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Imagining physically impossible self-rotations: geometry is more important than gravity

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Abstract

Previous studies found that it is easier for observers to spatially update displays during imagined self-rotation versus array rotation. The present study examined whether either the physics of gravity or the geometric relationship between the viewer and array guided this self-rotation advantage. Experiments 1–3 preserved a real or imagined orthogonal relationship between the viewer and the array, requiring a rotation in the observer's transverse plane. Despite imagined self-rotations that defied gravity, a viewer advantage remained. Without this orthogonal relationship (Experiment 4), the viewer advantage was lost. We suggest that efficient transformation of the egocentric reference frame relies on the representation of body–environment relations that allow rotation around the observer's principal axis. This efficiency persists across different and conflicting physical and imagined postures. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

People have a remarkable ability to imagine the spatial positions of objects in the world across multiple views. This process of spatial updating can be carried out in different ways. To judge what an array of objects in the world looks like from another perspective, one could imagine a rotation of one's own viewpoint or imagine

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a rotation of the object itself. Recent work indicates clear differences in the cognitive mechanisms involved in performing these different types of imagined rotations (Wraga, Creem, & Proffitt, 2000). Several studies have shown an advantage in reaction time (RT) and accuracy for updating during imagined self-rotation versus imagined rotation of an array of objects or a single object (Amorim & Stucchi, 1997; Carpenter & Proffitt, in press; Presson, 1982; Wraga et al., 2000). Wraga et al. (2000) showed that this viewer rotation advantage generalized to many different conditions involving the imagined rotation of four-object and single-object displays in the transverse (ground) plane, perpendicular to the viewer's principal axis (see Fig. 1). Carpenter and Proffitt (in press) tested rotations in alternative planes and found that the viewer advantage only occurred in the transverse plane. The present

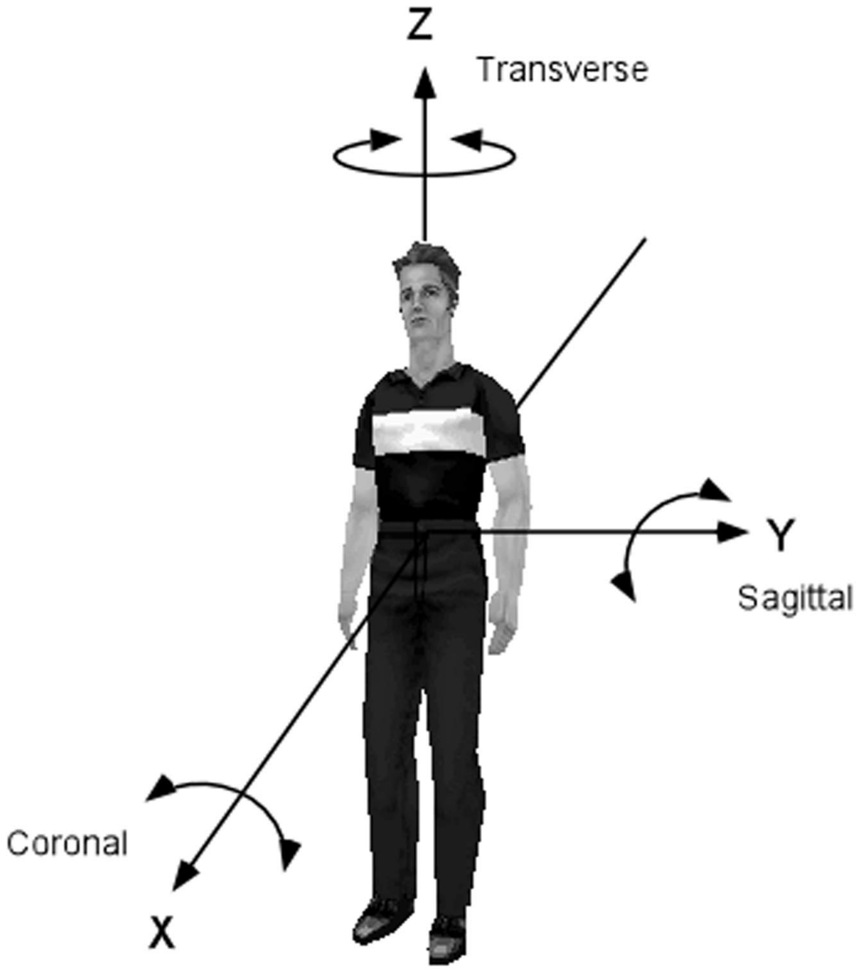

Fig. 1. Three axes of rotation tested in Carpenter and Proffitt (in press).

studies examined whether the advantage for imagined viewer rotations in the transverse plane was based on implicit constraints of gravity or the geometrical constraints of a familiar, perpendicular relationship between the observer's principal axis and the environment. We found that the viewer rotation advantage occurred in circumstances that defied gravity and involved conflicts between imagined and physical postures. The critical variable for updating efficiency was whether imagined rotation was transverse to the imagined orientation of the participant.

1.1. An advantage for updating during viewer versus array rotations

The cognitive task of imagining what an array of objects in the world would look like after an observer or the array has rotated has been examined extensively in recent studies (Amorim & Stucchi, 1997; Huttenlocher & Presson, 1979; Presson, 1980, 1982; Wraga et al., 2000). Initial studies by Presson and colleagues compared imagined viewer and object rotations in adults and children finding varying results depending on the type of information given (Huttenlocher & Presson, 1979; Presson, 1980, 1982). More recently, Amorim and Stucchi (1997) found a viewer advantage in a study comparing imagined object and self-rotation. They asked participants to imagine that they were standing outside of a huge clock that was lying on the horizontal ground plane. Instead of hour and minute hands, the participants were to imagine that an upright three-dimensional uppercase letter "F" was in the center the clock. In the viewer task, they imagined moving to a given location around the periphery of the clock and updated the position of the letter from their new perspective. In the object task, they imagined that the letter was pointing to a new position around the clock and updated their own position on the clock with respect to the new letter position. Performance on the viewer task was faster and more accurate.

Wraga et al. (2000) conducted six variations on a task initially conducted by Presson (1982) in which participants were asked to spatially update the positions of objects or parts of objects during imagined self-rotation or object rotation. In all of the experiments, participants stood facing four objects in a diamond-shaped array placed on pedestals on the floor. They first memorized the position of the objects. In testing, they were given a degree of rotation and a position in the array, and they were asked to name the object that corresponded to the given position after either imagined self or array rotation without vision (e.g. "Rotate 90°, what's on the right?"). Wraga et al. found that when the question was phrased in this way, the viewer task was faster and more accurate. They proposed that the consistent viewer advantage resulted from the human cognitive 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.

Based on the evidence that the viewer advantage in all of the studies comparing viewer and object rotation resulted from rotations relative to the observer's transverse plane, Carpenter and Proffitt (in press) investigated whether the same advantage would hold with rotations in other planes. They asked participants to perform in similar array and viewer tasks as in Wraga et al. (2000) using transverse, coronal, and sagittal rotations (see Fig. 1). They replicated the general viewer advantage for rotations in the transverse plane. However, viewer performance declined to the level of array performance in the coronal and sagittal rotation conditions. There are several alternative explanations for the specificity of superior imagined viewer rotations in the transverse plane. It could be that participants were better at imagining this rotation because it obeyed gravitational constraints, allowing for the physical possibility of moving around on the ground plane. It could also be that the viewer advantage resulted from a rotation that allowed an orthogonal relationship between the observer's principal (i.e. longest) axis and the objects.

