

Spatial updating of virtual displays during self- and display rotation

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In four experiments, we examined observers' ability to locate objects in virtual displays while rotating to new perspectives. In Experiment 1, participants updated the locations of previously seen landmarks in a display while rotating themselves to new views (viewer task) or while rotating the display itself (display task). Updating was faster and more accurate in the viewer task than in the display task. In Experiment 2, we compared updating performance during active and passive self-rotation. Participants rotated themselves in a swivel chair (active task) or were rotated in the chair by the experimenter (passive task). A minimal advantage was found for the active task. In the final experiments, we tested similar manipulations with an asymmetrical display. In Experiment 3, updating during the viewer task was again superior to updating during the display task. In Experiment 4, we found no difference in updating between active and passive self-movement. These results are discussed in terms of differences in sources of extraretinal information available in each movement condition.

A remarkable accomplishment of the human perceptual system is the experience of a stable world amid changing perspectives. When movement occurs, the cognitive system updates the locations and orientations of objects in the environment accordingly. For example, when an observer turns 90° clockwise, a chair that was initially on the right is now perceived as being in front of the observer. Likewise, when the chair itself is moved from its rightward position to in front of the stationary observer, it is not perceived as a new object in a different location, but rather as the same chair having undergone a displacement. A recent trend in research in how the cognitive system achieves such stability is to focus primarily on the nature of retinal inputs, independently of the type of perspective change carried out (e.g., Biederman & Gerhardstein, 1993, 1995; Bühlhoff & Edelman, 1992; Tarr, 1995; Tarr & Bühlhoff, 1995; Tarr & Pinker, 1989). Few researchers have examined the role that perspective

change itself may play (Simons & Wang, 1998; Wang & Simons, 1999). Although the examples of viewer and object movement described above may result in successful updating, the questions of whether these processes are similarly efficient and, if not, what factors may contribute to the differences are empirical ones. The aim of this paper is to examine these issues more closely.

There is some evidence suggesting that spatial updating is not equivalent across different types of perspective change. In much of this work, observers' updating performance during *imagined* self- and display movement has been examined (e.g., Amorim & Stucchi, 1997; Huttenlocher & Presson, 1979; Presson, 1982; Wraga, Creem, & Proffitt, 2000). In these experiments, blindfolded participants typically update the memorized locations of objects in a display after either imagining themselves rotating about the display or imagining the display itself rotating. Updating performance is usually found to be faster and more accurate after imagined rotations of the viewer than of the display. This advantage has been shown to persist whether the observer is immersed within the display or separate from it, and also when the display configuration is reduced to only one object (Wraga et al., 2000).

A viewer advantage also has been found for spatial updating during physical movement of the self versus physical movement of the display. Simons and Wang (1998) showed that participants' ability to detect covert changes of a configuration of objects viewed from different perspectives depended on whether the display or the observer

This research was supported by NIMH Grants MH11462 and MH52640, NASA Grant NCC2925, and CMU/DARPA Grant 539689-52273. The authors thank Maryam Allahyar, Heinrich Bühlhoff, Jack Loomis, Donald Parker, and Bernhard Riecke for comments on an earlier draft. We thank David Staack for creating the virtual scene and Chris Sturgil for painting it. We thank Mackenzie Carpenter, Jeanine Stefanucci, and Anil Asrani for assistance in data collection. Correspondence concerning this article should be addressed to M. Wraga, Smith College, Department of Psychology, Northampton, MA 01063 (e-mail: mwraga@smith.edu).

moved. Performance was quite good for view changes produced by observer movement; however, it deteriorated when the changes were caused by rotations of the display itself. The latter result persisted even when participants actively controlled the rotation of the display via an attached rod (Wang & Simons, 1999).

A common factor of these experiments is that optical information for the self- and display transformations was not available. In the imagined-movement studies, transformations were performed from memory; in the physical-movement studies, the displays were covered during transformations. In the absence of optical information specifying perspective change, the observer must solve these tasks solely by transforming representations of the spatial reference frames corresponding to each imagined movement. Imagined viewer rotation involves transformation of the egocentric reference frame, which specifies an object's location and orientation with respect to the intrinsic axes of the observer's body (see, e.g., Howard, 1982). Imagined display rotation involves transformation of the object-relative reference frame, which specifies the relationship of one object to others (see, e.g., Easton & Sholl, 1995). The difficulties found in imagined display rotations performed from memory have been attributed to cognitive deficits in transforming cohesive representations of the object-relative reference frame (Wraga et al., 2000).

How does the presence of optical information affect updating performance during viewer and display movement? One might predict that optical flow generated by a moving environment would improve updating performance to that of viewer movement, perhaps by diminishing observers' need to rely on representations of the object-relative frame. However, several studies suggest that updating during viewer movement continues to remain advantageous under full-cue conditions (Chance, Gaunet, Beall, & Loomis, 1998; Christou & Bühlhoff, 1999; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Pausch, Proffitt, & Williams, 1997). For example, Chance et al. (1998) tested participants' ability to update targets encountered while they were immersed in virtual mazes. The participants traversed the mazes using different locomotion modes. In the walking condition, they walked normally through a given virtual path. In the visual condition, they transported themselves through the path via a hand-held joystick and thus received only visual information. Despite the fact that optical flow information was nearly identical across conditions, Chance et al. found that updating performance during walking was superior to updating performance during visual transport. Pausch et al. (1997) found similar results in a task in which participants immersed in a virtual room searched for items in it by turning about the room via a head-tracked virtual reality (VR) system or via a hand-tracked joystick. The participants were better able to keep track of the search space during the former movement than during the latter, even though optical information was

held constant across conditions. Collectively, these findings suggest that sources other than retinal inputs may be critical to spatial updating during self-movement.

Going Beyond the Retina

The sources of extraretinal information available during viewer and display movement usually are not equivalent. During viewer movement, changes in optical information are accompanied by inputs from proprioceptive and vestibular systems. When an observer walks, for example, proprioceptive information specifying such movement is elicited from contact of the soles of the feet with the ground and from receptors in the muscles, tendons, and joints of the legs. The vestibular system registers information for the position of the head with respect to the gravitation vertical, and for linear body acceleration via the otolith organs and angular body acceleration via the semicircular canals. In contrast, such information is unavailable during display movement, unless there is some observer interaction with the display.

The findings of Chance et al. (1998) and Pausch et al. (1997) mentioned previously implicate proprioceptive and vestibular systems in spatial updating during viewer movement. Further evidence comes from studies on navigation without vision, which have shown that human beings are capable of reconstructing whole-body displacements using proprioceptive and vestibular inputs only, a process termed *path integration* (e.g., Berthoz, Israël, Georges-François, Grasso, & Tsuzuku, 1995; Grasso, Glasauer, Georges-François, & Israël, 1999; Loomis, Klatzky, Golledge, & Philbeck, 1999). (For related abilities in animals, see, e.g., McNaughton, Chen, & Markus, 1991; Samsonovich & McNaughton, 1997.) For example, Grasso et al. (1999) found that blindfolded participants transported in motorized vehicles could reproduce linear displacements of distances of up to 10 m, even when prevented from utilizing the same speed characteristics used during initial movement. Replications of angular whole-body displacements also have been tested. Brookes, Gresty, Nakamura, and Metcalfe (1993) found that normal observers who were rotated in darkness up to 180° could accurately counterrotate themselves back to their starting positions. Interestingly, patients with vestibular deficits were unsuccessful at performing the same task.

The contribution of vestibular and proprioceptive information to spatial updating also has been assessed in studies showing superior performance with physical versus imagined self-movement (e.g., Farrell & Robertson, 1998; Presson & Montello, 1994; Rieser, 1989; Rieser, Garing, & Young, 1994; Rieser, Guth, & Hill, 1986). For example, Rieser (1989) found that blindfolded participants' ability to point to the location of an object from a novel perspective was more accurate when they were physically moved to the viewpoint than when they merely imagined moving to it. Moreover, updating during physical self-movement has been shown to be independent of the distance traversed. Researchers have interpreted the

latter finding as evidence of “automatic” processing: The proprioceptive information available during self-movement ensures that an observer’s egocentric reference frame is always aligned with his or her current perspective. Updating thus occurs in tandem with movement (Farrell & Robertson, 1998; Presson, 1982; Rieser, 1989).

Another difference between viewer and object movement is that the perspective change accompanying the former is usually actively self-produced, whereas that of the latter is not. The critical extraretinal information underlying this distinction is most likely efference copies of motor commands (Bridgeman, 1986; von Holst & Mittelstaedt, 1950). When an observer moves his body, a copy of the motor commands sent to the muscles may be incorporated into the representation of that action, where it can be used to update changes in position as they occur. Direct comparisons of active and passive movement for spatial tasks have yielded mixed results (e.g., Gugerty, 1997; Larish & Andersen, 1995; Péruch, Vercher, & Gauthier, 1995; Wang & Simons, 1999; Yardley & Higgins, 1998). For example, active participants are better than passively moved participants at predicting future self-positions within simulated optic flow fields (Larish & Andersen, 1995). Active navigation through a simulated driving scene also has been shown to elicit greater recall of the locations of potentially dangerous cars than passive navigation (Gugerty, 1997). However, other studies suggest that active control may be less critical to spatial processing. Wang and Simons (1999) found that participants who were passively moved to a new viewpoint about a display were as accurate at updating the display as participants who had actively moved. Yardley and Higgins (1998) found a similar result for updating during unidirectional angular displacements up to 180°. In this experiment, blindfolded participants imagined that a large circle in which they stood was a clock face. After passive or active rotation of their bodies about the clock’s center, the participants updated their new locations by reporting which number of the clock they would now be facing. Performance was found to be equivalent across both types of movement. However, an active-movement advantage emerged in a subsequent experiment, in which participants actively or passively moved through a combined series of two to three counterdirectional rotations. These results suggest that active control may be important for keeping track of more complex, multidirectional movements.

