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Updating space during imagined self- and array translations

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Previous work has demonstrated superior spatial updating performance during imagined viewer rotation versus imagined object/array rotation. Studies have also suggested that rotations are more difficult to process than translations. In three studies, we examined whether the advantage seen for updating during imagined self-rotations would generalize to translations. The participants updated the positions of objects in a line extending either to the front and back of the viewer or to the right and left after imagining viewer or array translation. Experiments 1 and 2 replicated the effects seen in imagined rotation tasks. A response time and accuracy advantage was found for imagined viewer translation versus imagined array translation. In Experiment 3, we directly compared real and imagined self- and array translations and demonstrated an advantage for real versus imagined array translation. The results suggest that the advantage for imagined viewer transformations is not a function of the specific transformation, but rather of the ability to imagine and predict the outcome of a moving frame of reference.

Spatial updating can be defined as the human ability to keep track of spatial locations relative to oneself during one's own movement or movement of objects in the environment. People achieve this goal quite well in a number of circumstances. Researchers have examined the processes underlying spatial updating using different paradigms involving real and imagined spatial transformations. The focus of this paper is on one paradigm used in investigating the mechanisms subserving imagined transformations of the self versus imagined transformations of an external array of objects. In other words, we compare the human ability to transform one's own intrinsic reference frame with the ability to transform a configuration's extrinsic reference frame in the context of a spatial updating task. This concept, with respect to rotation, has been examined in several recent studies (Amorim & Stucchi, 1997; Carpenter & Proffitt, 2001; Creem, Wraga, & Proffitt, 2001; Presson, 1982; Tversky, Kim, & Cohen, 1999; Wraga, Creem, & Proffitt, 2000b). The distinction is notable because often both types of transformations will result in the same end state. For example, when giving a lecture, suppose you wanted to determine what a slide looked like from your audience's point of view. You could imagine yourself rotating to face the slide, or you could imagine the slide rotating to face you. Despite the apparent similarity of these transformations, recent studies have generalized an advantage for updating during imagined self- versus array rotations. The present study demonstrates an advantage for viewer- versus array-*translations* similar to that seen for *rotations*.

The focus on translations in the present paper stems from previous research in which spatial decisions after self-translational and -rotational transformations have been compared, with an advantage found for translations in comparison with rotations (Presson & Montello, 1994; Rieser, 1989). Pure rotational movements involve a change in orientation with respect to a reference axis, without linear displacement,[1] whereas translations involve only linear displacement without a change in orientation. Despite the findings of the ease of imagined *self*-rotations in comparison with imagined *object* rotations described above, studies suggest that imagined self-*rotations* are difficult in comparison with imagined self-*translations*, and that the addition of physical self-movement facilitates updating for rotation but not for translation. Distinctions between rotations and translations have also been seen in other cognitive domains. For example, in a perceptual organization task, translation served as a moving frame of reference more easily than rotation (Bertamini & Proffitt, 2000). In a task of memory for motion, humans remembered the direction of translational movement better than that of rotational movement (Price & Gilden, 2000).

The relative difficulty of processing rotations in comparison with processing translations led to the primary question of the present studies: Will the advantage seen for imagined self-rotations versus array rotations generalize to translations? Wraga et al. (2000b) suggested that the ease of imagined self-rotations could be a result of the human ability to transform a familiar frame of reference (i.e., one's body) more cohesively than an object or array's frame of reference. Imagined rotations have been proposed to be difficult in comparison with translations, however, because of the resulting conflict between one's

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physical frame of reference (front, back, left, and right with respect to the observer) and a new imagined reference frame in which these positions must change. In the present study, we created an imagined transformation task that involved imagined linear translation without rotation of either the viewer or an array of objects. We also introduced physical movement into both tasks. The results demonstrate an updating advantage for imagined self- versus array translation similar to that found with rotation. The addition of visual movement of the array facilitated updating with array translation to the level of self-translation. These results suggest that the distinction between viewer and array transformations cannot be attributed solely to rotations and may lie in humans' differential ability to imagine and predict the result of moving a frame of reference.

Egocentric and Object-Relative Reference Frames

The distinction between imagined transformations of the self and of objects can be examined by defining the spatial frames of reference that are involved. The spatial reference frame specifies what kind of location is represented (McCloskey, 2001). The egocentric reference frame represents locations relative to a viewer's own body or body part. The object-relative reference frame represents locations with respect to an object's (or array's) own intrinsic coordinate system. Different goals or tasks may require the recruitment of a specific reference frame or combination of reference frames. For example, reaching to pick up a cup of coffee involves both an object-relative representation of the handle relative to the cup as well as an arm- and hand-centered representation of the location of the cup relative to the viewer's immediate position for action. The use of reference frames is central to understanding both linguistic (Bryant, Tversky, & Franklin, 1992; Talmy, 1983) and perceptual representations of space. Research domains of animal neurophysiology (Colby & Goldberg, 1999), human neuropsychology (Behrmann & Moscovitch, 1994; McCloskey & Rapp, 2000), and human visual cognition (Easton & Sholl, 1995; Rieser, 1989; Tversky et al., 1999) have demonstrated distinctions between the underlying representations involved in object-relative and egocentric reference frames.

Viewer and Array Rotations

Imagined transformations involve mentally manipulating and updating reference frames. In a typical self-rotation task, the viewer must imagine a change in his or her own egocentric perspective as the object and environmental positions remain constant. This rotation may involve a fixed movement around the object (as the moon rotates around the earth) or a self-rotation in place involving no linear displacement of the observer. In an object- or array-rotation task, the viewer imagines a transformation of the array's reference frame relative to a stable viewer and environment. Much of the earlier studies on imagined rotations focused on the classic paradigm of mental object rotation (e.g., Cooper & Shepard, 1973; Shepard & Metzler, 1971). These studies indicated that people are able to imagine rotations of objects in both the picture plane and in depth in a manner analogous to physical rotation, to determine whether two objects are the same shape or different shapes. In comparisons of spatial updating after imagined object or viewer transformations, however, studies have indicated a consistent advantage for the viewer-centered transformation. In most such studies, imagined rotation of the viewer around a given object or array has been compared with the imagined rotation of the object/array itself. For example, Amorim and Stucchi (1997) asked participants to view a large uppercase letter F within an imagined clock. Their viewer-centered task required an imagined self-rotation around the F, whereas their object-centered task required imagined rotation of the letter F. The viewer-centered task was performed more efficiently than the object-centered task. Earlier studies by Presson (1982) required observers to imagine viewer or array rotations with respect to an array of four objects. Presson presented participants with different types of questions and found that the format of the question influenced whether there was an advantage in the viewer- or array-rotation task. When the question was phrased so as to name an object (e.g., "Rotate 90°; where is the drum?"), array rotation was superior to viewer rotation. When the question was phrased to name a position (e.g., "Rotate 90°; what's on your right?"), an advantage was found for the viewer-rotation task. These studies suggest that the array-rotation task could be easily performed only when a strategy of imagining the movement of a single object, rather than that of a cohesive array of multiple objects, could be used.