1.2. Do transformations follow principles of physics or geometry?

Research has indicated that space can be mentally represented and transformed in multiple ways. Notably, the ease of imagining spatial transformations varies greatly between experimental designs. Performance depends on the reference frame that is rotated (as described above), as well as the axes of rotation and the type of task required. For example, studies have demonstrated the difficulty of imagining rotations about oblique axes (Pani, 1993), and differences between recognition tasks and those that require the prediction of the end-state of a rotation (Parsons, 1995; Rock, 1989).

The question of the present study is one that applies to other realms of mental rotation as well: to what extent do imagined rotations follow physical laws? It is clear from the now classic studies of Roger Shepard and colleagues (Shepard & Cooper, 1982; Shepard & Metzler, 1971) that images of objects can be mentally rotated through continuous trajectories as if they were being physically rotated in space. Adherence to physical principles can be seen in mental rotation of body parts as well as in transformations involving external objects. Parsons (1987a,b) found strong correlations between the time to simulate the motion of one's own hands, feet, or body and the time to make a left–right judgment about the body or body part. As in Shepard's object discrimination tasks, the latency to make left–right judgments depended on the orientation difference between the stimulus and the canonical orientation of the person's body part. In subsequent studies, Parsons (1994) found that mental simulation time of hand movement was consistent with actual movement time. These findings together suggest that people imagined their hand moving into the orientation of the stimulus through a trajectory similar to one for physical motion.

Further evidence for the influence of physical constraints on imagined transformations comes from the similarity between mental and physical rotation. Several recent studies have convincingly shown that mental rotation relies on motor processes using dual-task paradigms that required both mentally rotating an image and manually rotating a dial or a joystick (Wexler, Kosslyn, & Berthoz, 1998; Wohlschlager & Wohlschlager, 1998). Wohlschlager and Wohlschlager found that motor rotation of a dial in a direction concordant with mental rotation facilitated performance, whereas motor rotation in a discordant direction inhibited performance. Wexler et al. (1998) demonstrated that a change in the speed of motor rotation of a joystick correspondingly affected the speed of mental rotation. In addition to these behavioral studies, several recent functional neuroimaging studies have found premotor activation during imagined rotation tasks (Cohen et al., 1996; Kosslyn, Digirolamo, Thompson, & Alpert, 1998; Parsons et al., 1995).

However, other research suggests that imagined movements may be discrete, rather than smooth analog transformations (Gilden, Blake, & Hurst, 1995; Hegarty, 1992). In addition, some studies suggest that principles of geometric relations, rather than physics, truly guide representations of real and imagined transformations (Shepard, 1984; Shiffrar & Shepard, 1991). Shiffrar and Shepard (1991) asked observers to judge whether two actual rotations of a cube were the same or different. They found that response latencies were faster and more accurate when the rotational axis was aligned with a natural axis of the object, the environment, or both. Although the physical dynamics of all the rotations tested were the same (i.e. the rotation was about a principle axis of the body's mass distribution), they differed in their geometrical relations to the environmental frame and to the object-relative frame of the cube. RTs were fastest in the conditions when the rotational axis was aligned with the environmental vertical. These studies suggest the importance of geometrical relations, but they also demonstrate the importance of the environmental vertical for ease of rotation. This may arise from our continuous experience with the earth's gravitational field (Shepard, 1984). Despite evidence for the lack of influence of the physics of motion, the physics of gravity appear to remain influential.

The difficulty with the extrapolation of motion around oblique axes seen in Shiffrar and Shepard's study is consistent with what has been seen in mental rotation studies (Massironi & Luccio, 1992; Pani, 1993; Pani & Dupree, 1994; Parsons, 1995). Parsons (1995) asked participants to imagine the rotation of a Shepard–Metzler three-dimensional cube figure along a specific axis to a given degree and then to decide whether a presented figure correctly matched the imagined object. He found that this task was difficult to perform overall, but specifically, the geometric relationships between the object, axes of rotation, and the environment predicted the level of performance. As in Shiffrar and Shepard (1991), performance was superior when the axes of the object, rotation, and gravitational vertical were aligned. Pani and Dupree (1994) investigated the influence of axis of rotation in imagined rotation using a stimulus of a square attached to a rod. Participants were instructed to imagine rotations of the square using the rod as the axis of rotation, and responded by orienting another square to demonstrate the predicted outcome. The results indicated clearly that performance was best when the rod was aligned vertically with the environment. All of these studies together suggest the importance of the geometric relationship between the axes of the object, rotation, and environmental frame. Performance on both imagined and perceived rotations is improved when these axes are aligned. These studies also suggest an advantage for rotation around the vertical defined by gravity. However, as in Carpenter and Proffitt (in press), vertical alignment with the environment and gravity were typically confounded. Our aim was to separate the two factors in an imagined viewer and array rotation task.

1.3. Overview to the experiments

We conducted a series of four experiments to investigate the conditions under which an advantage for self-rotation is apparent in a spatial updating task. We used a paradigm similar to that used in Wraga et al. (2000). Participants performed imagined viewer and array rotations in the context of spatially updating the positions of four objects in an array. Our main goal was to determine whether a self-rotation advantage would continue to appear when participants were asked to perform self-rotations that did not obey gravity. We manipulated both the *physical* and *imagined* relationship of the observer to the array/environment.

In Experiment 1, participants lay supine, perpendicular to an array of objects hanging on the wall. Participants imagined rotating around the outside of the array (as if walking on the wall) or imagined the objects rotating like a wheel. In Experiment 2, participants lay in the same position as in Experiment 1. However, the array of objects was placed on the ground plane. Participants were instructed to imagine standing and to imagine rotating around the array on the ground plane, or to imagine the array rotating around its center. In Experiment 3, participants physically stood facing the array, but imagined lying orthogonal to it to perform a transverse rotation. In Experiment 4, participants physically stood in the same position as in Experiment 3, but were instructed to imagine a coronal (rotating as if doing a cartwheel), rather than a transverse rotation. The results indicated a RT advantage for viewer rotation compared to array rotation in the first three experiments. All of these experiments involved either physical or imagined orthogonal observer–array relations (a representation of the body's vertical axis perpendicular to the array), leading to a transverse rotation around the observer's principal axis. When a non-orthogonal relationship between the observer and array was created in Experiment 4, the advantage for viewer rotation was lost. We suggest that the viewer rotation advantage is defined relative to the viewer's imagined position, not to the environment.

2. General method

Four experiments were conducted. In this section, we describe aspects of the method common to all of the experiments. Details specific to each experiment are included within each experimental section.

2.1. Materials

The array consisted of four different objects placed in a diamond-shape configuration. The objects were all plastic toys: a 12×4 cm orange phone, a 15×18 cm blue hammer, a 15×7 cm white car, and a 9×6 cm yellow egg. The objects were either affixed with Velcro to the center of each side of a 75 cm square black board hung on the wall (Experiments 1, 3, and 4), or placed on four wooden stands (92 cm in height) positioned to form the same size array (Experiment 2). A cot (180 cm in length) was used for the supine experiments. RTs were recorded using a Timex chronograph stopwatch.