Overview of the Experiments

To examine these issues further, we conducted a series of experiments in which updating performance during viewer movement was compared with updating performance during movement of a display about the viewer. We used a novel spatial updating task, which employed a room-like display created in VR. Our specific aim was to examine updating during viewer and display movement within a perceptual context. We wished to extend

the viewer updating advantage found by Simons and Wang (1998), Wraga et al. (2000), and others to the domain previously used by Chance et al. (1998) and Pausch et al. (1997), in which optical information was continuously present. Thus, we predicted that participants’ performance would be faster and more accurate during viewer rotation than during display rotation. With optical information kept similar over viewer and display movement conditions, we also were able to assess the contribution of some sources of extraretinal information to spatial updating. We speculated that vestibular and proprioceptive information found in viewer movement would facilitate spatial updating performance, but that active control of movement would play a less important role.

We conducted four experiments to test these hypotheses. In the first two, a symmetrical VR display was used. In Experiment 1, participants either rotated the display about themselves (*display task*) or rotated themselves in place about the display (*viewer task*). In Experiment 2, we assessed the role of extraretinal information in the viewer advantage by comparing updating performance during active versus passive self-movement. In the active task, seated participants searched for items in the display by rotating themselves in a swivel chair. In the passive task, participants were rotated in the chair by the experimenter. In Experiments 3 and 4, similar manipulations were tested using a more complex display, which consisted of a round room with five alcoves appearing in an asymmetrical configuration.

**EXPERIMENT 1
Viewer and Display Rotations:
Symmetrical Display**

In the first experiment, we examined participants’ ability to update the locations of objects within a symmetrical, four-object display. Previous research has shown that people are faster and more accurate at keeping track of their surroundings during imagined self-movement about a simple symmetrical display than during imagined movement of the display about themselves (Wraga et al., 2000). In the present experiment, we tested for a similar trend for updating during physical movement with optical information fully available. Participants were required to rotate in place to find a given object appearing in one of four alcoves in a square VR room. On finding the object, they were asked to locate another alcove with respect to the new viewpoint. The participants searched the virtual room by either turning themselves in place (*viewer task*) or by turning the virtual room around their stationary bodies via a handheld joystick (*display task*). Thus, beyond the optical information present, the viewer task involved proprioceptive inputs from the soles of the feet and the legs, as well as vestibular inputs. The display task involved proprioceptive inputs specific to hand positioning with respect to the joystick—that is, haptic information.

We predicted that updating performance would be faster and more accurate in the viewer task than in the display task.

Method

Participants. Twenty-four University of Virginia students (14 female, 10 male) participated in the experiment as part of a research credit requirement. All of the participants were tested individually. None knew of the hypothesis being tested.

Equipment and Stimuli. The virtual environment was designed and created using Alice, a 3-D computer graphics authoring software program. Alice was run on a Gateway 2000 computer with a 233-MHz Intel Pentium processor via a Monster 3-D PCI Video Multimedia Device graphics card. The stimuli were transmitted to a Virtuality Visette Pro head-mounted display (HMD), which had two active-matrix color LCDs operating in a pseudo-VGA video format. The resolution of each display screen was 640 (horizontal) \times 480 (vertical) pixels per color pixel. The field of view (FOV) per eye was 60° (horizontal) \times 46.8° (vertical). Viewing in the HMD was biocular: The two display screens presented the same image to each eye. The images were viewed through collimating lenses that allowed the observer's eyes to focus at optical infinity.

Stimuli were tracked with a Polhemus InsideTrak magnetic tracking system. This system consisted of six-degrees-of-freedom trackers, which continuously recorded and updated x , y , and z coordinates as well as pitch, roll, and yaw movements. The end-to-end latency between observer movement and scene updating was approximately 100 msec. In the viewer task, the tracking system recorded the movement of the viewer's head in the HMD. To emulate real optical flow during self-movement, the virtual world moved in the direction opposite that of head movement. In the display task, stimuli were transmitted to the HMD, but the HMD was not tracked. Instead, the tracking system recorded the movement of a 15 \times 15.5 \times

4.5 cm hand-held joystick. A 14-cm handle controlled roll and yaw through 360° of movement; pitch was controlled via a 4-cm-diam dial atop the handle. The speed of these movements was controlled by the participant. To emulate real room movement, the virtual world moved in the same direction as joystick movement.

The virtual scene consisted of a 2.7 \times 2.7 \times 2.7 m cube-like room with white walls of minimal texture, but sufficient for specifying optical flow (see Figure 1). On the floor appeared a gray carpet, also of minimal texture. The room was illuminated from an invisible light source positioned 4 m above the floor's center. Each wall contained a 45 \times 56 \times 74 cm alcove, or shelf, designed to hold single objects. The alcoves were centered on each wall at a height of 1.08 m from the ground. Each alcove was a different color (green, yellow, blue, and red). To further differentiate them, the uppermost part of each was marked with a distinctive pattern (e.g., dots, checkerboard, stripes). The four objects appearing in the alcoves were 3-D objects rendered in Alice: a 56 \times 16 \times 48 cm horse, a 69 \times 30 \times 34 cm truck, a 72 \times 36 \times 36 cm fish, and a 58 \times 28 \times 57 cm chicken.

The participant was positioned in the center of the room, 1.2 m from the alcoves. When looking directly at one alcove, the FOV at that distance included the alcove itself and approximately 16° of wall on either side of it; thus, only one alcove could be viewed at a time.

Procedure. All the participants performed in both the viewer and display movement conditions. Before the participants put on the HMD, the experimenter gave them a general description of the virtual room layout. Once the HMD was on, the participants found themselves in the center of the virtual room (see Figure 1). They were permitted to explore the room for as long as they wished by "looking" up and down each of its walls. During the training phase of the viewer task, they explored by turning their bodies in place while tilting their heads. During the training phase of the display task, they controlled the pitch¹ and rotation of the room via the joystick. Once they were acclimated to the virtual space ($M = 1.5$ min), the participants were systematically shown the locations of the four

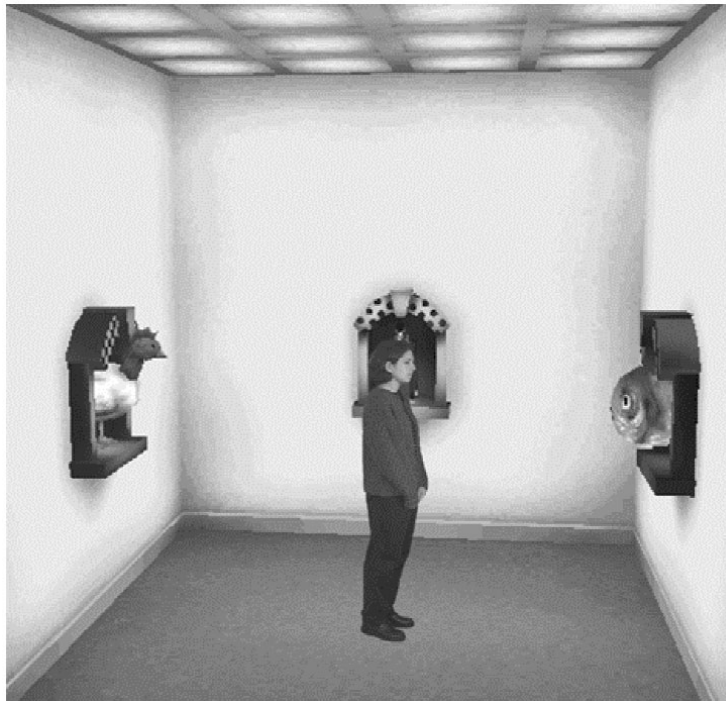


Figure 1. View of the virtual display used in Experiments 1 and 2, with observer added. In the actual experiments, the participants could view only one alcove at a time.

alcoves. They learned the alcove locations (i.e., front, back, right, and left) with respect to a default start position. They were allowed to move freely and were given as much time as necessary to memorize the locations. They were then tested for the alcove locations from a stationary position. Criteria for learning were met if the participants could identify the alcove locations correctly within 1 sec. During the testing and subsequent trials of the viewer task, the participants were instructed to face forward while turning.