Wraga et al. (2000b) conducted six variations on Presson's (1982) tasks in which participants were asked to spatially update the positions of objects or parts of objects during imagined self- or object rotations of 0°, 90°, 180°, and 270°. In these experiments, the participants stood facing four objects placed on pedestals on the floor in a diamond-shaped array. After memorizing the positions of the objects, the participants were given a degree of rotation and a position in the array and were asked to name the object that corresponded to the given position after either imagined self- or array rotation (e.g., "Rotate 90°; what's on the right?"). When the question was phrased in this way, the viewer-rotation task was faster and more accurate. The response time (RT) functions for the two tasks were very different. In the array-rotation task, RT increased with greater degrees of rotation to 270°, whereas in the viewer-rotation task, RT showed a much flatter function peaking at 180° and then leveling off. Wraga et al. (2000b) proposed that the consistent viewer advantage resulted from the human ability to transform the egocentric frame of reference cohesively and efficiently. In contrast, the array-rotation task involved transformation of the object-relative frame, which may be represented and transformed with less internal cohesion. They demonstrated this claim by increasing the internal cohesion of the array (i.e., using an object with a familiar configuration) and improving array performance. A comparison was also made between standing outside of an array of objects (and rotating around the array) and standing within the array (and rotating in place). A viewer-rotation advantage was found for both tasks. In other studies (Zacks, Mires, Tversky, & Hazeltine, 2002; Zacks, Rypma, Gabrieli, Tversky, & Glover, 1999), visually presented pictures of bodies have been used and object-centered (a same/different response) or egocentric (handedness) decisions have been compared, and, again, systematic RT differences between the two tasks were found.

Viewer Rotations and Translations

Despite the consistent findings of an advantage for imagined viewer rotations versus imagined object rotations, other studies with a focus on comparing real and imagined transformations have shown that imagined self-rotations are difficult, at least relative to imagined self-translations. The rotation conditions have typically involved imagined self-rotations of the viewer while the viewer is standing in place. For example, Rieser (1989) asked participants to point at a given object as if they were standing at another object in the translation task, in comparison with facing the object in the rotation task. For rotation, RT increased as a function of the amount of rotation required. In contrast, performance after imagined translation to a new object did not differ from the baseline of no change in point of observation. Rieser explained the distinction in performance between translation and rotation as a result of the frames of reference involved in updating of spatial representations. He proposed that without movement, observers access object-to-object relations rather than self-to-object relations, which do not change as a result of translation of observation point but do change with rotation. Easton and Sholl (1995) suggested, however, that object-to-object coding is only used for regular arrays and that more complex, irregular arrays recruit self-to-object spatial relations.

Presson and Montello (1994) replicated Rieser's (1989) results, finding that updating was superior when real movement was compared with imagined movement for rotation but not for translation. They suggested that the difficulty in imagined rotations could be partially explained by a conflict between primary and secondary frames of reference. The primary egocentric frame of reference consists of one's front/back, left/right, and up/down axes relative to the immediate environment. Imagining a rotation requires the construction of a secondary egocentric frame of reference (a new front, back, left, and right) which conflicts with the primary frame of reference. Real rotation eliminates this conflict by aligning the two frames of reference. With imagined translation, the axes of one's primary frame of reference remain parallel to those of the secondary frame of reference, allowing for ease of pointing to an object from a new observation point.

OVERVIEW OF THE EXPERIMENTS

The aim of present studies was to use an imagined transformation and updating paradigm comparable to those of Wraga et al. (2000b) and Creem et al. (2001), but involving translation rather than rotation. In the first two experiments, imagined viewer and imagined array translations in either the frontal or the sagittal plane were directly compared. Experiment 3 introduced physical movement into the task to assess the influence of real motion on updating with both self- and array translations.

General Method and Analyses

Three experiments were conducted using similar methodologies and analyses. The aspects shared by all of the experiments are described below. Details specific to each experiment are included within each experimental section.

Materials. A Styrofoam board (96 in. long × 4 in. wide × 2 in. high) and seven 1.5-in^3 colored (red, orange, yellow, green, blue, pink, and violet) cubes were used. The board was placed on two adjacent (60 in. long × 30 in. wide × 30 in. high) tables about waist-high. RTs were recorded using a Timex stopwatch (Experiments 1 and 2) or a computer timer (Experiment 3).

Design. The participants performed in two task sessions (viewer and array translation in Experiments 1 and 2; real and imagined translation in Experiment 3). The order of the tasks was counterbalanced across participants. Each direction (forward/backward or left/right), position (front/back or left/right), and steps (zero, one, two, and three) was matched for a unique trial, and each trial was presented twice, for a total of 28 trials in each session.[2]

Analyses. For each experiment, average RT for correct trials for each task condition, direction, position, and steps was calculated for each participant (across two trials for each cell).[3] In Experiments 1 and 2, the mean RTs of 20 participants were analyzed with a 2 (task) × 2 (direction) × 4 (steps) × 2 (task order) mixed analysis of variance (ANOVA) with task, direction, and steps as within-participants variables and task order as a between-participants variable. Mean percent of correct responses for 20 participants was analyzed with a 2 (task) × 2 (direction) × 4 (steps) × 2 (task order) mixed ANOVA with task, direction, and steps as within-participants variables and task order as a between-participants variable. Separate 2 (task) × 2 (position) × 4 (steps) × 2 (task order) ANOVAs were conducted on RT and accuracy data to assess effects of position (front vs. back or left vs. right). In Experiment 3, the mean RTs and accuracy data of 40 participants were analyzed with a 2 (array-translation/viewer-translation task) × 2 (real/imagined movement) × 2 (direction) × 4 (steps) mixed ANOVA as well as separate 2 (movement) × 2 (direction) × 4 (steps) × 2 (task order) ANOVAs for each task (viewer translation and array translation).

EXPERIMENT 1
Imagined Front/Back Translation

Method

Participants. Twenty undergraduate students (9 male, 11 female) from the University of Utah participated in the experiment as part of a research-credit requirement. Three additional participants were removed because their accuracy was less than 50%.