2.2. Procedure

Participants performed in two imagined rotation conditions, viewer and array. First, they learned the positions of the objects in the array in terms of top, bottom, left, and right. They were told to memorize the positions, and then were tested with eyes closed to ensure that they had learned the configuration. For the rotation tasks, participants were blindfolded and were presented aurally with a degree of rotation and a position in the array on each trial. For example, the experimenter might ask, "90, what is on the right?" The degrees of rotation given were 0, 90, 180, and 270.[1] In the viewer task, participants imagined that they were rotating around the outside of the array, while continuing to face the objects. In the array task, participants imagined that the array was rotating around its center. They were instructed to begin each trial from their original physical position. Participants were instructed to imagine the rotation and then respond as quickly and accurately as possible by naming the object that corresponded to the position given. RT was measured from the end of the experimenter's question to the beginning of the participant's response. At the end of the first condition, the objects were placed in a new configuration in the array and the second condition was performed.

2.3. Design

The order of tasks was counterbalanced across participants. Imagined rotations were always performed clockwise because previous studies showed that there was no difference in performance as a function of direction of rotation (Wraga et al., 2000). Each of the positions in the array was matched with each of the rotation degrees for a total of 16 trials in each task (four trials for each degree). Trials were randomly presented.

2.4. Analysis

Response latency and accuracy were recorded and analyzed.[2] The data were

[1] The four orthogonal angles were used to remain methodologically consistent with the previous experiments (Carpenter & Proffitt, in press; Wraga et al., 2000) that motivated the present experiment. Future research should examine the effect of more varied angles.

[2] Response latency has been the primary dependent variable used in mental rotation tasks of both objects and viewers for nearly three decades (Farrell & Robertson, 1998; Presson, 1982; Shepard & Cooper, 1982; Shepard & Metzler, 1971; Wohlschlager & Wohlschlager, 1998; Wraga et al., 2000). Shepard and colleagues used evidence of a linear increase in RT with the angular disparity of a stimulus to support the claim of analogous processes for mental and physical rotation. Typically, error rates are also measured in mental rotation studies, to allow for analysis of correct-only responses and to provide another measure of cognitive performance. In recent imagined viewer rotation studies, deviation of pointing error has also been used (Farrell & Robertson, 1998; Presson & Montello, 1994). Rotation studies of objects and viewers typically have indicated that error rates correspond to response latencies, finding that increasing angles of rotation led to larger RT and error.

transformed to allow for a symmetrical distribution (Tukey, 1977). A log transformation was applied to RT data and a square-root transformation was applied to error data. A 2 (task order) × 2 (sex) × 2 (task) × 4 (degree) ANOVA was performed on latency and accuracy data, with task order and sex as between-subject variables and task and degree as within-subject variables.

3. Experiment 1

In the first experiment, we preserved the orthogonal relationship between the observer and the array that would be found in a normal environment. However, instead of standing looking at an array of objects on the ground, the participant lay supine, perpendicular to an array of objects hanging on the wall (see Fig. 2). We examined the ability of participants to imagine rotating around the objects "as if walking on the wall" or to imagine the array of objects rotating "like a wheel". Imagined viewer and array rotations were performed. An advantage for the viewer task compared to the array task would suggest that the ease of egocentric transformations seen in past studies was not entirely a result of a rotation that adheres to gravitational constraints.

3.1. Method

3.1.1. Participants

Twenty-four University of Virginia students (12 F, 12 M) participated as a partial requirement for course credit. Two additional participants were removed from the experiment for not following directions. All participants were tested individually. None knew of the hypothesis being tested.

3.1.2. Procedure

Participants lay supine on a cot, facing the array of objects hanging on the wall 100 cm away (see Fig. 2). In the viewer task, they imagined rotating clockwise around the outside of the array as if walking on the wall. In the array task, they imagined the array rotating like a wheel.

3.2. Results

3.2.1. Latency

Participants performed the viewer task ($M = 2.09$ s)[3] more quickly than the array task ($M = 3.49$ s) ($F(1,20) = 15.11$, $P < 0.011$).[4] Fig. 3a presents mean RT and standard errors as a function of degree of rotation. The ANOVA also revealed an effect of degree ($F(3,60) = 53.46$, $P < 0.001$), and a significant task × degree inter-

[3] Although mean log RT was analyzed, mean scores are reported in seconds in all experiments for clarity.

[4] Mean RTs that were greater than three standard deviations above the overall mean of a given array or viewer degree condition were replaced with the group mean for that condition (e.g. array 270°). In Experiment 1, two array and one viewer mean RTs were replaced.

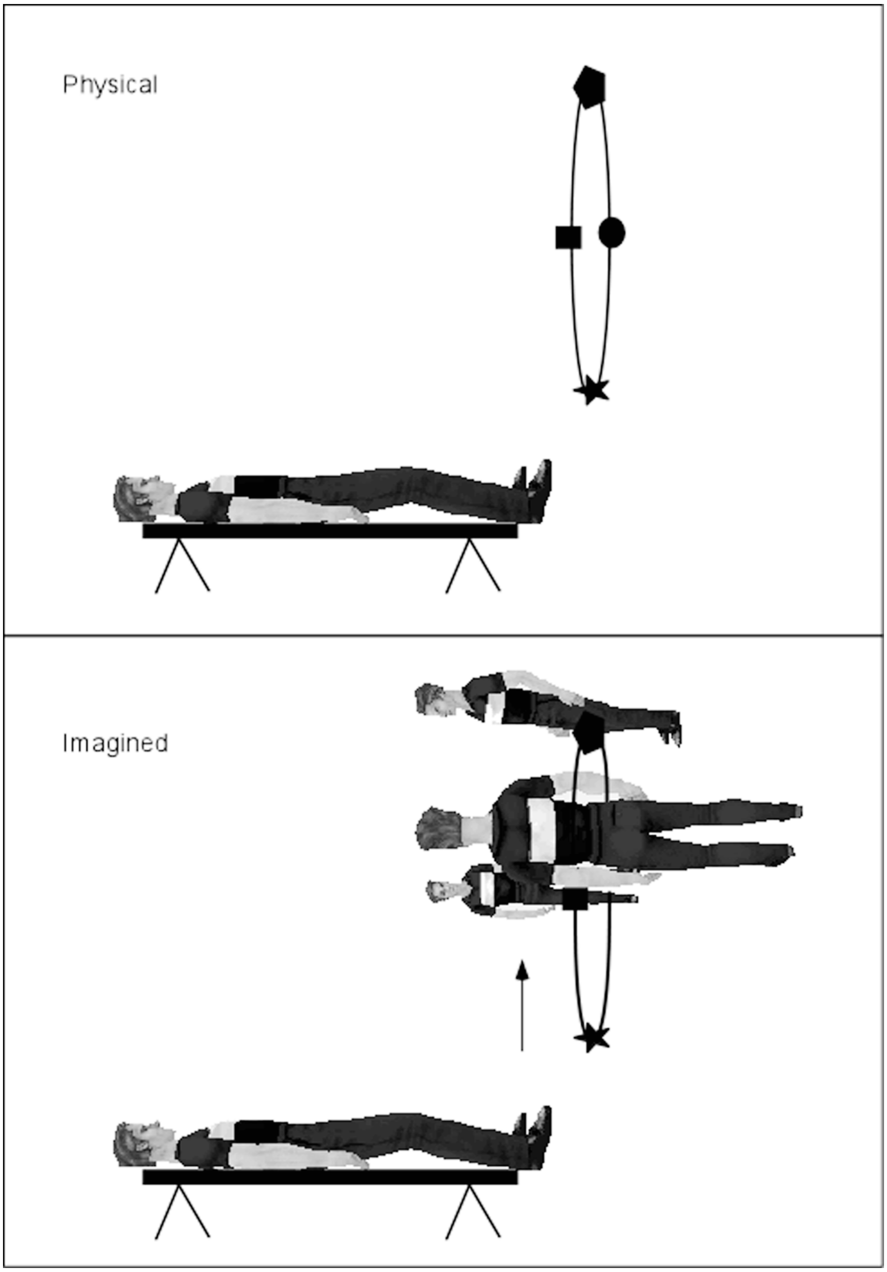

Fig. 2. Physical and imagined positions of the observer relative to the array in Experiment 1.