Each task was comprised of two components: rotation and location. The participants were told to perform each as quickly as possible. On each trial, one object appeared randomly in each of the four alcoves. The participants first were instructed to find an object (e.g., "Find the chicken") by either rotating themselves counterclockwise (viewer task) or by using the joystick to rotate the room counterclockwise around themselves (display task). The HMD allowed free movement of the head; however, the participants were instructed to face forward during the rotation and location phases. When the participants indicated verbally that they had found the object, the experimenter "froze" the virtual world by temporarily decoupling the HMD or joystick tracking via a buttonpress. This ensured that the participants could not view other alcoves by self- or joystick movement. The participants then were asked to locate one of the alcoves with respect to the new viewpoint (e.g., "Where's the blue alcove?"). They answered verbally with a position relative to themselves (e.g., "left"). After a response was given, the virtual world was unfrozen and the participants returned (via self- or joystick movement) to the default starting position for the next trial. After completing one task, the participants were given a short break out of the HMD before beginning the second task. For the second task, they were presented with a new room (consisting of the same alcoves arranged in a different configuration), and the acclimation and learning procedures were repeated. Response latency (measured from the end of the presentation of a stimulus to the onset of the participant's response) was recorded for both rotation and location components using the computer's timer. The timer was controlled by the experimenter. The experimenter pressed the space bar on the keyboard to initiate and end the timed event. For the location tasks, number of errors also was recorded.

Design. Each participant performed both tasks (viewer and display). Task order was counterbalanced across participants. The locations of the alcoves appeared quasi-randomly across tasks, with the constraint that no alcove occupied the same position twice. Each of the four search degrees of rotation (0°, 90°, 180°, and 270°) was matched with each of the alcove updating locations (front, back, left, and right) for a total of 16 trials in each task. The trials appeared in random order.

Results

Unless otherwise noted, we performed a 2 (task) × 4 (rotation magnitude) × 2 (task order) × 2 (sex) mixed-design analysis of variance (ANOVA) on the data for the experimental subcomponents listed below.²

Rotation latency. No difference in search time was found between viewer and display tasks (see Table 1).

Table 1
Mean Search Latencies (in Seconds) and Standard Errors (SEs) in Experiments 1 and 2

Experiment	Task	Rotation Magnitude							
		0°		90°		180°		270°	
		<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
1	Viewer	0.90	.04	2.09	.38	3.15	.49	4.14	.15
	Display	0.92	.04	2.38	.17	3.13	.15	4.09	.24
2	Active	0.70	.04	2.94	.12	5.32	.23	7.12	.30
	Passive	0.68	.05	4.83	.22	8.93	.28	13.02	.45

The ANOVA revealed only a main effect of rotation magnitude [$F(3,60) = 234.73, p < .001$]. As would be expected, time to search increased linearly with the angular distance of viewer and display movement. There were no other significant effects or interactions.

Location latency. The principal finding was that participants were faster at updating during viewer ($M = 1.42$ sec) than during display ($M = 1.88$ sec) movement. Figure 2A shows mean reaction times (RTs) and standard errors for viewer and display tasks as a function of the magnitude of search rotation. The ANOVA yielded a main effect of task [$F(1,20) = 10.27, p < .001$], but no other effects including rotation magnitude ($p = .20$) and no significant interactions. Thus, updating responses in both tasks were unaffected by the magnitude of initial search rotation.

In an additional analysis, we assessed RTs as a function of the angular distance between new view and alcove to be located. The ANOVA performed on the mean scores replicated the main effect of task [$F(1,20) = 13.58, p < .001$]. The effect of rotation magnitude also was significant [$F(3,60) = 11.83, p < .001$]. Linear contrasts for the rotation magnitude effect yielded a significant RT increase from 0° and 90° distances ($p < .001$), but no differences between RTs for rotations of 90°, 180°, and 270°. We also found a significant task × rotation magnitude interaction [$F(3,60) = 2.92, p < .05$]; however, post hoc comparisons revealed no significant difference in rotation magnitude across tasks. To examine the interaction in a different way, we used paired-sample *t* tests to compare the RTs of the two tasks for each degree of rotation (e.g., Viewer 0 vs. Display 0). At 0°, there was no difference in RT across tasks ($p = .55$). Display RTs were significantly longer than viewer RTs for 90° ($p < .033$) and 270° ($p < .005$). At 180°, display RTs were marginally greater than viewer RTs ($p < .058$; see Figure 2B).

Location accuracy. The principal finding was that the participants made fewer errors in the viewer task ($M = 0.18$) than in the display task ($M = 0.60$). Figure 3A shows mean errors for the two tasks as a function of the magnitude of search rotation. The ANOVA yielded a main effect of task [$F(1,20) = 15.11, p < .001$], but no effect of rotation magnitude ($p = .32$) and no significant interactions.

We also assessed errors as a function of the angular distance between new viewpoint and alcove to be located (see Figure 3B). The ANOVA replicated the main effect of task [$F(1,20) = 13.62, p < .001$] and also yielded a main effect of rotation magnitude [$F(3,60) = 6.92, p < .001$]. Simple contrasts for the rotation magnitude effect yielded an increase in errors from 0° to 90° [$F(1,20) = 15.36, p < .001$], no change from 90° to 180° ($p < .627$), and an increase from 180° to 270° [$F(1,20) = 5.98, p < .03$]. There were no significant interactions.

Discussion

As was predicted, the participants were faster and made fewer errors at spatial updating while rotating their bodies within a virtual room than while rotating the room itself. The fact that rotation times were more or

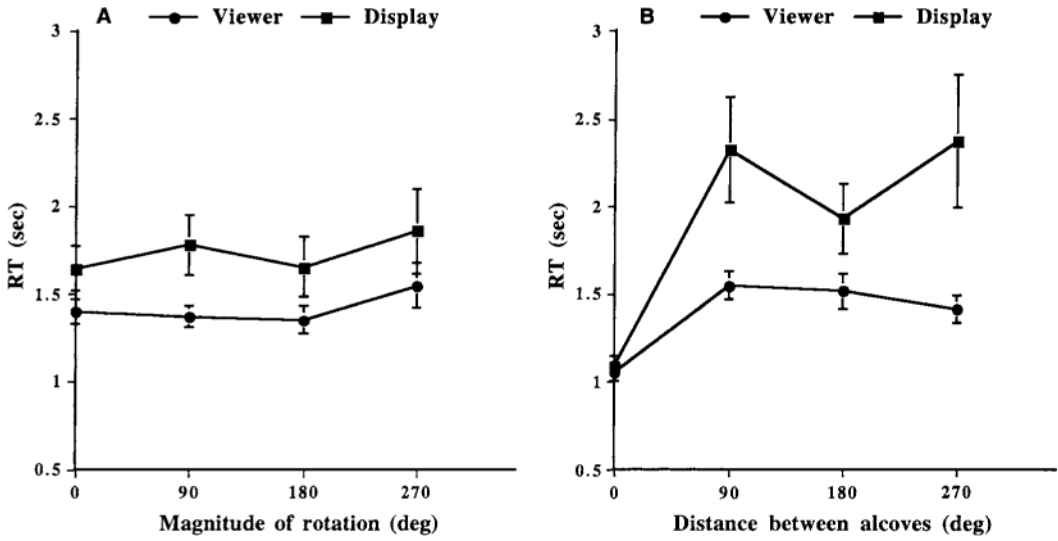


Figure 2. Mean reaction times (RTs) and standard errors in Experiment 1 as a function of (A) magnitude of search rotation and (B) distance between alcoves.

less identical across display and viewer tasks suggests that performance differences in updating were not attributable to differences in the movement devices per se (i.e., joystick vs. HMD). These findings are in line with those of other full-cue studies (Chance et al., 1998; Klatzky et al., 1998; Pausch et al., 1997), as well as those in which optical information was not available (e.g., Presson, 1982; Simons & Wang, 1998; Wang & Simons, 1999; Wraga et al., 2000). They lend support to the notion that updating during viewer and display movement may be subserved by different mechanisms. Such mechanisms might, at least in part, differ by the type and/or amount of extraretinal information available. The dis-

play task elicited haptic information specifying the position of the hand with respect to the joystick, whereas the viewer task elicited proprioceptive inputs for leg position and foot placement as well as vestibular inputs for angular body acceleration. The role of such information in viewer updating was investigated further in Experiment 2.

One way in which viewer and display tasks were similar is that updating RTs in both were unaffected by the magnitude of the search rotation. Although the viewer finding is in agreement with findings of previous studies suggesting that updating occurs in tandem with self-movement (e.g., Farrell & Robertson, 1998; Rieser, 1989), the identi-

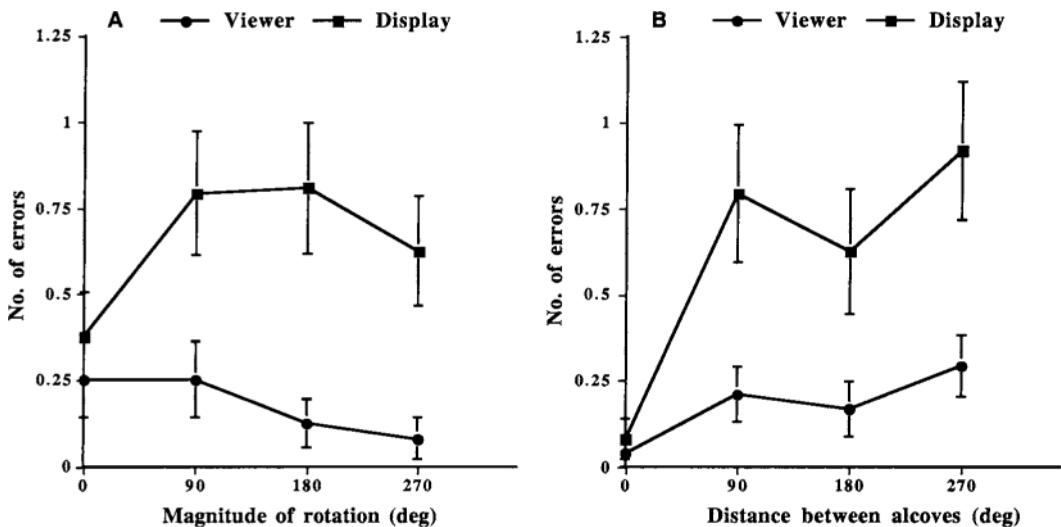


Figure 3. Mean errors (out of a possible 16) and standard errors in Experiment 1 as a function of (A) magnitude of search rotation and (B) distance between alcoves.

cal finding for the display task is, to the best of our knowledge, the first of its kind. Previous studies (e.g., Parsons, 1995; Wraga et al., 2000) have shown updating RTs for imagined object rotations to increase with angular distance. A plausible explanation for the automaticity of display-rotation updating found here might be the presence of visual information during rotation, which could be used to solidify the representation of the rotating display. This issue was addressed further in Experiment 3.