Procedure. The participants stood with the table and board placed to their left (see Figures 1A and 1B). They were aligned with the center cube, with the board extending in front of and behind them. They memorized the positions of the colored cubes with respect to steps relative to themselves (zero, one, two, or three steps in front or in back). They were given as much time as they needed

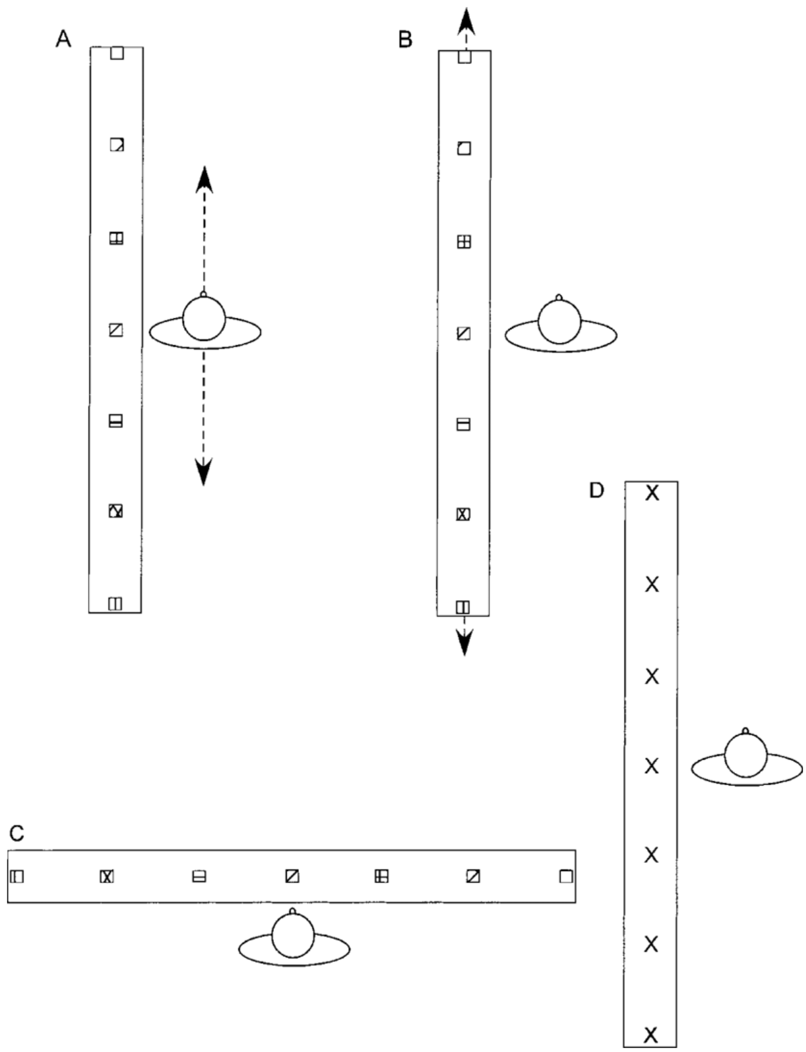

Figure 1. Bird's eye view of the displays in (A) Experiment 1, viewer translation; (B) Experiment 1, object translation; (C) Experiment 2; and (D) Experiment 3.

to memorize the configuration and were tested for the colored cube corresponding to each position with their eyes closed. The experiment began only after the participant could name all of the colors accurately. Before each task began, the participant was blindfolded. The task was performed without vision.

In the viewer-translation task, the participants were told to imagine moving forward or backward a given number of steps and then to name the color of the object either directly in front of or behind them. On each trial, the experimenter gave them an instruction that consisted of the number of steps, the direction, and the position. For example, the participant would hear "Two forward, front." On this trial, they would imagine taking two steps forward and then name the object that would be directly in front of them after the imagined translation. RT was recorded from the end of the experimenter's instruction to the beginning of the participant's response using an experimenter-controlled stopwatch. The experimenters were not aware of the predictions of the study. Verbal responses of the color names were also recorded, to assess accuracy. At the end of the first task, the objects were placed in new positions and the participants learned a second configuration before starting the second task.

In the array-translation task, the participants heard the instructions framed in the same way but were instructed to imagine that the board was moving and that they were remaining stationary. The experimenter demonstrated the imagined movement of the board by physically moving the board before the task started. During the task, the board remained stationary and the participants imagined it moving the given number of steps in the given direction. RT and responses were recorded as in the viewer-translation task.

Results

Latency. The participants performed more quickly in the viewer-translation task (M = 1.67 sec) than in the array-translation task (M = 3.25 sec; see Figure 2A). The ANOVA revealed a significant effect of task [$F(1,18) = 192.71, p < .001$] and steps [$F(3,54) = 30.21, p < .001$], a task × steps interaction [$F(3,54) = 28.89, p < .001$], and a direction × steps interaction [$F(3,54) = 3.70, p < .05$]. There was no main effect or interaction with task order.

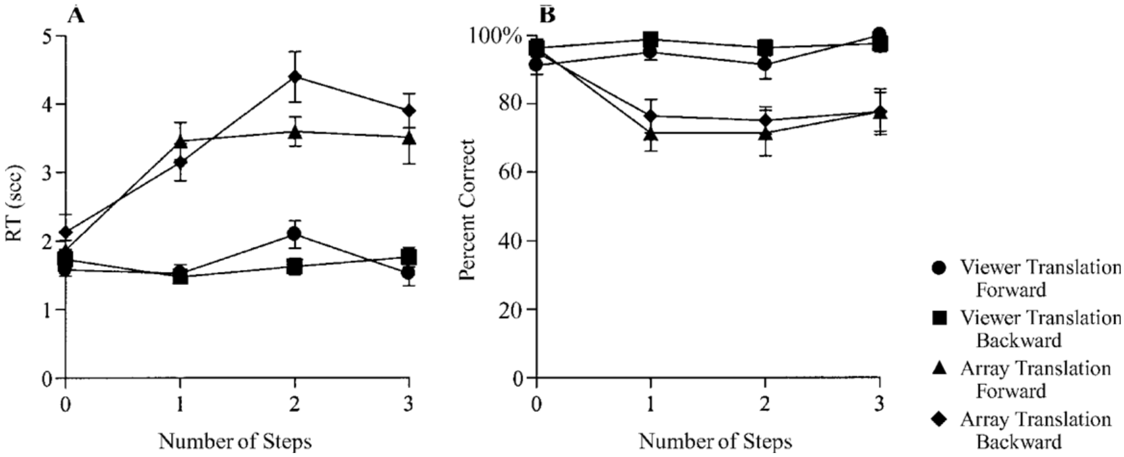

Figure 2. (A) Mean RT and (B) percent correct (±1 *SE*) for viewer- and array-translation tasks as a function of direction of movement and number of imagined steps in Experiment 1.