action ($F(3, 60) = 8.61$, $P < 0.001$), indicating that although RT increased with degrees above 0, the patterns of RT were different for the two tasks. Simple contrasts

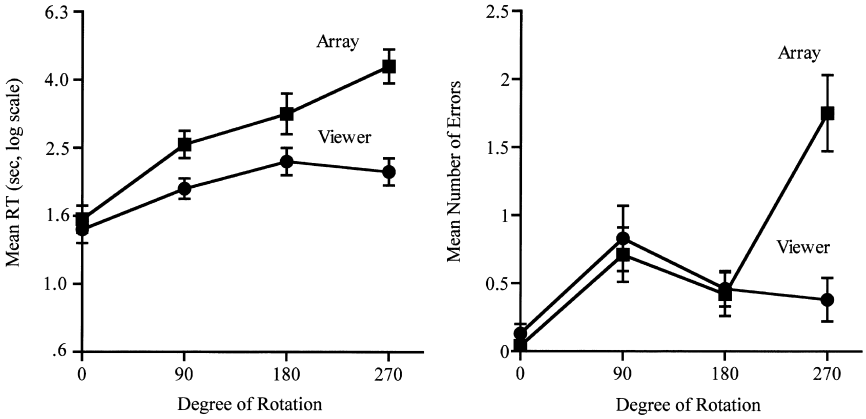

Fig. 3. (a) Mean RTs (±SE) and (b) number of errors (±SE) in Experiment 1. RT values are in seconds, depicted in log space.

revealed that RT increased up to the 270° rotation in array (180 vs. 270°, $P < 0.001$), but reached a peak at 180° in viewer (90 vs. 180°, $P < 0.02$; 180 vs. 270°, $P < 0.38$).

3.2.2. Accuracy

Although participants made fewer errors in viewer ($M = 0.45$ errors)[5] than array ($M = 0.73$ errors), the trend was not significant ($F(1,20) = 1.81$, $P < 0.2$). However, there was an effect of degree ($F(3,60) = 12.5$, $P < 0.001$) and a significant task × degree interaction ($F(3,60) = 9.09$, $P < 0.001$) (see Fig. 3b). Simple contrasts revealed that although errors increased at rotation degrees compared to 0 in both tasks (array: 0 vs. 90°, $P < 0.002$; viewer: 0 vs. 90°, $P < 0.01$), there was a dramatic increase in errors in array at 270° (180 vs. 270°, $P < 0.001$).

3.3. Discussion

In Experiment 1, the relative position of the observer to the array of objects remained orthogonal, resembling our experience in the real world. However, the observer–array configuration was physically rotated 90° so that the observer lay supine, facing an array hanging on the wall. This position required observers to imagine a viewer rotation that was physically impossible to perform. Despite this gravity-defying viewer rotation, our results were similar to those of Wraga et al. (2000). The viewer task was performed faster and more accurately than the array task and the two tasks resulted in different RT and accuracy functions. As in previous studies, a large increase in RT was apparent at 270° in the array task, but not in the viewer task. For accuracy, although there was no overall difference,

[5] Although the analysis was performed on a square root transformation of error, the mean number of errors is reported in the text in all experiments for clarity.

the interaction revealed an increase in the number of errors at 270° for the array task but not for the viewer task.

The present experiment suggests that the representation of an orthogonal viewer–array relationship is more important for a viewer advantage than the physical possibility of traversing around the array objects, in a case when *imagined* and *physical* positions of the viewer coexist. In the next two experiments, we investigated whether the representation of an orthogonal observer–array relationship would

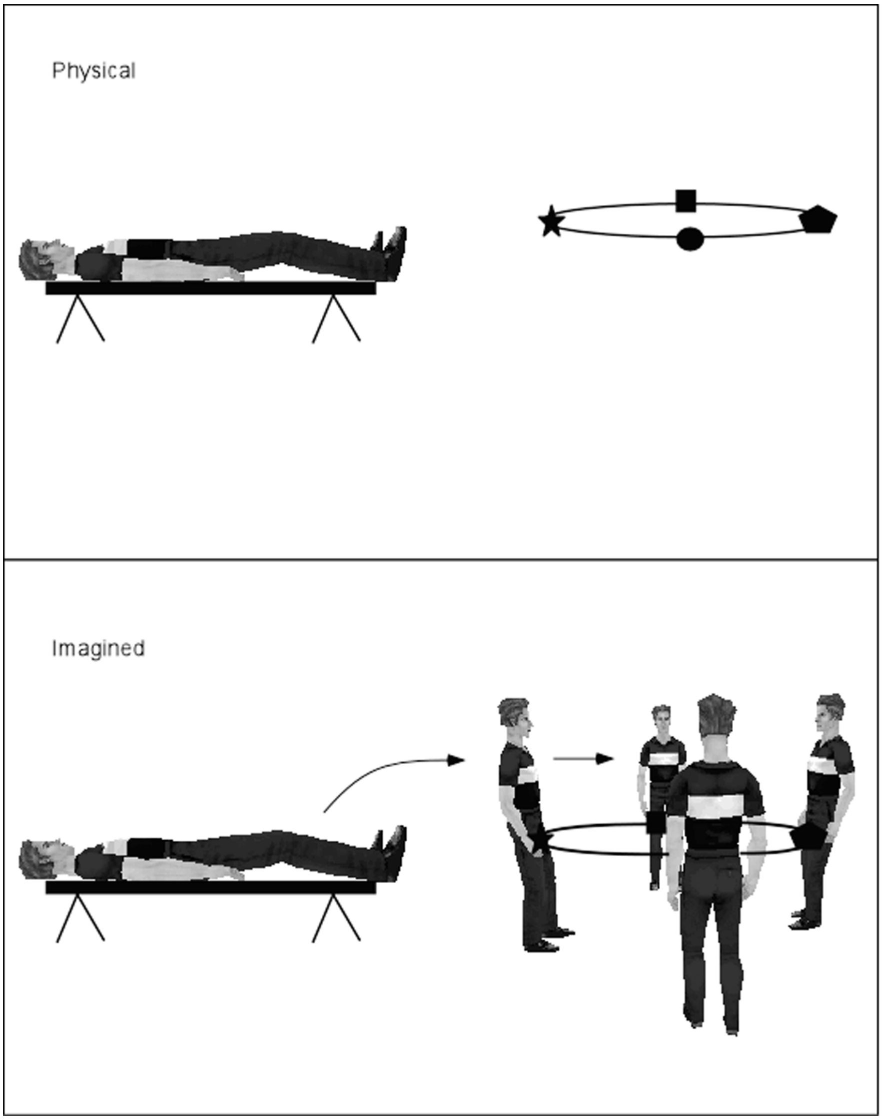

Fig. 4. Physical and imagined positions of the observer relative to the array in Experiment 2.

allow for a similar viewer advantage regardless of the participant's physical position.