EXPERIMENT 2
Active and Passive Viewer Rotations:
Symmetrical Display

Having demonstrated an updating advantage for viewer movement in Experiment 1, we were interested in discerning what sources of extraretinal information might contribute to this advantage. In Experiment 2, we used the same virtual room and rotation/location components as in Experiment 1, but we tested updating during viewer movement only. Specifically, we compared performance during active and passive self-rotations. In the active condition, participants sat in a rotating chair and searched the virtual room by rotating themselves in the chair. Extraretinal information available in this condition included vestibular inputs similar to those described in Experiment 1; proprioceptive inputs from the soles of the feet, the legs, and changes in pressure on the skin's surface produced by the chair movement; as well as efference copies of motor commands. In the passive condition, seated participants were rotated in the chair by the experimenter. Extraretinal information available included vestibular inputs and, possibly, proprioceptive inputs from changes in pressure on the skin's surface produced by the chair movement. These conditions allowed us to test the relative advantages of active versus passive control to spatial updating during self-movement within a full perceptual context. On the basis of previous studies (e.g., Wang & Simons, 1999; Yardley & Higgins, 1998), we expected the gain from active movement to be minimal.

Method

Participants. Twenty-four University of Virginia students (14 female, 10 male) participated in the experiment as part of a research credit requirement. All of the participants were tested individually. None knew of the hypothesis being tested.

Materials. The materials used were the same as those of Experiment 1.

Procedure. The procedure was identical to that of Experiment 1, except for the following changes. The participants performed in two task conditions: active and passive. Both tasks employed head tracking via the HMD as in the viewer task of Experiment 1; no joystick was used. The HMD allowed free movement of the head during training; however, as in Experiment 1, the participants were instructed to face forward during the rotation and location phases. In the active task, the participants sat in a rotating chair. To learn the display and to search for items in the rotation component, they rotated themselves clockwise in the chair using their feet. In the passive task, the participants also sat in the chair but were turned by the experimenter during the training and rotation phases. For each trial,

the participants in the passive task adjusted the position of their feet so that they did not move or touch the ground during rotation. The participants were rotated at a mean angular velocity of approximately 20°/sec.³

Design. The design was identical to that of Experiment 1. The order of tasks (active and passive) was counterbalanced across participants.

Results

Unless otherwise noted, we performed a 2 (task) × 4 (rotation magnitude) × 2 (task order) × 2 (sex) mixed-design ANOVA on the data for the experimental sub-components listed below.

Rotation latency. Because the two search tasks were not equivalent (i.e., one was under active control and the other was not), we did not perform parametric tests on the rotation data. Mean time to search for objects took longer in the passive task in comparison with the active task. As in Experiment 1, time to search increased linearly with degree of rotation (see Table 1).

Location latency. The principal finding was that the participants were slightly but significantly faster at updating during active ($M = 1.24$ sec) than during passive ($M = 1.34$ sec) viewer movement. Figure 4A shows mean RTs and standard errors for passive and active conditions as a function of search rotation magnitude. The ANOVA performed on the mean scores revealed main effects of task [$F(1,20) = 5.43, p < .03$] and rotation magnitude [$F(3,60) = 3.18, p < .03$]. Planned simple contrasts revealed no difference between each of the degrees of rotation. A significant sex × task interaction also was found [$F(1,20) = 5.40, p < .03$]. Post hoc analyses revealed that the males produced the elevated latency in the passive task [passive, $M = 1.41$ sec; active, $M = 1.16$ sec; $F(1,9) = 7.09, p < .03$], whereas the females did not (passive, $M = 1.28$ sec; active, $M = 1.28$ sec; $p = .99$).

We also assessed RTs as a function of the angular distance between new view and updating alcove (see Figure 4B). The ANOVA performed on the mean scores replicated the main effect of task [$F(1,20) = 5.44, p < .03$]. We also found a significant effect of rotation magnitude [$F(3,60) = 24.10, p < .001$]. Linear contrasts for the rotation magnitude effect yielded significant increases in RT between all degrees of rotation (0°–90°, $p < .001$; 90°–180°, $p < .001$; 180°–270°, $p < .005$). The task × task order interaction also was significant [$F(1,20) = 5.45, p < .03$]. Post hoc analyses revealed that the RT difference across tasks occurred for participants who performed the passive task first [$F(1,11) = 9.34, p < .01$], but not for those who performed it after the active task ($p = .835$).

Location accuracy. In general, the participants made few errors. We found no difference in error between the active ($M = 0.21$) and passive ($M = 0.24$) tasks. Figure 5A shows mean errors for passive and active tasks as a function of search rotation. The ANOVA performed on mean errors revealed no main effects or interactions. Figure 5B shows mean errors for the two tasks as a function of the angular distance between new viewpoint and

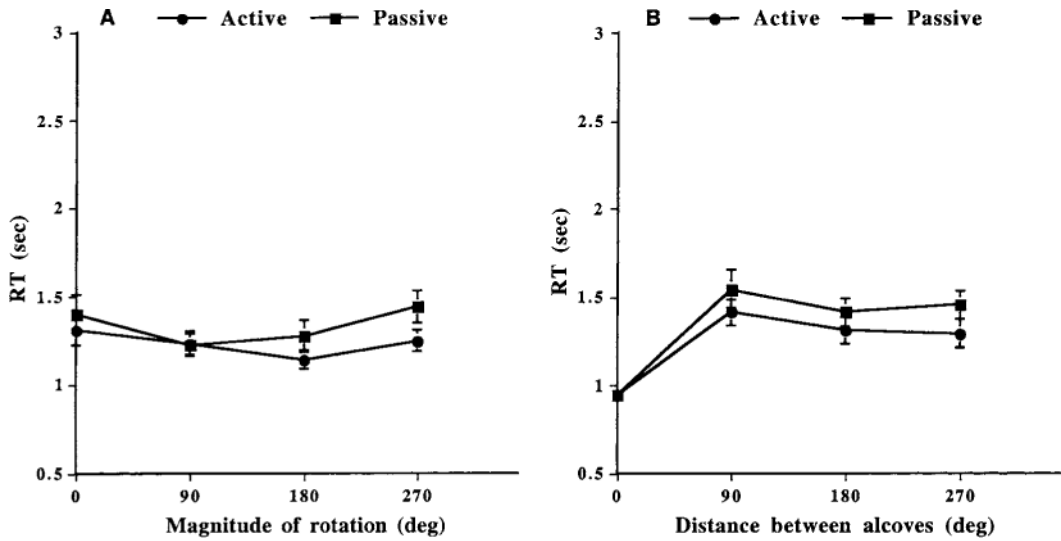


Figure 4. Mean reaction times (RTs) and standard errors in Experiment 2 as a function of (A) magnitude of search rotation and (B) distance between alcoves.

updating alcove. The ANOVA revealed no main effects or significant interactions.

Discussion

The participants who were passively moved to new views were slightly albeit significantly slower at updating ($M_{diff} = +100$ msec) than those who actively moved themselves. However, error rates were similarly low across both tasks, and the level of updating automaticity did not differ across tasks. Thus, the gain in updating performance from self-initiated movement appears to be minimal. Similar findings have been obtained for self-rotations up to 180° (Wang & Simons, 1999; Yardley &

Higgins, 1998). The present findings extend the active-passive similarity to self-rotations of up to 270°. More importantly, the minimal difference between updating conditions suggests that the vestibular and proprioceptive information common to both active and passive tasks may play a more critical role in spatial updating than do efference copies of motor commands, which are available in active movement only.