Separate 2 (direction) × 4 (steps) ANOVAs were performed on mean RT for the viewer- and array-translation tasks to assess the task interactions. Both tasks indicated an effect of steps [viewer translation: $F(3,57) = 3.43, p < .05$; array translation: $F(3,57) = 39.21, p < .001$], but, as Figure 2A demonstrates, the functions were very different. In the viewer-translation task, RT hovered between 1.5 and 2 sec, but in the array-translation task, RT increased as a function of steps. Additional 2 (direction) × 3 (steps) ANOVAs were performed on the mean RT for the viewer- and array-translation tasks, with the 0-step trials removed to assess whether the step effect resulted only from the difference between 0 steps and more than 0 steps. The effect of steps was maintained for both tasks [viewer translation: $F(2,38) = 5.46, p < .01$; array translation: $F(2,38) = 6.56, p < .01$]. Repeated contrasts for the viewer-translation task revealed that RT increased from one to two steps ($p < .01$) and decreased from two to three steps ($p < .01$). Repeated contrasts for the array-translation task indicated that RT increased as a function of steps from one to two ($p < .001$) but not from two to three ($p = .15$). The position ANOVA found no difference in RT for front and back correct responses.

Accuracy. As can be seen in Figure 2B, the participants performed more accurately in the viewer-translation task ($M = 95.8\%$) than in the array-translation task ($M = 80\%$). The ANOVA revealed a significant effect of task [$F(1,18) = 60.045, p < .001$], steps [$F(3,54) = 5.16, p < .01$], steps × task order [$F(3,54) = 3.21, p < .05$], and task × steps [$F(3,54) = 9.77, p < .001$]. Separate 2 (direction) × 4 (steps) × 2 (task order) ANOVAs were performed on percent correct for each task (viewer translation and array translation) to assess the task interactions. In the viewer-translation task, there was no difference in accuracy as a function of steps ($p = .18$). In the array-translation task, accuracy decreased significantly from 0 to 1 step ($p < .001$) but did not continue to decrease as a function of more steps (1 to 2, $p = .9$; 2 to 3, $p = .5$). The position ANOVA found no difference in accuracy for front and back responses.

Discussion

Imagined viewer translation was performed more quickly and accurately than imagined array translation. Whereas the viewer-translation task demonstrated essentially a flat RT function with respect to steps, the array-translation task RT increased significantly from 0 to 1 to 2 steps. For accuracy, there was no difference between steps for the viewer-translation task, but the array-translation task showed decreased accuracy for number of steps greater than 0. These findings suggest that the distinction between imagined object and viewer rotations seen in several previous experiments can be extended to translation as well, using a similar paradigm. The RT and accuracy functions showed significantly different patterns, suggesting that the array and viewer translations recruit different mechanisms. The flat functions for the viewer-translation task suggest that the observers were able to imagine themselves in a new position and to update the positions of objects without additional processing time, regardless of the distance of the imagined movement that was required. In the array-translation task, the participants found it more difficult to imagine and update the array of blocks, showing increasing RT and errors with increasing steps. The lack of monotonic RT increase at three steps may be a result of the fact that the position instruction was limited to either front or back (but not both), depending on the direction of movement, so the observer may have begun to update before the position was named.

EXPERIMENT 2
Imagined Left/Right Translation

In Experiment 2, we aimed to replicate the first experiment, requiring translation in the frontal plane so that observers needed to update a new left/right position rather than a front/back position. Franklin and Tversky's (1990) spatial framework model suggests that objects in the left/right direction relative to the observer may be less accessible in mental representations because of the lack of asymmetry with respect to the body. We examined whether we would find a decrement in performance when imagining left/right translation of the viewer or array in comparison with the findings for forward/backward movement in Experiment 1. On the basis of the robust findings of Experiment 1, we expected to see a similar advantage for viewer translation in comparison with array translation with right/left updating.

Method

Participants. Twenty undergraduate students (9 male, 11 female) from the University of Utah participated in the experiment as part of a research credit requirement. None of them had participated in Experiment 1. Five additional participants were excluded from the analyses because their accuracy was equal to or less than 50% correct.

Procedure. The same procedure was used as in Experiment 1 except for the placement of the board and the direction of translation. The participants stood with the table and board in front of them (see Figure 1C). They were aligned with the center cube with the board extending to the right and left of them. They memorized the positions of the colored cubes with respect to steps relative to themselves (zero, one, two, or three steps to the right or left). In the viewer-translation task, the participants were told to imagine moving to the right or left by taking a given number of side steps and then to name the color of the object either directly to the right or to the left of them. As in Experiment 1, the experimenter gave them an instruction on each trial that pertained to the number of steps, direction, and position. For example, the participant would hear "Two right, left." On this trial, they would imagine taking two steps to the right and then name the object that would be directly to the left of them after the imagined translation. In the array-translation task, the participants imagined the array moving to the left or right as they remained stationary.

Results

Latency. The participants responded more quickly and differently as a function of steps in the viewer-translation task (M = 1.93 sec) than in the array-translation task (M = 3.54 sec; see Figure 3A). The ANOVA showed an effect of task [$F(1,18) = 146.26$, $p < .001$] and steps [$F(3,54) = 20.31$, $p < .001$] and a task × steps interaction [$F(3,54) = 19.93$, $p < .001$]. There was no main effect or interaction with task order. As in Experiment 1, the two tasks demonstrated different RT patterns as a function of steps. Whereas the viewer-translation task function remained relatively unchanged across steps, RT increased in the array-translation task at one and two steps. Additional 2 (direction) × 3 (steps) ANOVAs were performed on the mean RT for the viewer- and array-translation tasks with the 0-step trials removed to assess whether the step effect resulted only from the difference between zero steps and more than zero steps. The effect of steps was maintained for both tasks [viewer translation: $F(2,38) = 9.33$, $p < .001$; array translation: $F(2,38) = 4.38$, $p < .05$]. In the viewer-translation task, repeated contrasts indicated an increase in RT from one to two steps ($p < .001$). In the array-translation task, RT increased from one to two steps ($p < .05$) but not from two to three steps ($p = .35$). The position ANOVA indicated no difference in RT as a function of left or right position for either task.

Accuracy. The participants responded more accurately in the viewer-translation task (M = 93.13 %) than in the array-translation task (M = 87.33%; see Figure 3B). The ANOVA revealed a significant effect of task [$F(1,18) = 12.67$, $p < .01$], steps [$F(3,54) = 4.19$, $p < .01$], and task × steps [$F(3,54) = 3.41$, $p < .05$]. In an examination of the task × steps interaction, repeated contrasts demonstrated no difference between steps for the viewer-translation task. For the array-translation task, there was a significant decrease in percent correct from zero to one step ($p < .01$). The position ANOVA showed no difference in accuracy between right and left position responses.