4. Experiment 2

Similar to the design of Experiment 1, observers lay supine while performing the viewer and array tasks of Experiment 2. Unlike the first experiment, however, the array consisted of pedestals placed on the ground. Thus, participants' bodies were parallel to the array. We examined observers' abilities to imagine standing orthogonal to the array and to either imagine moving around the array, or to imagine the array rotating around its center. In this manipulation, observers' physical body positions did not afford rotating easily, but their imagined posture (i.e. standing) would allow transverse rotation on the ground plane as in the Wraga et al. studies. We reasoned that the advantage for *physical* orthogonal observer–array positions might generalize to *imagined* orthogonal relations, and thus, we predicted a continued advantage for the viewer task over the array task.

4.1. Method

4.1.1. Participants

Twenty-three University of Virginia students (11 F, 12 M) participated as a partial requirement for course credit. Eight additional participants were removed either for their inability to follow instructions ($n = 5$) or for having more than a 50% error rate ($n = 3$). All participants were tested individually. None knew of the hypothesis being tested.

4.1.2. Procedure

Participants lay down on a cot with the array of objects on pedestals at their feet 100 cm away from the end of the cot. They imagined that they were standing orthogonal to the array and performed both array and viewer tasks (see Fig. 4).

4.2. Results

4.2.1. Latency

As in Experiment 1, participants performed the viewer task ($M = 1.93$ s) more quickly than the array task ($M = 2.87$ s) ($F(1,19) = 36.04$, $P < 0.001$) (see Fig. 5a).[6] Furthermore, the analysis revealed an effect of degree ($F(3,57) = 41.91$, $P < 0.001$), and a task × degree interaction ($F(3,57) = 8.30$, $P < 0.001$). Similar to Experiment 1, RT increased to 270° in array (180 vs. 270°, $P < 0.001$) but peaked at 180° in viewer (90 vs. 180°, $P < 0.005$).

[6] Mean RTs that were greater than three standard deviations above the overall mean of a given array or viewer degree condition were replaced with the group mean for that condition (e.g. array 270°). In Experiment 2, one array and one viewer mean RT were replaced.

4.2.2. Accuracy

Participants were marginally more accurate in the viewer ($M = 0.32$ errors) compared to the array task ($M = 0.64$ errors) ($F(1, 19) = 3.87$, $P < 0.064$). The analysis also indicated an effect of degree ($F(3, 57) = 19.92$, $P < 0.001$) and a task × degree interaction ($F(3, 57) = 7.80$, $P < 0.001$) (see Fig. 5b). Contrast comparisons revealed the same pattern of errors as in Experiment 1.

4.3. Discussion

As in Experiment 1, we found reduced RT and errors in the viewer task compared to the array task. Observers were able to imagine standing perpendicular to the array. Despite the conflict between the participants' physical horizontal position and their imagined standing position, participants' performance closely resembled that in Experiment 1 and in the previous Wraga et al. experiments. RT and errors increased at 270° for the array task, but not for the viewer task.

Although this experiment suggests that an advantage for self-rotation compared to array rotation may rely on *physical* or *imagined* orthogonal observer–array relations, we can only generalize these results to imagined rotation on the ground plane. In the next experiment, we asked whether the advantage would continue to exist when both the imagined rotation position *and* imagined self-rotations defied gravity.

5. Experiment 3

Experiment 3 essentially combined the manipulations of the first two experiments. In Experiment 1, participants physically lay orthogonal to the array and rotated along the wall, whereas in Experiment 2, participants physically lay parallel to the array, imagined standing orthogonal to the array, and rotated on the ground. In the present experiment, participants physically stood parallel to an array on the wall,

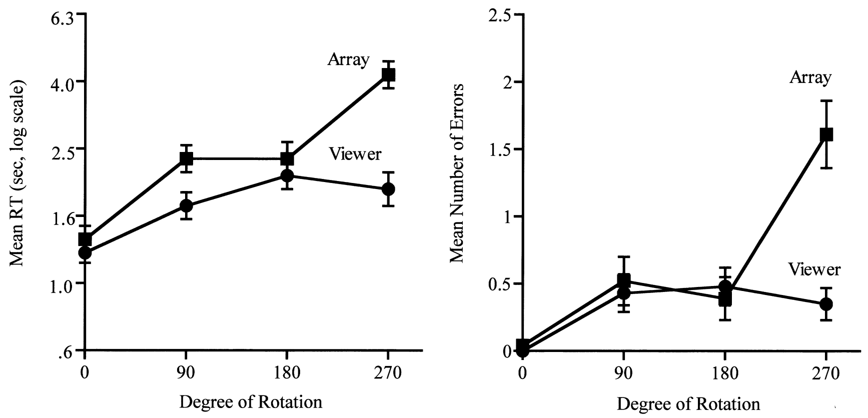

Fig. 5. (a) Mean RTs (±SE) and (b) number of errors (±SE) in Experiment 2. RT values are in seconds, depicted in log space.