An alternative explanation of the findings above is that the symmetrical display we used was too simplistic. Differences in spatial updating performance as a function of display complexity have been reported elsewhere (Easton & Sholl, 1995). The display used in the

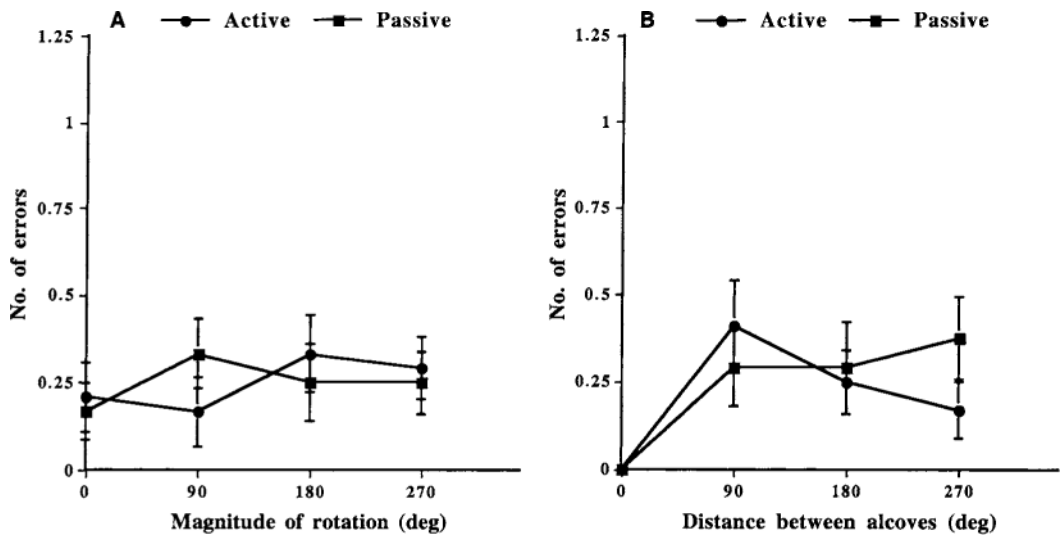


Figure 5. Mean errors (out of a possible 16) and standard errors in Experiment 2 as a function of (A) magnitude of search rotation and (B) distance between alcoves.

present study was sufficiently elementary in that it might have masked real differences between active and passive tasks as well as any lag between physical and projected egocentric reference frames. The symmetrical display contained alcoves that were aligned with the axes of the body. The participants may have been able to use such coordinates to encode the alcove locations, which in turn may have rendered the task nearly effortless. A more complex, asymmetrical display might reveal substantive differences in updating ability across active and passive viewer conditions. We addressed this issue further in Experiments 3 and 4.

We found two noteworthy interactions for location latency. Analysis of the sex \times task interaction revealed that the males had relative difficulties in the passive task, whereas the females did not. Sex differences in spatial cognitive abilities are well documented in the literature (see, e.g., Halpern, 1986), and recent studies have begun to elucidate their neural underpinnings (e.g., Grön, Wunderlich, Spitzer, Tomczak, & Riepe, 2000; Jordan, Wüstenberg, Heinze, Peters, & Jäncke, 2002; Viaud-Delmon, Ivanenko, Berthoz, & Jouvent, 1998). However, most spatial cognition studies showing sex differences have indicated a trend opposite to the one we found: relative difficulties in performance for females versus males. The critical factor in the males' poor performance during the passive task of Experiment 2 may have been the speed at which the participants were rotated, which was about 40% slower than in the active task (passive, $M = 20^\circ/\text{sec}$; active, $M = 34^\circ/\text{sec}$). Because of this speed discrepancy, signals for angular body acceleration picked up by the semicircular canals of the vestibular system differed across tasks. Viaud-Delmon et al. (1998) demonstrated that males tend to use vestibular signals in spatial processing tasks to a greater extent than females, who rely more on visual cues. Thus, we might expect the difficulties in males' performance to dissipate with more congruent rotation speeds across tasks. We address this issue further in Experiment 4.

The second interaction of note pertained to all participants. Those who performed the passive task first experienced difficulties in comparison with those who performed the active task first. Interpretation of the second interaction seems clear-cut: The participants who performed the active task first showed faster updating in the subsequent, passive task in comparison with those who performed the passive task first. Those in the former order thus exhibited a transfer of updating ability from active to passive viewer tasks. This is an interesting finding that warrants further investigation.

EXPERIMENT 3 Viewer and Display Rotations: Asymmetrical Display

In Experiment 3, we tested whether the viewer advantage of Experiment 1 would hold for a more complex, asymmetrical display. Easton and Sholl (1995) found

that participants performing imaginal self-movement were relatively faster and more accurate at spatial updating when positioned within symmetrical displays of well-known configurations such as circles. Performance declined when the circular displays were altered so that the relationship among their individual objects was asymmetrical; moreover, updating with these displays did not show the flat automaticity function. In the present experiment, we used a circular virtual room, which contained five alcoves arranged in an asymmetrical configuration (see Figure 6). As in Experiment 1, the participants updated the location of objects in the circular room during both viewer and display rotations.

Because the display was asymmetrical, we were no longer able to use a verbal updating response. Instead, the participants updated the locations of the alcoves by pointing a compass. This afforded us the opportunity to test the generalizability of the viewer updating advantage to different response measures. We predicted that updating performance would be faster and more accurate in the viewer task than in the display task, but that automaticity in both might dissipate.

Method

Participants. Twenty-three University of Virginia students (12 female, 11 male) participated in the experiment as part of a research credit requirement. One additional participant felt ill and did not complete the experiment. All of the participants were tested individually. None knew of the research hypothesis being tested.

Equipment and Stimuli. For the asymmetrical display, a new virtual room was created using the computers and software discussed in the Method section of Experiment 1. The virtual room consisted of a circular room 4.72 m in diameter and 2.43 m high, with white, textureless walls. The floor covering and lighting were identical to those of Experiment 1. Five alcoves of dimensions identical to those of Experiment 1 appeared on the walls. If 0° is con-

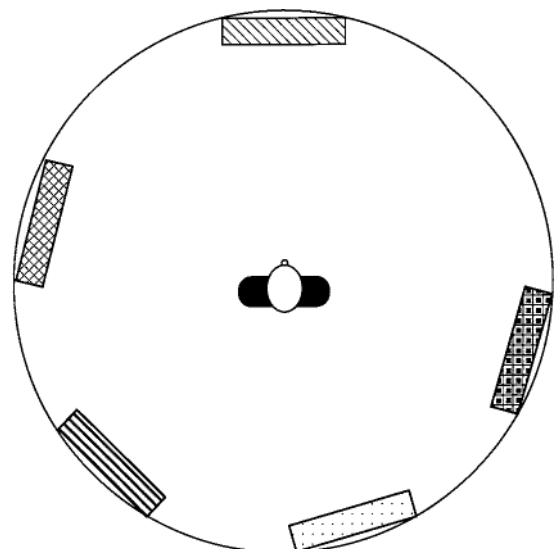


Figure 6. Overhead schematic of the asymmetrical display used in Experiments 3 and 4.



Figure 7. The virtual compass used in Experiments 3 and 4. The participants were instructed to think of themselves as the figure standing in the center of the compass. They then used the joystick dial held in their hands to move the virtual compass arrow to the desired position.

sidered the point which the participants initially faced, the alcoves appeared at 0° , 75° , 133° , 196° , and 259° counterclockwise around the circular room (see Figure 6). They were centered at a height of 1.08 m from the ground. Four of the alcoves were the same colors as in Experiment 1; the fifth was purple. The four 3-D objects from Experiment 1 also were used; the fifth was a $73 \times 24 \times 46$ cm trolley. Tracking for the HMD and joystick was identical to that of Experiment 1.

In addition to the virtual scene, a 20-cm-diam, 2-cm-high circular compass was rendered for recording pointing responses (see Figure 7). The compass was gray in color. When it appeared, it was directly in front of the participant in the virtual scene, at a distance of 30 cm. Emanating from its center was a 10-cm-long yellow arrow whose movement was controlled by the dial of the joystick. Positioned atop the endpoint of the pointer (i.e., within the center of the compass) was a 30-cm-tall standing human figure, which served to orient the participant with respect to the compass. The arrow could be turned 360° , in the transverse plane only.

The participant was positioned in the center of the room, 1.8 m from the alcoves. When looking directly at one alcove, the FOV at that distance included the alcove itself and approximately 21° of wall on either side of it; thus, only one alcove could be viewed at a time.

Procedure. Each participant performed in both viewer and display tasks; physical movement in both tasks was carried out in a counterclockwise direction. As in the previous experiments, the participants first learned the location of the alcoves from a default start position. However, instead of verbally naming the position of an alcove, they pointed to it using the virtual compass. Criteria for learning were met if the participants pointed within 10° of the center of each alcove location. As before, the experimental tasks consisted of rotation and location components. As soon as the participants rotated to find a given object, the virtual room was frozen and the compass appeared. They were instructed to think of themselves as the figure standing in the center of the compass. They then used the joystick dial to move the compass arrow to the desired position.

Once this was achieved, the participants pressed a button on the joystick.

The computer recorded both degree of unsigned error (measured in degrees from the center of each alcove) and response latency (measured from the end of the presentation of a stimulus to the end of the pointing response) for the updating component, although error was our principal dependent measure. Because there were 10 possible angular differences between the new view locations and the updating alcoves, some of which were very similar (e.g., 63° and 58°), the data were grouped into five distinct categories. We achieved this by taking the average of unsigned error between alcoves of similar angular distance from the new views. The resulting categories were 0° , 61° , 88° , 127° , and 170° .

Design. The design was identical to that of Experiment 1.

