, recent evidence suggests that spatial integration is a resource-limited process (Pearson, Logie, & Gilhooly, 1999; Vecchi & Richardson, 2000), and sex differences favoring males in spatial WM capacity (Capitani, Laiacona, & Ciceri, 1991) could explain why males integrate views and females do not. However, it is unclear to what extent the mechanisms that underlie the integration of spatial information from either dynamic visual models or static maps displayed on the desktop are similar to those that underlie integration during nonsighted navigation when totally immersed in three-dimensional space.

We have not yet discussed mental rotation ability, which is a competency directly relevant to orientation-specific performance and for which there are well-documented sex differences (e.g., Linn & Peterson, 1985; Voyer et al., 1995). When an orientation-specific path representation mediates performance on contra-aligned trials, a 180° geometric transformation is needed to compute the correct response angle. We have suggested that their proficiency in mental rotation could, in part, explain why males may have preferred an imagery strategy in the 0-turn spatial-memory task of Experiment 2. Aside from influencing strategy choice, we can find no obvious link between mental rotation and the competencies contributing to orientation-free performance.

### *Summary*

Although they have similar self-to-object updating ability, males and females appear to solve in different ways a standard test of the orientation-specificity of spatial memory. Prior findings of orientation-free performance following passive transport from the study site to the test site (Presson et al., 1989; Presson & Hazelrigg, 1984; Sholl & Nolin, 1997) are likely due to the following combination of factors. In the case of females, orientation-free performance is likely attributable to retrieval from an updated self-to-object representation in WM. Retrieval from an updated WM representation is apt to occur if the trajectories are not sufficiently complex to be reliably disorienting or if auditory cues, which were not routinely masked in earlier studies, serve as directional beacons during transport. In the case of males, orientation-free performance is likely attributable to retrieval from an orientation-free memory representation. Males appear to build up orientation-free representations from the multiple virtual views experienced while they were still oriented to the test space.

Although the present findings help to clarify the factors producing orientation-free performance in prior studies, they raise questions about the factors that contributed to the orientation-specific performance observed in the present study. In the present experiments, alignment effects were observed for males when a short

<sup>7</sup> Generally, the behavioral evidence for an orientation strategy is the relative accuracy with which people are able to point in the direction of nonvisible targets from a specified reference location. The behavioral evidence for a route strategy is the relative disadvantage manifested when people are forced to solve navigational problems in the absence of stable landmarks.

trajectory linked the study and test sites and for females when the linkage was via an extended trajectory. Of particular interest is (a) whether the orientation-specific representation that produced alignment effects in these conditions resided in WM or LTM and (b) the resulting implications for self-to-object updating. A more general objective for future research is a better understanding of the role of the visuospatial WM systems and processes in the formation of large-scale spatial memories by males and females.

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