Comparison of Experiments 1 and 2

Between-experiments [2 (task) × 4 (steps) × 2 (experiment)] ANOVAs on RT and accuracy were per-

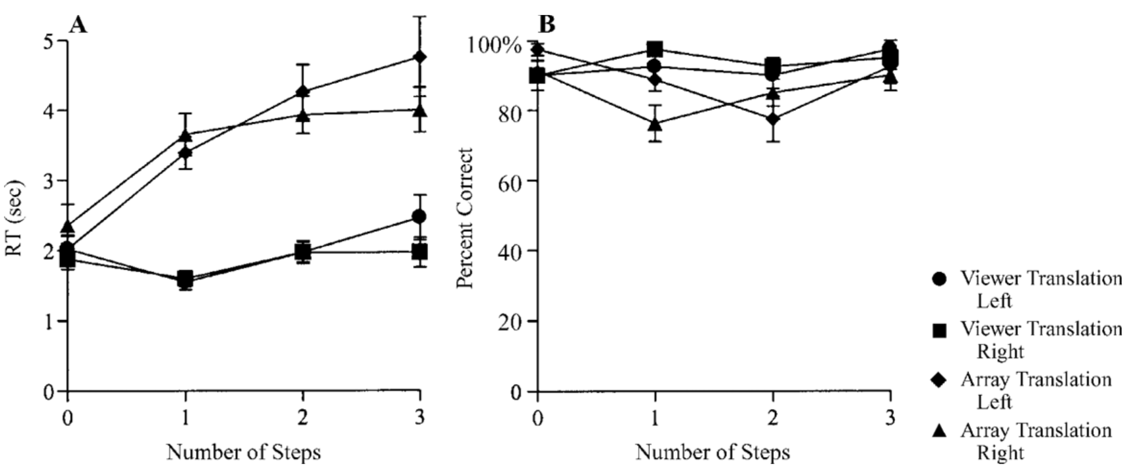

Figure 3. (A) Mean RT and (B) percent correct (±1 *SE*) for viewer- and array-translation tasks as a function of direction of movement and number of imagined steps in Experiment 2.

formed to compare the difference in movement direction (front/back vs. left/right) in Experiments 1 and 2. In all, there was no difference in RT between Experiments 1 and 2 ($p = .23$). For accuracy, a task × experiment interaction [$F(1,38) = 14.44, p < .05$] indicated that although there was no difference between experiments in the viewer-translation task ($p = .26$), the array-translation task was performed more accurately in Experiment 2 with right/left movement (87.33%) than in Experiment 1 with forward/backward movement [80%; $F(1,38) = 5.93, p < .05$].

Discussion

As was predicted, the results of Experiment 2 replicated those of Experiment 1. The participants were faster and more accurate at updating the positions of objects after imagined viewer translation than after imagined array translation. Both RT and accuracy functions were similar to those seen in Experiment 1, although accuracy was higher on the array translation task in Experiment 2. These findings suggest that updating after simple translations in the sagittal or frontal plane is quite different for viewer and array transformations. As in the rotation studies, a consistent advantage was found for imagined viewer transformations. These results suggest, then, that the distinction between viewer and object transformations seen in previous studies was not a result only of the rotational component. The difficulty could rest in people's differential ability to predict the outcome of a moving frame of reference (in rotation or translation) other than one with which humans have extensive experience (e.g., one's own body). In fact, Carpenter and Proffitt (2001) and Creem et al. (2001) found that even imagined rotations of one's body could be as difficult as imagined rotations of arrays of objects when self-rotations did not involve rotation around one's own real or imagined principal axis. In Experiment 3, we tested this hypothesis by introducing real movement of one's egocentric frame of reference and the array's global frame of reference and compared updating performance across real and imagined conditions.

The lack of an advantage for front/back over left/right decisions as seen in Franklin and Tversky (1990) may have resulted from the simple linear array presented in the present experiment. Previous studies in which a left/right disadvantage has been found in comparison with front/back or head/feet have used descriptions of scenes in which objects were present in all of these dimensions and rotation tasks were used. Because our translation task did not involve rotation and presented a simple array of objects, we might not expect a difference in access to right/left spatial positions.

EXPERIMENT 3
Real Versus Imagined Translation

The results of the first two experiments demonstrated a consistent advantage for imagined viewer translation in comparison with imagined array translation. In Experiment 3, we tested whether the addition of physical movement of the array or of the viewer would facilitate updating in comparison with imagined movement conditions. On the basis of previous results using different translation paradigms (Presson & Montello, 1994; Rieser, 1989), we predicted that a direct comparison of real and imagined self-movement would lead to little difference in performance. However, experiments in several related areas of research led to conflicting predictions about the influence of physical movement of an object array's frame of reference on updating. In a scene recognition task, Wang and Simons (1999) found that visual information about the rotation of a display did not facilitate change detection performance to match that seen with observer rotation. However, in updating tasks involving visual translation without body movement, participants appear to treat the information about a translating display in a similar way as information about translation resulting from the physical movement of one's body (Klatzky, Loomis, Beall, Chance, & Golledge, 1998; May & Klatzky, 2000; Redlick, Jenkin, & Harris, 2001). These results might suggest that visual information specifying object movement would lead to updating performance comparable to that seen with self-movement.

In a mixed within- and between-participants design, we compared imagined versus real array and viewer translations. One group of participants performed both the imagined and the real array-translation tasks, whereas a second group of participants performed both the imagined and the real viewer-translation tasks. In this way, we could examine a within-participants comparison of physical versus imagined movement for each task and also compare the nature of the task (array vs. viewer) between participants. We did not conduct an entire within-participants design because of the potential interference that might result from learning four different object-array configurations. All of our previous studies (e.g., Creem et al., 2001; Wraga et al., 2000b) required the learning of only two configurations, and we wanted this to remain constant. Because of the nature of the visual and motor manipulations, the methodology was changed on two dimensions from the previous two experiments. First, the participants' eyes remained open throughout the experiment to allow for vision of the moving display (although the objects to be updated were removed from the display) or vision while the participant was physically walking. Second, a 2-sec delay was introduced between the movement cue (e.g., "Two forward") and the named position (e.g., "Front") to allow for physical movement of the display or one's body.

Method

Participants. Forty undergraduate students (19 male, 21 female) from the University of Utah participated in the experiment as part of a research-credit requirement. None of them had participated in either of the previous experiments.

Procedure. Twenty participants performed in two sessions of array translation (real and imagined), and 20 different participants performed in two sessions of viewer translation (real and imagined). The array was presented as in Experiment 1, with the board and table extending in front of and behind the observer. The participants memorized the configuration of the colored cubes with respect to steps as in the previous experiments. Unlike in Experiments 1 and 2, after the positions of the cubes were memorized the cubes were removed from the board and the participant was able to view the board and the positions (without the cubes) while performing the array- and viewer-translation tasks. The position of each of the cubes was visually marked with an X (see Figure 1D).