Results

Rotation latency. The participants were slightly but significantly faster at turning to objects in the viewer task in comparison with the display task (see Table 2). Because the alcoves were placed asymmetrically around the circular room, differences in movement of the virtual world with respect to the viewer task (contradirectional to viewer movement) versus that with respect to the display task (unidirectional to joystick movement) resulted in a discrepancy in the angular distance traversed in each. The degrees of rotation for the viewer task were 0° , 75° , 133° , 196° , and 259° ; for display, they were 0° , 101° , 164° , 227° , and 285° . Because of the difference in angular search distance across tasks, all analyses based on initial search rotation were collapsed over rotation magnitude. A 2 (task) \times 2 (task order) \times 2 (sex) ANOVA showed a main effect of task [$F(1,19) = 18.38, p < .001$]. There were no other significant effects or interactions.

Table 2
Mean Search Latencies (in Seconds) and Standard Errors (SEs) in Experiments 3 and 4

Experiment	Task	Rotation Magnitude									
		0° (0°)		75° (101°)		133° (164°)		196° (227°)		259° (285°)	
		<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
3	Viewer	0.75	.04	2.49	.13	3.67	.15	5.23	.33	6.76	.39
	Display	0.82	.06	3.68	.18	4.80	.24	5.43	.30	7.01	.33
4	Active	0.97	.11	2.79	.44	3.79	.27	5.21	.18	7.14	.14
	Passive	0.78	.08	3.61	.16	5.35	.15	7.41	.14	9.52	.21

Note—The second values for rotation magnitude (in parentheses) apply to the display task of Experiment 3 only.

Location accuracy. The principal finding was that the participants were more accurate at pointing in the viewer task ($M = 21.2^\circ$ error) than in the display task ($M = 26.2^\circ$ error). Figure 8A shows mean unsigned error for both tasks as a function of the magnitude of search rotation. A 2 (task) \times 2 (task order) \times 2 (sex) ANOVA revealed a main effect of task [$F(1,19) = 4.06, p < .05$]. We performed separate 5 (rotation magnitude) \times 2 (task order) \times 2 (sex) ANOVAs for viewer and display tasks to assess the influence of rotation magnitude on pointing scores. The viewer analysis revealed an effect of rotation magnitude [$F(4,76) = 6.70, p < .001$]. Simple contrasts indicated an increase in error up to 133° (0° – $75^\circ, p < .05$; 75° – $133^\circ, p < .05$), but no significant differences between subsequent degrees of rotation. The display analysis also revealed an effect of rotation magnitude [$F(4,76) = 2.93, p < .05$]. Contrasts indicated a marginal increase in error above 0° (0° – $101^\circ, p < .08$) but no significant differences between subsequent degrees of rotation.

We also analyzed pointing error as a function of the five alcove average distances (see Figure 8B). A 2 (task) \times 5 (rotation magnitude) \times 2 (sex) \times 2 (task order) ANOVA

replicated the main effect of task [$F(4,76) = 5.03, p < .04$]. We also found an effect of rotation magnitude [$F(4,76) = 30.22, p < .001$]. Linear contrasts for the rotation magnitude effect yielded significant differences between all stepwise comparisons. Pointing error increased at 61° and 127° (0° – $61^\circ, p < .001$; 88° – $127^\circ, p < .002$) and decreased at 88° and 170° (61° – $88^\circ, p < .002$; 127° – $170^\circ, p < .004$). No other effects or interactions were significant.

Location latency. The principal finding was that the participants were faster at updating in the viewer task ($M = 8.8$ sec) than in the display task ($M = 10.6$ sec). Moreover, display RTs varied as a function of search rotation, whereas viewer RTs did not. Figure 9A shows mean RTs and standard errors for each task as a function of the magnitude of search rotation. Collapsing over rotation magnitude, a 2 (task) \times 2 (sex) \times 2 (task order) ANOVA performed on the mean RT scores yielded a main effect of task [$F(1,19) = 11.50, p < .001$] and a significant task \times task order interaction [$F(1,19) = 5.95, p < .05$]. Post hoc analyses revealed that RTs in the display task ($M = 12.27$ sec) were slower than RTs in the viewer task ($M = 8.97$ sec) only when the display task

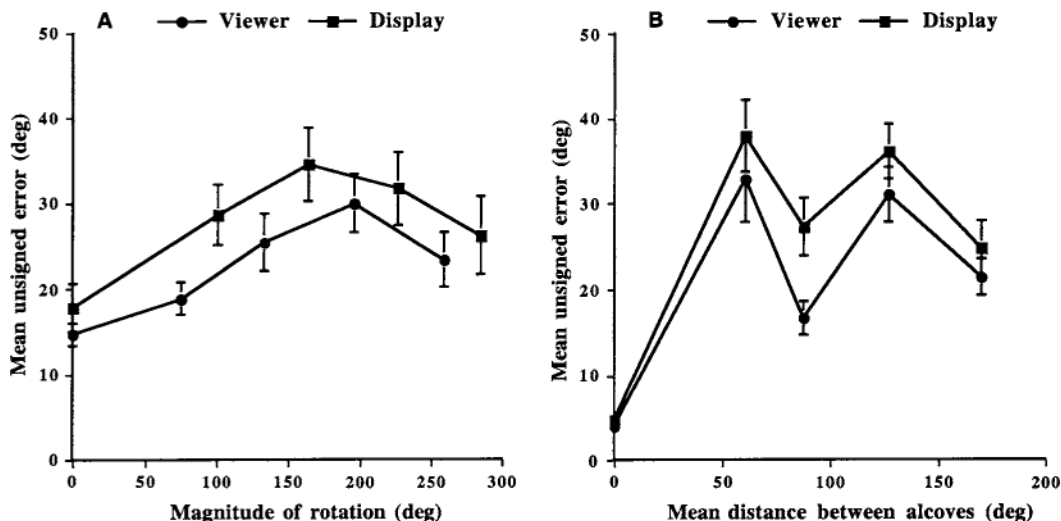


Figure 8. Mean unsigned pointing error and standard errors in Experiment 3 as a function of (A) magnitude of search rotation and (B) distance between alcoves.

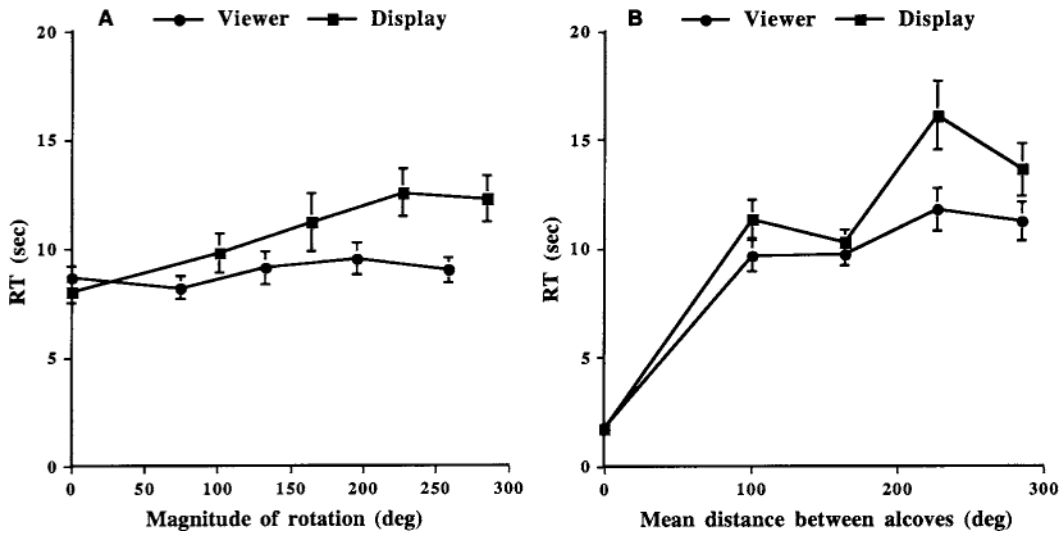


Figure 9. Mean reaction times (RTs) and standard errors in Experiment 3 as a function of (A) magnitude of search rotation and (B) distance between alcoves.

was performed first [$F(1,9) = 11.29, p < .01$]. When the display task occurred after the viewer task, RTs were not different ($M_s = 8.78$ and 9.33 for viewer and display tasks, respectively; $p = .40$). We performed separate 5 (degree) \times 2 (task order) \times 2 (sex) ANOVAs on RTs for viewer and display tasks to assess the influence of rotation magnitude. There was no effect of rotation magnitude for the viewer task ($p = .40$). An effect of rotation magnitude was found in the display analysis [$F(4,76) = 8.9, p < .001$]. Linear contrasts indicated an increase in RT from 0° to 101° ($p < .05$); however, subsequent step-wise comparisons were not significantly different from each other.

We also analyzed updating RTs as a function of the five alcove average distances (see Figure 9B). A 2 (task) \times 5 (rotation magnitude) \times 2 (sex) \times 2 (task order) ANOVA replicated the main effect of task [$F(1,19) = 11.33, p < .003$]. We also found an effect of rotation magnitude [$F(4,76) = 69.03, p < .001$]. Linear contrasts of the rotation magnitude effect revealed an increase in RT from 0° to 60° ($p < .001$), no difference from 61° to 88° ($p < .36$), an increase from 88° to 127° ($p < .001$), and a decrease from 127° to 170° ($p < .007$). The task \times task order interaction also was replicated [$F(1,19) = 6.56, p < .05$].