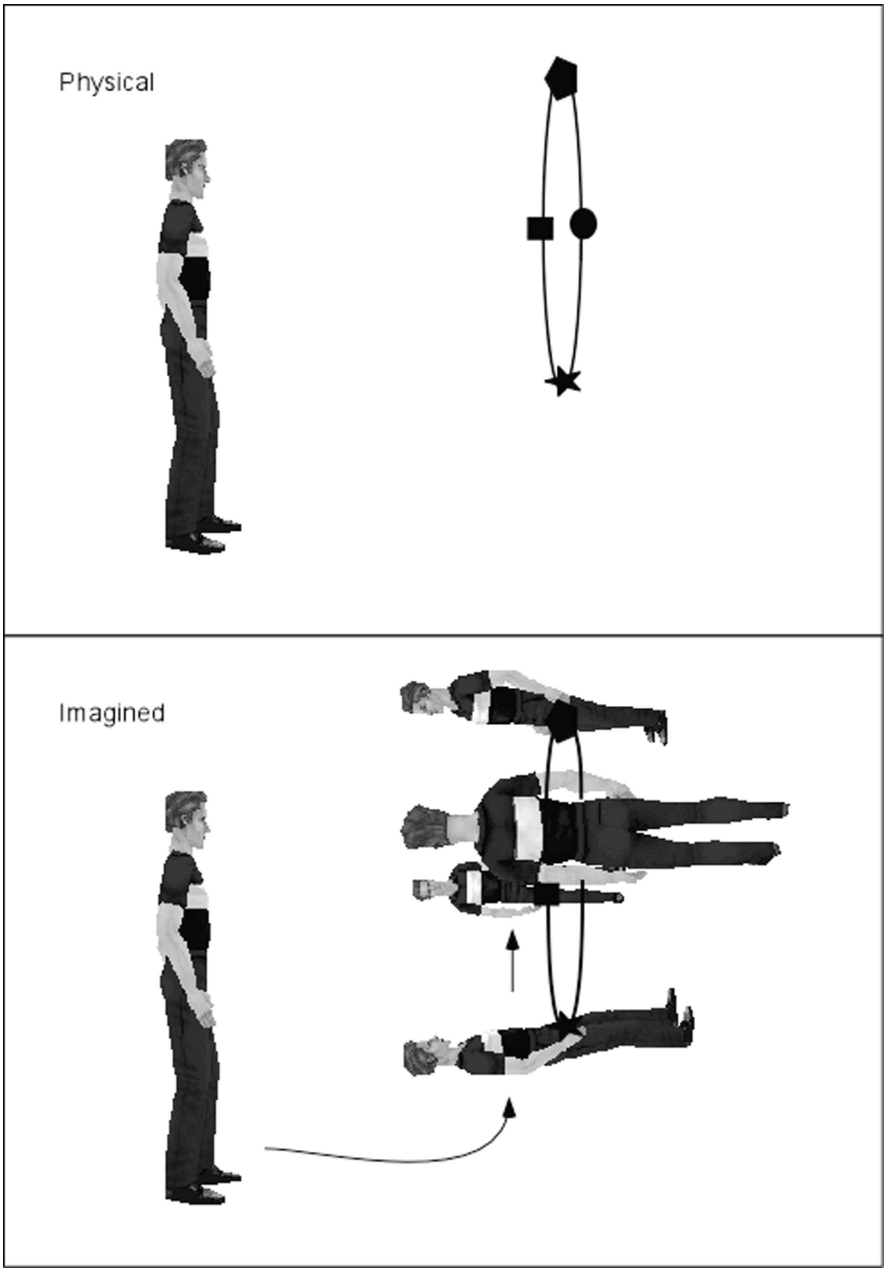

Fig. 6. Physical and imagined positions of the observer relative to the array in Experiment 3.

imagined lying orthogonal to the array, and rotated along the wall (see Fig. 6). Thus, this experiment required an imagined self-orientation, as well as a rotation, that defied gravity. Despite these obstacles, we predicted a continued self-rotation advantage.

5.1. Method

5.1.1. Participants

Twenty-four University of Virginia students (12 F, 12 M) participated as a partial requirement for course credit. Eight additional participants were removed either for their inability to follow instructions ($n = 5$) or for having more than a 50% error rate ($n = 3$). All participants were tested individually. None knew of the hypothesis being tested.

5.1.2. Procedure

Participants stood facing the array hanging on the wall about 100 cm away from the wall. They imagined lying perpendicular to the wall. In the viewer task, they imagined rotating around the outside of the array as if walking on the wall as in Experiment 1. In the array task, they imagined the array rotating like a wheel (see Fig. 6).

5.2. Results

5.2.1. Latency

As in the previous two experiments, participants responded more quickly in the viewer task ($M = 1.99$ s) compared to the array task ($M = 3.32$) ($F(1,20) = 35.98$, $P < 0.001$). The analysis also revealed an effect of degree ($F(3,60) = 42.51$, $P < 0.001$), and a significant task × degree interaction ($F(3,60) = 25.07$, $P < 0.001$). Simple comparisons revealed the same pattern of RT as in Experiments 1 and 2 (see Fig. 7a).

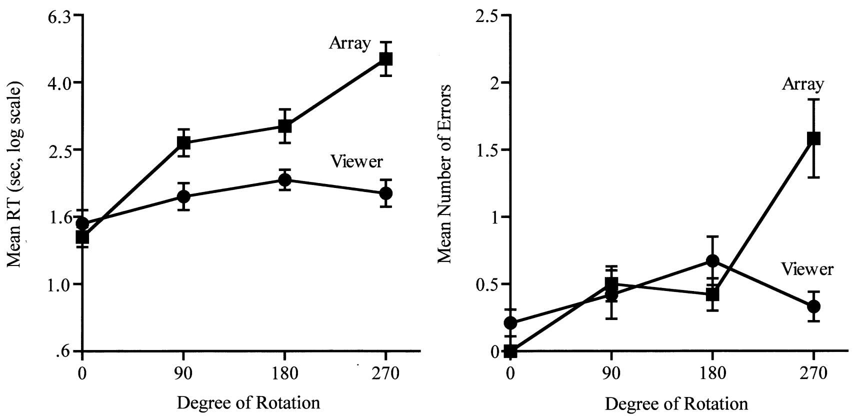

Fig. 7. (a) Mean RTs (±SE) and (b) number of errors (±SE) in Experiment 3. RT values are in seconds, depicted in log space.

5.2.2. Accuracy

The total number of errors in the array task was not significantly different than the viewer task ($F(1,20) = 1.97$, $P < 0.18$; $M = 0.63$ and 0.41 errors, respectively). However, the ANOVA did indicate an effect of degree ($F(3,60) = 8.62$, $P < 0.001$), and a task × degree interaction ($F(3,60) = 8.81$, $P < 0.001$) (see Fig. 7b). Simple comparisons revealed the same pattern of errors in array as in the previous experiments. There was no significant increase in error at all in viewer.

5.3. Discussion

The results of Experiment 3 followed the pattern of those of the first two experiments. Performance was better on the viewer task compared to the array task, and the rotation functions continued to follow the same pattern. Despite the fact that observers were required to imagine a body position that conflicted with their physical body position, and that they imagined a self-rotation that was not physically possible (walking along the wall), we continued to find superior performance on the viewer task compared to the array task. The latency and accuracy functions closely resembled those of Experiments 1 and 2.

This experiment, along with the first two studies, more convincingly indicates the importance of the geometrical relationship between the observer and the array for a self-rotation advantage. Given that the representation of this relationship was orthogonal, allowing for rotation around the body's principal axis, the ease of transverse self-rotation was not constrained by physical boundaries. The rotation required in Experiment 3 involved transverse rotation relative to the observer's imagined position. However, the rotation would be defined as coronal relative to the observer's actual environmental position. As in Experiment 2, participants were able to ignore their physical posture and imagine a new posture to perform the required rotation. One additional experiment seemed necessary to conclude an explanation in favor of geometrical relations over physically possible action. Experiment 4 asked participants to remain standing parallel to the array of objects and perform an imagined rotation in the participant's coronal plane.

6. Experiment 4

Carpenter and Proffitt (in press) found that an advantage for viewer rotation over array rotation did not hold for rotation in the sagittal and coronal planes relative to the observer. Our intent was to replicate this finding in the present experiment, using the materials and procedure of the first three experiments. Participants were placed in exactly the same position as in Experiment 3. However, they were not instructed to imagine a perpendicular position relative to the array and a transverse rotation. Instead, they were instructed to perform a coronal rotation as if "performing a cartwheel in the air" (see Fig. 8). Based on the previous results of Carpenter and Proffitt, and the suggestion of the importance of transverse rotations from Experiments 1–3, we predicted no advantage for viewer performance compared to array.

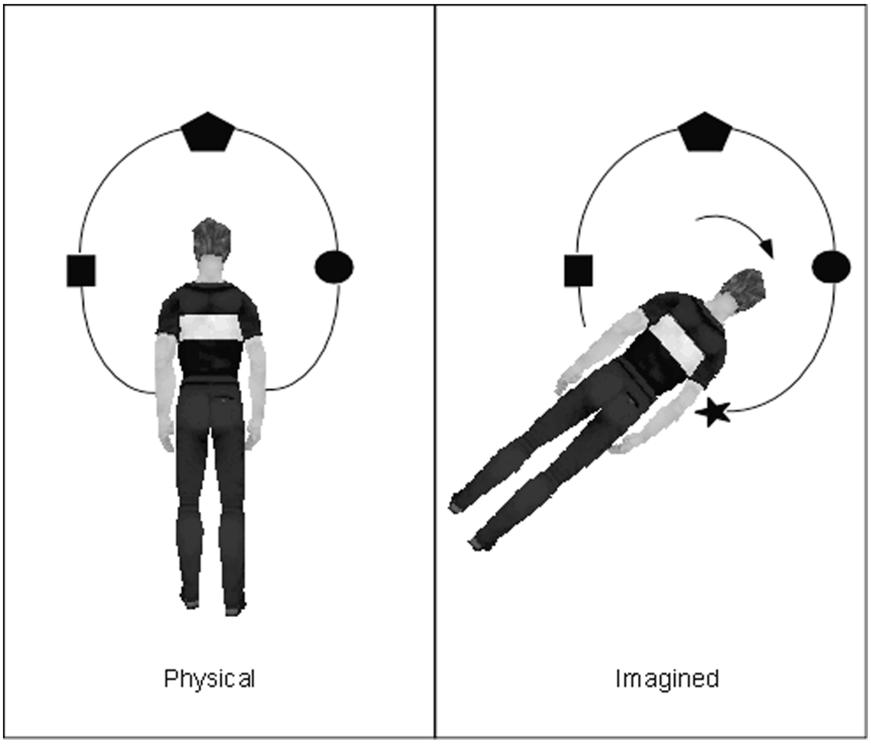

Fig. 8. Physical and imagined positions of the observer relative to the array in Experiment 4.