In each task, the participant heard the instructions as presented in Experiment 1, with one modification. A 2-sec delay was introduced between the presentation of the imagined movement (e.g., "Two forward") and the position (e.g., "Front"). This 2-sec period allowed the experimenter to physically move the board or the viewer to physically move.[4] In the *real-array-translation* task, the experimenter moved the board the given number of steps while the participant watched. In the *imagined-array-translation* task, the participant imagined that the board moved as in Experiment 1. In the *real-viewer-translation* task, the participants physically moved the given number of steps during the 2-sec delay. In the *imagined-viewer-translation* task, they imagined translation of themselves as in Experiment 1. The participants were instructed to respond as quickly as they could to identify the colored cube in the given position after the position was presented. Presentation of the prerecorded auditory instructions and recording of RT was performed using Superlab (Cedrus) in order to allow the experimenter to physically move the board and to allow precise timing of the 2-sec interval before the position was named. RT was recorded by the computer at the end of the instruction and was stopped by the experimenter with a mouse click when the participant responded. Verbal responses were recorded by the experimenter to assess accuracy.

Results

Latency. Overall, the real movement tasks were performed more quickly than the imagined movement tasks [$F(1,38) = 11.36, p < .01$], and the viewer-translation tasks were performed more quickly than the array-translation tasks [$F(1,38) = 8.41, p < .01$; see Figure 4]. A task $\times$ movement interaction [$F(1,38) = 10.63, p < .01$] indicated that the participants responded more quickly in the imagined viewer-translation task in comparison with the imagined array-translation task [$F(1,38) = 11.83, p < .001$], replicating the results of Experiments 1 and 2, but there was no difference between array- and viewer-translation performance in the real movement condition ($p = .39$). There was also an overall effect of steps [$F(3,144) = 9.32$, $p < .001$], a steps $\times$ movement interaction [$F(3,114) = 9.24, p < .001$], a steps $\times$ task interaction [$F(3,114) =$

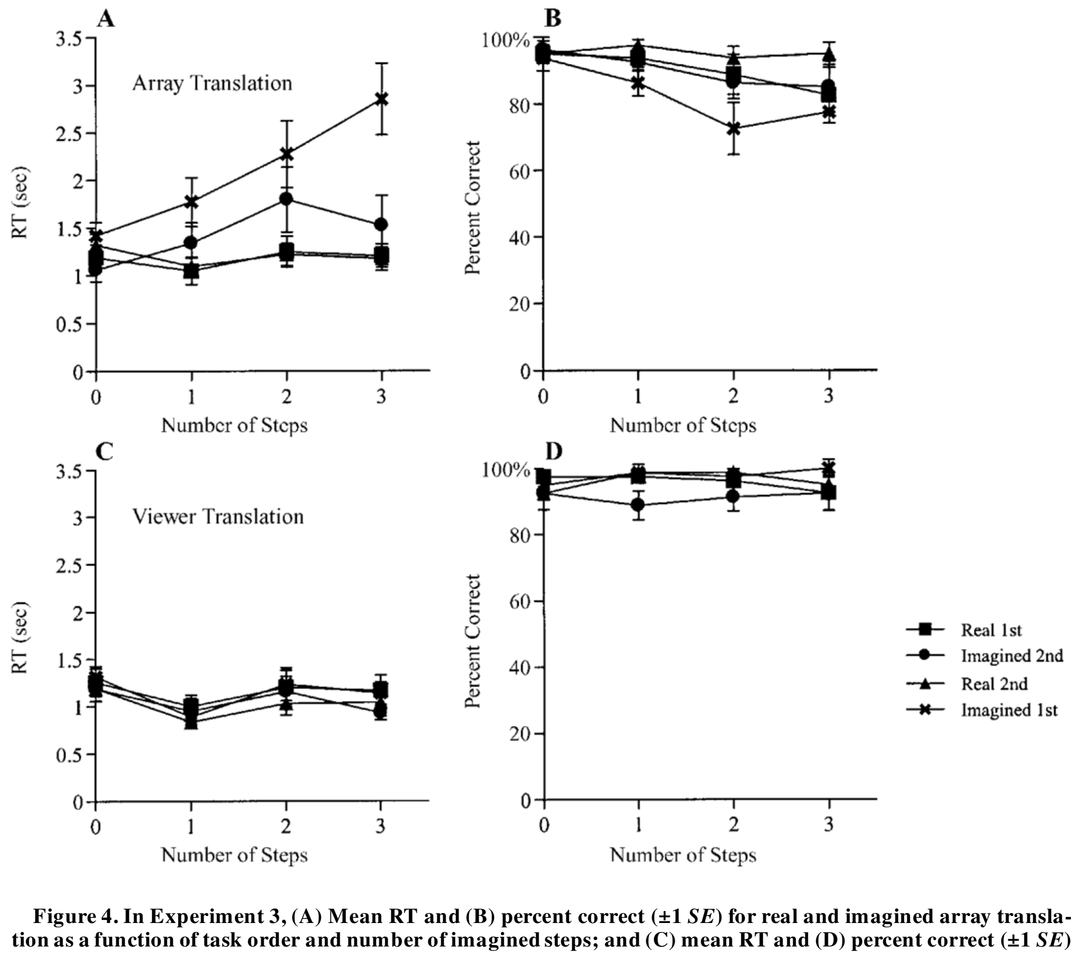

Figure 4. In Experiment 3, (A) Mean RT and (B) percent correct (±1 *SE*) for real and imagined array translation as a function of task order and number of imagined steps; and (C) mean RT and (D) percent correct (±1 *SE*) for real and imagined viewer translation as a function of task order and number of imagined steps.

5.83, $p < .001$], and a steps × task × movement interaction [$F(3,114) = 7.03$, $p < .001$].

The interactions were examined further with 2 (movement) × 2 (direction) × 2 (task order) × 4 (steps) ANOVAs performed for each task (viewer translation and array translation). The participants performed the real-array-translation task ($M = 1.18$ sec) more quickly than the imagined-array-translation task ($M = 1.75$ sec), even though they were presented with the same amount of time (2 sec) to *watch* or *imagine* the array transformation before the position was named (see Figure 4A). The array-translation analysis showed an effect of steps [$F(3,54) = 10.32$, $p < .001$] and a steps × movement interaction [$F(3,54) = 9.09$, $p < .001$]. The interaction indicated that in the real-array-translation task there was no effect of steps. In the imagined-array-translation task, repeated contrasts indicated that RT increased as a function of steps from zero to one ($p < .05$) and from one to two ($p < .05$). Although overall the imagined-array-translation task was performed more slowly than the real-array-translation task, a movement × task order interaction [$F(1,18) = 4.85$, $p < .05$] indicated that the order in which the array-translation tasks were performed influenced the task difference (see Figure 4A). When the real-array-translation task was performed before the imagined-array-translation task, there was no statistical difference between the two tasks [Ms = 1.17 sec, 1.42 sec for real and imagined tasks, respectively; $F(1,9) = 1.95$, $p < .2$]. When the imagined task was performed first, the participants performed more slowly on the imagined task ($M = 2.08$ sec) than on the real task ($M = 1.35$ sec). The position ANOVA indicated no difference in RT for front- versus back-position instructions.