Discussion

As was predicted, use of the asymmetrical display failed to dispel the viewer updating advantage. The participants pointed more accurately and quickly to alcove locations after self-rotation than after rotation of the display. These findings extend those of Experiment 1 to a more complex display configuration.

The basic replication of Experiment 1 notwithstanding, the results of the present experiment yielded at least

one noteworthy difference. The asymmetrical display brought about a dissociation of automatic processing across tasks. Like previous experiments with asymmetrical displays (Easton & Sholl, 1995), updating RTs in the display task did not reflect automaticity, in that they increased for search rotation magnitudes beyond 0° . However, RTs in the viewer task continued to exhibit the flat rotation function associated with automatic processing. How do we account for the latter finding? In our experiments, the participants had access to full optical information as well as to physical self-movement; in Easton and Sholl's study, the participants performed imagined movements from memory. One or both of these factors likely contributed to the automaticity found in the present viewer task. However, similar information present in the display task was not sufficient to facilitate automaticity. The difference in rotation functions across tasks suggests that the human cognitive system has more difficulty keeping track of the locations of objects during complex display movement than during viewer movement. An alternate explanation is that another confounding factor may have caused the automaticity effect to disappear in the object task. For example, our use of the asymmetrical display in Experiment 3 required a change in the type of response measure from a verbal task to a pointing task. Recent research indicates that the use of different response measures can affect spatial updating performance (De Vega & Rodrigo, 2001; Wraga, 2003). It is possible that the pointing response interfered with automaticity. However, it isn't clear why such a change, made to both tasks, would alter performance in the object task but not in the viewer task. Thus, this explanation seems untenable.

We also found that pointing errors and RTs were greater for angular distances that generally were misaligned

from the intrinsic axes of the human body. Error rates peaked for alcove locations at approximately 60° and 120°, both of which are oblique to the body axes. Similar patterns have been found in other spatial updating studies involving imagined viewer rotations (Hintzman, O'Dell, & Arndt, 1981; Wraga, 2003). These results are in line with Franklin and Tversky's (1990) spatial-framework model of space conceptualization, which posits that mental representations of space reflect the constraints of the physical body.

The relative length of participants' RTs and the relative degree of inaccuracy they exhibited warrant discussion. RTs were 9 sec on average, which is much longer than those reported elsewhere in the literature (<2 sec) for both physical and virtual displays (e.g., Farrell & Robertson, 1998; Riecke, von der Heyde, & Bühlhoff, 2001; Rieser, 1989). We attribute this difference in RT to the pointing response measure we used, rather than to any difficulties the participants may have had with the task per se. For each response, the participants first turned the dial of the joystick with their fingers to move the virtual compass and then pressed a button on the joystick when the compass was pointing in the correct direction. The precise movements needed to perform such a procedure take more time than those required with a more standard pointer. The magnitude of pointing error was about 20°, which also is somewhat higher than previously has been reported. For example, Farrell and Robertson (1998) reported errors of about 10°. However, in their study, participants received two trials for each rotation magnitude, and the results were averaged. In the present study, the participants performed only one trial of a particular rotation magnitude. Wraga (2003) also reported mean unsigned errors of 20° with one-trial pointing using a different pointing response measure. Thus, the relative increase in error we found is likely due to the fact that the participants did not experience practice.

Finally, the participants who performed the viewer task first showed faster updating in the subsequent (display) task in comparison with those who performed the display task first. This result is similar to the task × task order interaction of Experiment 2, except that updating ability transferred from the viewer task to the display task. Further investigation of this issue is required for elucidation of the transfer process; however these findings point to the general robustness of updating during active self-movement.

EXPERIMENT 4 Active and Passive Viewer Rotations: Asymmetrical Display

In the last experiment, we tested whether the asymmetrical room of Experiment 3 would affect updating performance during active versus passive movement. As in Experiment 2, the participants performed in active and passive self-rotations. In the active condition, the participants sat in a rotating chair and searched the virtual room

by rotating themselves in the chair. In the passive condition, the seated participants were rotated in the chair by the experimenter. Thus, the same contrast of extraretinal updating information as in Experiment 2—efference copies versus vestibular/proprioceptive information—was available in the present experiment. However, to make vestibular signals more equitable across tasks, we increased the speed of rotation in the passive condition. We expected that the gain in updating from active versus passive self-movement would be negligible and that updating in both would reflect automatic processing.

Method

Participants. Twenty-three University of Virginia students (10 female, 13 male) participated in the experiment as part of a research credit requirement. The data of 1 additional participant were lost due to computer error. All of the participants were tested individually. None knew of the hypothesis being tested.

Materials. The materials were the same as in Experiment 3.

Procedure. The active/passive manipulation was the same as in Experiment 2, except that in the passive condition, the participants were rotated at an average rate of 24°/sec.⁴ The participants used a compass to make responses, as in Experiment 3.

Design. The design was identical to that of Experiment 2.

Results

Unless otherwise noted, we performed a 2 (task) × 5 (rotation magnitude) × 2 (sex) × 2 (task order) mixed-design ANOVA on the data for the experimental sub-components listed below.⁵

Rotation latency. Because the two search tasks were not equivalent, parametric tests were not performed on the data. Mean time to search for objects took longer in the passive task in comparison with the active task. As in the other experiments, time to search increased linearly with degree of rotation (see Table 2).

Location accuracy. The principal finding was that the participants pointed with equal accuracy in both active ($M = 23.22^\circ$ error) and passive ($M = 22.94^\circ$ error) tasks. Figure 10A shows mean unsigned error and standard errors for both tasks as a function of the magnitude of search rotation. The ANOVA performed on the mean unsigned errors yielded only a main effect of rotation magnitude [$F(4,76) = 7.92, p < .001$]. The effect of task was not significant ($p = .56$), but the task × rotation magnitude interaction was significant [$F(4,76) = 2.96, p < .03$]. Post hoc analyses indicated an effect of rotation magnitude for both active [$F(4,76) = 6.8, p < .001$] and passive [$F(4,76) = 3.33, p < .05$] tasks. Linear contrasts for the active task result revealed an increase in error up to 133° (0°–75°, $p < .01$; 75°–133°, $p < .05$), but no further stepwise differences. Linear contrasts for the passive task result revealed an increase in error from 0° to 75° only ($p < .04$).

We also analyzed the pointing data as a function of the five alcove average distances (see Figure 10B). The ANOVA revealed a main effect of rotation magnitude only [$F(4,76) = 36.07, p < .001$]. Linear comparisons of the degree effect revealed that pointing error increased at

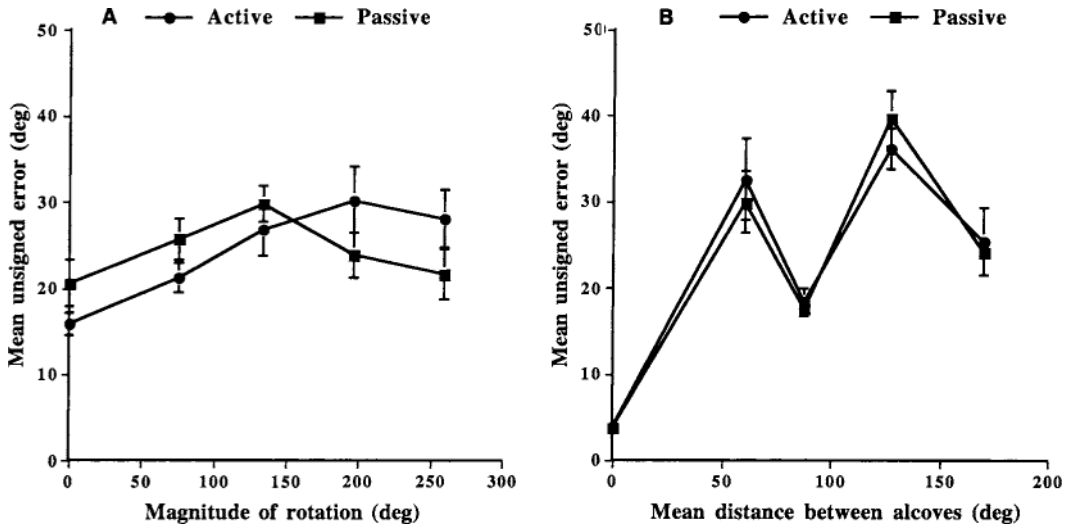


Figure 10. Mean unsigned pointing error and standard errors in Experiment 4 as a function of (A) magnitude of search rotation and (B) distance between alcoves.

61° and 127° (0°–61°, $p < .001$; 88°–127°, $p < .001$) and decreased at 88° and 170° (61°–88°, $p < .001$; 127°–170°, $p < .001$.)

Location latency. The principal finding was that the participants were no faster at updating in the active task ($M = 7.04$ sec) than in the passive task ($M = 7.27$ sec). Figure 11A shows mean RTs and standard errors for each task as a function of the magnitude of search rotation. The ANOVA performed on the mean RT scores yielded no significant effects of task ($p = .89$) or rotation magnitude ($p = .97$).

Mean RTs were also analyzed as a function of the five alcove distances. The ANOVA yielded a main effect of

rotation magnitude only [$F(4,76) = 100.44, p < .001$; see Figure 11B]. Linear comparisons for the rotation magnitude effect showed an increase in RT from 0° to 61° [$F(1,22) = 207.52, p < .001$], no difference between 61° and 88° ($p < .98$), an increase from 88° to 127° [$F(1,22) = 13.32, p < .002$], and no difference between 127° and 170° [$F(1,22) = 2.35, p < .14$].