6.1. Method

6.1.1. Participants

Twenty-three University of Virginia students (13 F, 10 M) participated as a partial requirement for course credit. Two additional participants were removed for not following instructions ($n = 1$) or for having more than a 50% error rate ($n = 1$). All participants were tested individually. None knew of the hypothesis being tested.

6.1.2. Procedure

Participants stood facing the array of objects on the wall as in Experiment 3. In the viewer task, they imagined themselves rotating in the coronal plane, as if they were performing a cartwheel-like transformation. In the array task, they imagined the array rotating like a wheel in front of them (see Fig. 8).

6.2. Results

6.2.1. Latency

As in Carpenter and Proffitt (in press), there was no difference in RT between array and viewer tasks ($M = 2.50$ and 2.21 s, respectively). The ANOVA failed to

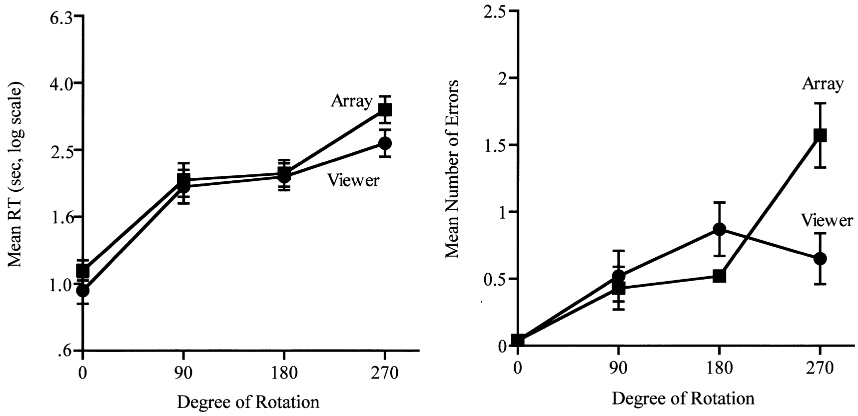

Fig. 9. (a) Mean RTs (±SE) and (b) number of errors (±SE) in Experiment 4. RT values are in seconds, depicted in log space.

reveal an effect of task ($F(1, 19) = 2.0$, $P < 0.2$). The only other effect was one of degree ($F(3, 57) = 66.63$, $P < 0.001$).[7] RT increased with rotation degree similarly in both tasks (see Fig. 9a).

6.2.2. Accuracy

There was no difference in accuracy between the array and viewer tasks ($F(1, 19) = 1.03$, $P < 0.33$; $M = 0.64$ and 0.52 errors, respectively). The ANOVA revealed an effect of degree ($F(3, 57) = 15.78$, $P < 0.001$) and a significant task × degree interaction ($F(3, 57) = 7.03$, $P < 0.001$). Simple contrasts revealed the consistent pattern of errors seen in all of the previous array tasks. For the viewer task, errors were greater for rotation degrees above 0, but did not differ further as a function of degree of rotation (0 vs. 90°, $P < 0.01$) (see Fig. 9b).

6.3. Discussion

Unlike the results of the previous three experiments, we found no difference in response latency between array and viewer tasks. These results replicate those of Carpenter and Proffitt (in press) and further implicate the representation of an orthogonal relationship between observer and objects as an important factor leading to the viewer task advantage. Participants stood in the same physical position as in Experiment 3. However, when required to imagine a coronal rotation, they showed similar performance on the viewer task as on the array task. Unlike the previous studies, RT in the viewer task increased with the 270° rotation to match the array task. This finding suggests that the rotation axis critical to a viewer rotation advan-

[7] Mean RTs that were greater than three standard deviations above the overall mean of a given array or viewer degree condition were replaced with the group mean for that condition (e.g. array 270°). In Experiment 4, one array and two viewer mean RTs were replaced.

tage is defined by a transverse rotation relative to the imagined position of the observer, rather than to the physical environment.

Somewhat surprisingly, the pattern of errors found in this experiment continued to resemble those of the first three experiments. There was no overall difference in the number of errors, but errors increased at 270° in the array task to a greater degree than in the viewer task. Although participants performed the viewer and array tasks equally as slowly, errors remained higher for the array task at 270°. Because errors have been generally low in all of our tasks (in the present paper as well as in the previous work of Wraga et al., 2000) we place more emphasis on the response latency measure as indicating the mechanisms of spatial updating. However, it should be noted that the results of Experiment 4 do show that a slight advantage remains for the viewer task as revealed through error rates.

7. General discussion

The present studies examined whether an updating advantage during imagined viewer rotation would continue to exist if the viewer rotation did not obey gravity. Several previous experiments had shown superior performance in updating the positions of objects, or parts of objects, after imagined self-rotation versus object rotation. Wraga et al. (2000) attributed this advantage to a difference in the way reference frames are transformed. They proposed that the representation of the egocentric reference frame may be transformed more cohesively than an object-relative reference frame. Carpenter and Proffitt (in press) found that this advantage held true only for rotations performed in the horizontal plane, but not for sagittal or coronal rotations. Our current studies investigated whether the egocentric rotation advantage in the transverse plane was a result of physically possible movement obeying gravity or specific to certain geometrical relations between the observer and objects. We found a viewer advantage in all cases in which a real or imagined orthogonal relationship between the viewer and objects was preserved allowing for a rotation around the viewer's principal axis, regardless of the physical possibility of movement.

Experiment 1 allowed a normal orthogonal observer–array relationship, but rotated the configuration 90° so that the observer was lying supine and the array was viewed on the wall. Observers imagined rotating around the array on the wall, or imagined the array rotating itself. Even though participants were asked to perform an imagined self-movement that could not be physically performed, updating was faster and more accurate in the viewer task compared to the array task.

Experiments 2 and 3 went further to examine cases in which the required imagined orthogonal observer–array position conflicted with the participants' physical postures. Experiment 2 asked observers to physically lie supine, but to imagine standing and rotating around an array on the ground, whereas Experiment 3 asked them to physically stand, but to imagine lying down and rotating around the array on the wall. Both of the experiments continued to find an updating advantage after imagined self-movement compared to the corresponding array rotation task.

Finally, Experiment 4 examined participants' performance on an updating task involving rotation in the coronal plane. Whereas participants physically stood in a position identical to that of Experiment 3, they did not imagine an orthogonal relation to the array and a transverse rotation. Under the circumstances of an imagined coronal rotation, performance on viewer and array tasks became indistinguishable in terms of RT. These results replicated Carpenter and Proffitt (in press) using the materials and design of the present experiments.