In contrast with the results of the array-translation task, Figure 4C shows that there was no difference in RT between the real-viewer-translation task and the imagined-viewer-translation task ($p = .89$). The only significant effect was an overall effect of steps [$F(3,54) = 8.12$, $p < .001$]. Planned contrasts indicated a decrease in RT from zero to one steps ($p < .001$) and an increase back from one to two steps ($p < .01$). Despite the differences in RT, the overall pattern of the real and imagined viewer-translation tasks was an essentially flat function.

Accuracy. Across both tasks and movement conditions, performance with real translation was more accurate than that with imagined translation [$F(1,38) = 4.22$, $p < .05$], and performance with viewer translation was more accurate than that with array translation [$F(1,38) = 4.96$, $p < .05$]. Although there was not a significant interaction between task and movement, 2 (task) × 2 (direction) × 4 (steps) ANOVAs performed separately on the real and imagined conditions indicated no difference between array- and viewer-translation tasks when real movement was allowed ($p = .18$) but greater accuracy in the viewer- than in the array-translation task for imagined movement [$F(1,38) = 4.61$, $p < .05$]. There were also an overall effect of steps [$F(3,114) = 4.27$, $p < .01$] and a steps × task interaction.

Separate 2 (movement) × 2 (direction) × 2 (task order) × 4 (steps) ANOVAs were performed for each task (viewer translation and array translation). The participants performed the real-array-translation task ($M = 92.64\%$) more accurately than the imagined-array-translation task [$M = 86.56\%$, $F(1,18) = 5.29$, $p < .05$; see Figure 4B]. A task × task order interaction [$F(1,18) = 5.29$, $p < .05$] indicated, consistently with the RT results, that the task effect was influenced by the order of real and imagined tasks. When the real movement was performed before imagined movement, there was no difference between the two tasks [Ms = 90% for both tasks; $F(1,9) = 0$, $p = 1$]. When imagined translation was performed before real translation, the participants performed the imagined task less accurately ($M = 83.13\%$) than the real task ($M = 95.31\%$). An overall effect of steps [$F(3,54) = 7.25$, $p < .001$] indicated a decrease in accuracy from one to two steps ($p < .05$). There was no effect of front/back position on accuracy. In contrast with the array-translation task, there was no difference in accuracy between the real- and imagined-viewer-translation-tasks ($p = .54$; see Figure 4D). There were no significant effects or interactions.

Discussion

Physical movement differentially affected the array- and viewer-translation tasks. For the array-translation task, physical translation of the object board facilitated updating in comparison with imagined movement of the array. With an equal 2-sec delay given to perform the transformation in both conditions, observers required additional time to update and made more errors in the imagined array-translation task. With real movement of the array, the flat RT function showed a pattern similar to that of the viewer-translation task seen in Experiments 1 and 2 and in the present experiment. There was no increase in RT with increasing steps, which suggests that the observers could update the positions of the objects in the array as it moved. In the imagined array-translation task, RT increased with increasing steps up to two steps, as in the previous experiments. The overall lower RT found in this experiment in comparison with those found in Experiments 1 and 2 may be attributed to the additional time given to the participants to begin the transformation. For the viewer-translation task, there was no difference between real and imagined self-translation, as was seen in previous real/imagined translation studies (Presson & Montello, 1994; Rieser, 1989).

An examination of the interactions in the array-translation task led to an intriguing effect of task order. The difference found between real and imagined array translation was larger when the imagined task was performed before the real-movement task in comparison with when it was performed after the real-movement task. Imagined translation improved when it was performed after real translation. This improvement could be attributed to a transfer of experience in seeing the moving frame of reference. After performing the real-movement task, the participants could have used their experience with the moving array to influence their imagined performance. These findings suggest that knowledge of the outcome of array movement can facilitate spatial updating without the presence of visual cues specifying the moving frame of reference. Schwartz and colleagues have shown that mental models of the consequences of actions can facilitate imagery and spatial updating in studies of tool use and imagery (Schwartz, 1999; Schwartz & Holton, 2000). For example, Schwartz and Holton showed that pulling a string on a spool facilitated or interfered with the speed of mental rotation of an object sitting on the spool, depending on the participant's mental model of the consequences of pulling on the string. Following this evidence, in the present study observers given a specific model of the consequences of array movement might later predict resulting spatial positions of the objects with greater ease. The real-movement task could have provided a framework for cohesive transformation of a frame of reference, making the extrinsic-transformation task more similar to the process of the egocentric viewer transformation. Notably, the present studies involved passive viewing of motion rather than active control over the movement of the array. It remains to be seen whether active control over array movement without coupled visual information would lead to facilitation in the array-translation task.

GENERAL DISCUSSION

In the present study, we examined whether the consistent advantage for imagined viewer versus imagined object rotation seen in other studies would extend to translational movement. Research in a number of domains has suggested that perceiving, remembering, and updating may be different for translation versus rotation (Bertamini & Proffitt, 2000; Chance, Gaunet, Beall, & Loomis, 1998; Presson & Montello, 1994; Price & Gilden, 2000; Rieser, 1989). Decrements in performance have been shown to result when tasks involve rotational in comparison with translational movements. These findings led us to question whether the advantage seen in imagined viewer rotations was a result of the difficulty of processing rotations. In three studies, observers stood next to an array of objects and imagined their own translation or the translation of the array of objects. We found that the participants updated the positions of objects more efficiently and accurately after imagined viewer translation in comparison with imagined array translation. When physical movement was added to the array-translation task, performance improved to match the efficiency of imagined/real viewer-translation performance. There was no performance difference between imagined and real viewer translation.

In Experiments 1 and 2, a paradigm that enabled the comparison of imagined array and viewer movement without involving rotation was used. Without vision, the participants were asked to imagine self-translation or array-translation and to update front/back or left/right positions from the new imagined position of their bodies or of the array. RT and errors increased as a function of steps for the array-translation task but not for the viewer-translation task.

In Experiment 3, we addressed the question of whether providing information about a moving frame of reference would facilitate updating of performance. After the positions of the objects in the array were memorized, the objects were removed and the participants performed the task with eyes open, to enable viewing of the display's moving frame of reference. This additional movement information facilitated updating in the array-translation task in comparison with the imagined movement condition. The participants performed equally well in the imagined and real self-translation tasks.