Discussion

Despite the presence of a more complex asymmetrical display, when participants were passively moved to new views in the display, they were as fast and accurate at updating alcove positions as when they actively moved

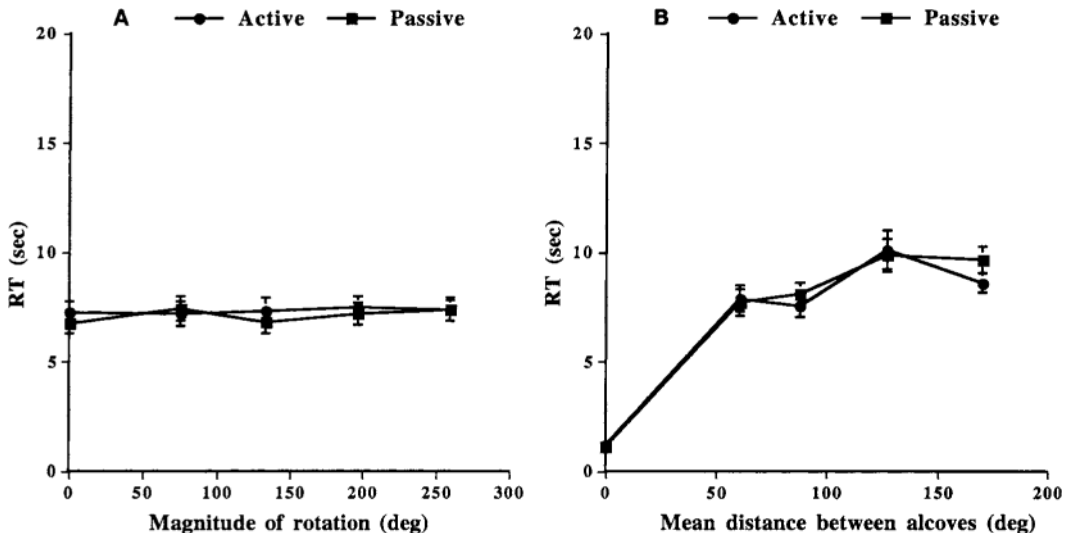


Figure 11. Mean reaction times (RTs) and standard errors in Experiment 4 as a function of (A) magnitude of search rotation and (B) distance between alcoves.

themselves. This similarity in performance was consistent across both males and females, which suggests that the former group benefited from slightly faster rotation speeds in the passive task. Thus, the gain in updating performance from self-initiated movement appears to be minimal. This finding lends support to the notion that vestibular and proprioceptive information common to both passive and active self-movement play a more critical role in spatial updating than efference copies of motor commands, available during active movement only.

The asymmetrical display had no impact on the degree to which updating was automatic during passive self-movement. Both tasks displayed equivalent automaticity across all degrees of search rotation. This finding is in contrast to those of previous studies showing that updating during passive self-movement deteriorates relative to that during active self-movement when more complex rotations are carried out (Yardley & Higgins, 1998). Further empirical testing is necessary to investigate this issue.

As in Experiment 3, pointing errors and RTs in both tasks were greater for angular distances of alcoves that were, on average, offset from the intrinsic axes of the human body. This finding extends Franklin and Tversky's (1990) spatial-framework model of space conceptualization to representations accessed during passive movement.

GENERAL DISCUSSION

In these experiments, we examined the role of perspective change in spatial updating of virtual displays. Under conditions in which optical information continuously was present, the participants searched for objects in a virtual room-like display by either rotating their bodies within the room or turning the room about themselves. They then updated the locations of landmarks from the new view. In addition to comparing effects of viewer and display rotation, we also compared updating during active and passive viewer rotation. We found a consistent advantage for updating during viewer versus display movement, across symmetrical and asymmetrical displays (Experiments 1 and 3). We also found the viewer updating advantage to be independent of active movement control (Experiments 2 and 4). These studies provide direct evidence that self-movement plays a key role in spatial updating tasks involving rotation movement within a full perceptual context.

Elsewhere, we and others have interpreted the viewer updating advantage from an evolutionary perspective (Farrell & Robertson, 1998; Simons & Wang, 1998; Wraga et al., 2000). Human beings have evolved as moving organisms in an environment that is mostly stable and that rarely rotates, if ever. Thus, updating the world with respect to the self appears to be the more natural ability. This view is consistent with recent studies demonstrating a viewer updating advantage when optical information specifying viewer and display movement was either

available (Chance et al., 1998; Christou & Bühlhoff, 1999; Klatzky et al., 1998; Pausch et al., 1997) or unavailable (e.g., Presson, 1982; Simons & Wang, 1998; Wraga et al., 2000) to the participant. Collectively, these findings suggest that the mechanisms underlying spatial updating operate similarly within perceptual and representational contexts.

The present findings also lend support to the notion that updating during viewer and object movement may be subserved by multiple mechanisms. We previously have proposed that such mechanisms may be differentiated on the basis of variations in the way the human cognitive system transforms representations of the egocentric and object-relative reference frames, respectively. Representations of the self appear to be rotated in a cohesive fashion, whereas representations of displays appear to be rotated somewhat piecemeal (Wraga et al., 2000). The present findings lend support to the notion that proprioceptive and vestibular information activated during viewer movement may also contribute to the viewer advantage. When the participants rotated themselves in place during the viewer task, changes in optical flow were accompanied by the appropriate concomitant activation of inputs from the feet, legs, and body. In contrast, when the participants turned the display via the hand-held joystick, only haptic information was available, which was somewhat decoupled from room movement. In accordance with the findings of Chance et al. (1998), the self-movement condition led to superior updating performance. Although the present study cannot distinguish precisely what sources of information contributed to performance differences across viewer and display movement, it is likely that the relative availability of proprioceptive and vestibular information is at least partly responsible for the findings. Future studies designed to address this question could equate viewer and display tasks by including a viewer rotation task in which the participant causes his or her body to move via a hand-held joystick.

Stronger conclusions can be drawn about the contribution of efference copy to the viewer updating advantage. The results of Experiments 2 and 4 indicated that updating performance during passive self-rotation was more or less equivalent to that during active self-rotation. Thus, under some circumstances, efference copies of motor commands elicited during self-initiated movement may be less critical to spatial updating than other sources, such as vestibular and proprioceptive information. These findings are consistent with some spatial cognition studies (Wang & Simons, 1999; Yardley & Higgins, 1998), but not others (e.g., Gugerty, 1997; Larish & Andersen, 1995; Péruch et al., 1995). One possible explanation for this discrepancy is the complexity of the self-movement tested. All of the studies showing a negligible active-movement effect have involved unidirectional whole-body rotations; those showing an active-movement advantage have involved multidirectional combinations of whole-body rotations and translations. As

was demonstrated by Yardley and Higgins (1998), active movement plays a more prominent role in spatial updating when participants are rotated in multiple directions. This issue warrants further empirical investigation.

The differences in updating automaticity that we found are also noteworthy. As in previous studies (e.g., Farrell & Robertson, 1998; Rieser, 1989), updating RTs during self-movement were found to be independent of the magnitude of search rotation, which suggests that they occurred on line with self-movement (Rieser, 1989). This finding held for active and passive self-movement as well as for updating of symmetrical and asymmetrical displays. In contrast, updating automaticity during display movement varied as a function of the complexity of the display. Updating was automatic for the symmetrical display. However, as was reflected in RTs that increased beyond 0°, updating during rotation of the asymmetrical array required more cognitive effort. Taken together, these findings suggest that updating automaticity during viewer movement generalizes to multiple situations, whereas updating automaticity during display movement may be limited to simple displays. The requirement of additional cognitive processing as a function of complexity in the latter case is consistent with studies on object recognition. Recognition of objects with visually distinctive parts has been shown to be viewpoint invariant (see, e.g., Biederman & Gerhardstein, 1993, 1995). However, the recognition of visually similar objects appears to involve an additional transformational step to reconcile initial and current views (see, e.g., Bühlhoff & Edelman, 1992; Tarr, 1995; Tarr & Bühlhoff, 1995; Tarr & Pinker, 1989).

In summary, our study indicates that spatial updating during viewer rotation is superior to that during rotation of the display about the self, even within a full perceptual context. Superior updating during self-movement may benefit predominantly from vestibular and proprioceptive inputs, which are not usually available during display movement.

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NOTES

1. The participant could use the joystick's pitch function only during the exploration phase; it was turned off during the testing phase and was thus unavailable.
2. RTs and errors were grouped by either initial rotation degree or angular distance between alcoves before outliers were replaced. Outliers for values that exceeded 3 SDs above the group condition mean were replaced by that mean. Thus, effects that differ slightly in initial rotation versus angular distance analyses are a result of the different outlier replacement methods.
3. During pilot testing, we determined that this speed eliminated the onset of motion sickness.
4. During pilot testing, we determined that this increase in speed introduced only a minimal risk of motion sickness.
5. Pointing data were collapsed over five angular distances, as in Experiment 3.

(Manuscript received May 13, 2002;
 revision accepted for publication September 20, 2003.)