Although we have focused on participants' response latencies as the primary measure of imagined rotation and updating, the accuracy measures are also important to consider. Overall, our findings indicate that viewer rotation is easier than array rotation when the rotation is performed around one's principal axis, regardless of gravity. However, two accuracy findings suggest that our results may not be completely clear-cut. First, we continued to find an error difference in Experiment 4, in which the viewer task was performed more accurately than the array task at 270°, suggesting that the tasks were not completely equal. Second, Experiments 2 and 3, in which participants faced a conflicting real and imagined position, indicated somewhat higher attrition rates of participants than the other experiments. In all of the experiments, participants were removed from the study if they did not follow directions or if they scored below 50% correct. Experiments 2 and 3 showed superior viewer compared to array performance, but the higher attrition rates compared to Experiments 1 and 4 suggest that rotations that involved a conflicting real and imagined position may have been more difficult than those involving no conflict. Alternatively, the higher attrition rates could have been randomly caused by individual differences in participants. Our previous studies have found varied attrition rates across experimental conditions (see Wraga et al., 2000). Future research could examine this issue further.

The present experiments introduced imagined rotations of the self that were described as "physically impossible". The word "impossible" here refers to transformations that could not be performed in the experience of an ordinary person. For example, people do not perform transverse rotations orthogonal to the ground plane (Experiments 1 and 3) or coronal rotations in the air (Experiment 4). Truly, these rotations can be physically performed in extraordinary circumstances as seen by the abilities of gymnasts. However, there is a distinction between the rare case of a gymnast performing a transient gravity-defying flip and the more common sustained task of imagining transformations and updating positions of objects in the environment.

Together, these four experiments help to answer the question of how closely imagined transformations follow physical properties of the world. Although correlations between physical and imagined rotations have been found with both cognitive (Shepard & Cooper, 1982; Wexler et al., 1998; Wohlschlager & Wohlschlager, 1998) and neuroimaging methods (Cohen et al., 1996; Parsons et al., 1995), principles of kinematic geometry have also been shown to define the ease of object rotations, stressing the importance of the alignment of axes of the viewer, object, and rotation (Pani, 1993; Parsons, 1995). Our present studies examined the importance of the relationship between viewer, rotation, and object axes uniquely by using a task that involved full-body rotations in the context of a spatial updating task. Parsons (1987b) found that the abilities of observers to perform rotations of line-drawings of bodies was dependent on the axis of rotation. Similar to Parsons, we found that rotations about one's vertical axis (the horizontal or transverse plane) were easier to perform than rotations in the picture plane (coronal) relative to array rotations. In addition, we found that one critical factor involved in the updating advantage for viewer versus array rotation was the representation of an orthogonal relationship between the viewer and the array of objects. As long as the observer performed an imagined rotation in the transverse plane relative to the *imagined self-position*, the advantage remained. Participants could easily perform imagined rotations that they could not physically perform when they were instructed to imagine a familiar relationship between themselves and objects in the environment.

These studies further clarify the human ability to transform a representation of the egocentric frame of reference. Wraga et al. (2000) showed that the human cognitive system was more efficient at transforming the egocentric frame than an object-relative reference frame. The present studies indicate that this efficient ability remains not only for imagined rotations that defy gravity defined by the physical environment, but also for rotations that involve a conflict between the physical and imagined postures of the viewer. Observers were able to disregard their physical positions in order to imagine the instructed viewer–array relationship. The ease of this imagined task may have been a result of the familiar orthogonal representation that was required. Future work could assess the effects of conflicting physical and imagined postures for less ecologically valid body–environment relations.

The ability to imagine physically impossible movements seen in the present studies has implications for understanding of motor imagery. Several studies indicate that representations of actions follow biomechanical constraints. In a mental rotation task, Parsons (1994) showed that the time to determine whether a pictorial stimulus was a right or left hand was similar to the time needed to actually move the hand at a given orientation. Furthermore, Parsons (1987a) found that the times for mentally rotating a hand or foot into awkward postures corresponded with times for movement along biomechanically plausible trajectories. In a recent study, de'Sperati and Stucchi (1997) asked right-handed participants to view a screwdriver rotating around its central axis, to imagine their right hand grasping the tool, and to determine whether it was screwing or unscrewing. They found that stimulus orientations that were awkward for a right-handed grasp led to longer RTs. However, when asked to imagine grasping with the left hand, overall RTs increased and the differences between awkward and comfortable orientations disappeared. The authors suggested that people used a motor imagery strategy that was grounded in biomechanical constraints. In addition, in a task involving the perception of apparent motion of limbs, Shiffrar and Freyd (1990) found that people tend to perceive trajectories that do not violate laws of biological motion.

Although the examples described above suggest that mental representations of actions follow physical constraints, our studies indicate that imagined body rotations are constrained by experience with geometric relations between the self and objects in the world, rather than the physical constraints of gravity. This apparent difference suggests that there may be a distinction between imagined *body-part* and *whole-body* rotation. Buxbaum and Coslett (2000) have made a distinction between "intrinsic" spatial coding, specifying the dynamic positions of body parts with respect to each other (Vindras & Viviani, 1998), and "extrinsic" egocentric encoding of object location relative to the self. It may be that body-part decision tasks are constrained by the physics of body movement. It may also be that experience with movement of one's own body parts led to the advantage seen in these studies (e.g. Parsons, 1987a, 1994) for physically possible movements. These two alternatives cannot be decoupled easily in intrinsic tasks because of the nature of encoding body parts relative to each other. Experience with movement is confounded with biomechanical constraints. In the present studies, using a task in which external objects were encoded relative to the self, we were able to decouple the constraints of gravity from the constraints of experience of rotation around one's principal axis.[8]

It is not our intent to make general claims about the influence of physics on rotations. Certainly, an advantage for rotations around any object's *or* viewer's principal axis follows the physics of *rotations* although it might not always follow the physical constraints of *gravity*. Our first three experiments showed that gravitational constraints alone did not predict the ease of imagined self-rotations. However, the experiments together suggest that an advantage for self-rotation relies on representing body–environment relations as they are in a physical world constrained by gravity. Although imagined viewer rotations can be performed easily in situations that defy gravity, and furthermore contradict the physical position of the viewer, they still follow geometrical constraints that are ultimately guided by our experience with a gravitational field. We interact with objects and transform our frame of reference around our vertical axis because of gravity. We have little opportunity to perform the coronal transformation of Experiment 4. The present studies show that as long as a representation of the viewer–array relationship allows for rotation around the principal axis of the viewer, this imagined rotation can be of a physically impossible movement.

8. Conclusion

In summary, an advantage for updating during viewer versus object rotation is a robust finding in many circumstances. The work of Wraga et al. (2000) illustrated that this effect generalizes to a variety of different displays. Several other studies have found similar advantages for updating displays during real movement (Simons & Wang, 1998; Wraga, Creem, & Proffitt, 2001). We found that the viewer advantage, seen in transverse rotations, was more attributable to a consistent representation of an orthogonal relationship between viewer and objects than to physically possible movement along the ground plane. Although imagined self-movement does not rely on internalized principles of gravity, the efficiency of rotations relative to

[8] In our tasks, the rotational axis relative to the viewer was confounded with the imagined relationship of the viewer and the array. Future research could separate these variables to further generalize our results.

the body's vertical axis may result from our everyday experience with transverse rotations in the world.

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