Our findings indicate, first, that the difficulty in performing rotational transformations cannot fully account for distinctions seen between imagined object and viewer transformations. In Experiments 1 and 2, a difference between the efficiency and accuracy of imagined transformations that involved only translation was demonstrated. We also found that physical movement of an array that was specified visually, without physical contact with the observer, led to facilitation of updating. These findings lend support to the notion that the ease with which frames of reference may be transformed influences the speed and accuracy of spatial updating. When information about an array's moving frame of reference was provided, the participants were able to update the locations of the objects without the recruitment of additional processing time, leading to a flat RT function. Furthermore, additional information about the array's moving frame of reference appeared to transfer to the imagined translation task when the real translation was experienced first. These findings suggest that knowledge of the outcome of array movement can facilitate spatial updating without the presence of visual cues to specify the moving frame of reference.

The present study demonstrates a distinction between imagined array- and viewer-translation tasks that is consistent with previous studies of rotation. We have suggested that it is more difficult to mentally transform an extrinsic frame of reference in comparison with one's own intrinsic frame of reference in the context of egocentric updating. There may be, however, several factors that influence this spatial transformation ability. One factor is spatial language. Bryant et al. (1992) and Bryant (1993) have demonstrated that the same types of spatial frameworks are used during perception of scenes and decisions about verbal descriptions of scenes. In both cases, people favor a deictic system (Levelt, 1984) in which prepositions are used relative to one's own egocentric axes. In the present tasks, observers were asked to imagine either themselves or the array moving forward or backward. It could be that it was more difficult to comprehend movement of an array forward or backward because of the tendency to interpret spatial prepositions relative to oneself. An analysis of errors in Experiments 1 and 2 indicated that 49% of *array*-translation errors could be identified as correct answers given a *viewer* transformation. The finding that observers spontaneously switched to the viewer-translation task could suggest both the difficulty of imagining the spatial transformation of the array and the possibility that interpretation of spatial language played a role. Evidence from the rotation studies of Wraga et al. (2000b) favors the transformation account. They showed improved performance on the array-translation task when the cohesiveness of the array was increased, still using the same verbal-instruction task. However, future studies are needed to assess more fully the influence of spatial prepositions on nonegocentric transformation tasks.

A second factor to consider is the way in which the observers were instructed to encode object positions. In both the array- and the viewer-translation tasks, they were taught the positions of objects with respect to steps from themselves. This egocentric encoding may have impaired the ability to imagine the objects relative to the array's framework during the imagined movement. Future manipulations may vary the frames of reference used during encoding and assess the ability of imagined self- or object transformations. In a real-walking task, Wraga, Creem, and Proffitt (2000a) found that the frame of reference used in initial coding of a Müller-Lyer figure influenced the effect of the illusion on walking extent.

A final factor is that in the present studies linear translation was tested using only linear arrays, and, thus, we cannot make definitive claims about the viewer- and array-translation distinction for other types of arrays. Previous studies on imagined *self*-transformations used more complex nonlinear configurations of objects for both rotation and translation (Presson & Montello, 1994; Rieser, 1989). We predict that since viewer and array distinctions were found for simple linear arrays, the performance difference should be maintained or even become larger for nonlinear configurations. Future studies using nonlinear arrays would help to examine the generalizability of distinctions between array and viewer translation.

We have used the notion of a spatial reference frame both as a means to provide a structure in which locations are specified (Bryant et al., 1992; Rieser, 1989) and as a framework used in imagined transformations (Amorim & Stucchi, 1997; Wraga et al., 2000b; Zacks et al., 2002). With a stationary reference frame, locations may be represented with respect to the body, an object, an object configuration, or the environment. Imagined transformations involve the mental manipulation of this reference frame in order to predict new spatial locations. The present studies explicitly required the observer to predict the spatial locations of objects with respect to the imagined translation of their own or of the array's frame of reference. As was described above, this moving frame of reference may be distinct from the way the objects were spatially encoded.

The present study does not suggest that the mechanisms underlying rotational and translational transformations are the same, but only that the differences do not fully account for the distinction between viewer and object transformation ability. Research in several domains clearly demonstrates distinctions between rotations and translations. Behavioral differences in updating involving rotations versus translations are apparent with both nonvisual (imagined) and visual (virtual-environment) tasks. Studies using virtual environments have shown decrements in updating performance when visual information specifying rotation is not accompanied by physical body rotation, but they have shown less of a performance distinction between conditions that couple translational body movement with visual translation and those that do not (Chance et al., 1998; Klatzky et al., 1998; Redlick et al., 2001; Richardson, Montello, & Hegarty, 1999; Wraga, Creem, & Proffitt, in press).

The results of Experiment 3 with real movement of the array suggest that the ability to transform and predict the end result of a transformation may be critical to efficient updating. As active observers, we have the ability to predict and update our own movements. Providing this information for the translation of the array's frame of reference had a strong facilitation effect on updating. In general, studies using virtual environments suggest that translational visual optic flow may lead to an updating experience similar to that of physical translation (Redlick et al., 2001), even though rotational visual information alone is not as effective. Our findings of facilitation in updating with array translation are consistent with the findings of those studies. Admittedly, there is a difference between the translational flow of an environment and the translational movement of a group of objects. More studies are needed to assess the generalizability of the facilitation effect of visual information about a moving frame of reference for *arrays of objects* versus *environments* and for *rotation* versus *translation.* It remains to be seen whether the facilitation effects seen with visual translation in the present study would be apparent for visual rotational movements of an array as well.

In conclusion, research in perception, memory, and spatial representation has shown differences in the ease with which tasks involving translations and rotations are performed. Within spatial updating tasks, researchers have consistently found an advantage for imagined viewer rotations in comparison with imagined object or array rotations. We asked whether this viewer advantage would remain for imagined translation or whether the ease of processing translations would lead to equivalent performance for viewer and array transformations. We found a consistent advantage for viewer translation over array translation. The manipulations of physical movement of the array and the observer demonstrated that updating could be facilitated for array translation when the array movement was specified visually. These findings suggest that the distinction between viewer and array transformations may be attributed to an ability to imagine and predict the outcome of moving frames of reference. Humans have expertise with respect to predicting the outcome of moving their egocentric frames of reference (in ecologically valid ways) and may improve their performance at predicting extrinsic movement when provided with the visual experience of the intended moving reference frame.

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NOTES

1. Studies of self-rotations have involved both pure rotations of the observer standing in place and rotations plus translations, in which the observer rotates around a central object.

2. Only one position instruction (either "front" or "back") could be asked at three steps (forward and backward) because the translation reached the endpoint of the board, leading to 14 instead of 16 unique trials.

3. Trials greater than 3 *SD*s from the mean (calculated across all participants) of a given cell were replaced with the mean of that cell. In Experiment 1, 1.4% of the trials were replaced, 2.5% were replaced in Experiment 2, and 2% were replaced in Experiment 3.

4. Pilot trials indicated that this amount of time was necessary and sufficient to complete the greatest movement (three steps) of the board or of the observer.

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