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Thinking Outside the Body: An Advantage for Spatial Updating During Imagined Versus Physical Self-Rotation

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Three studies examined effects of different response measures on spatial updating during self-rotation. In Experiment 1, participants located objects in an array with a pointer after physical self-rotation, imagined self-rotation, and a rotation condition in which they ignored superfluous sensorimotor signals. In line with previous research, updating performance was found to be superior in the physical self-rotation condition compared with the other 2. In Experiment 2, participants performed in identical movement conditions but located objects by verbal labeling rather than pointing. Within the verbal modality, an advantage for updating during imagined self-rotation was found. In Experiment 3, participants performed physical and imagined self-rotations only and used a pointing response offset from their physical reference frames. Performance was again superior during imagined self-rotations. The results suggest that it is not language processing per se that improves updating performance but rather a general reduction of the conflict between physical and projected egocentric reference frames.

To keep track of an observer's location during self-movement, the human cognitive system must continuously update spatial information with respect to the environment and the body. The former case involves the environmental reference frame, which encodes spatial information with respect to the cardinal directions; the latter involves the egocentric reference frame, which encodes an object's position and orientation with respect to the coordinate system of the body. Researchers have proposed that spatial updating during self-movement is accomplished through continual alignment of the egocentric reference frame with the observer's current heading (e.g., Farrell & Robertson, 1998; Klatzky, Loomis, Beall, Chance, & Golledge, 1998). The precise mechanism underlying this alignment process is unclear, but it is thought that sensorimotor information such as vestibular and proprioceptive signals available during physical self-movement play a crucial role. Indeed, when these signals are absent, such as when an observer merely imagines rotating to a new viewpoint rather than physically rotating to it, spatial updating becomes relatively slow and cognitively effortful (e.g., Easton & Sholl, 1995; Farrell & Robertson, 1998; Klatzky et al., 1998; Presson & Montello, 1994; Rieser, 1989). However, such findings do not represent all imagined-self-rotation performance. A growing number of studies have shown spatial updating during imagined self-rotation to be relatively quick and effortless (e.g., Wraga, Creem, & Proffitt, 2000; Wraga, Creem-Regehr, & Proffitt, 2002) and even to defy physical laws under some circumstances (Creem, Wraga, & Proffitt, 2001; Wraga, 1998). What might account for such inconsistencies in spatial updating during imagined self-rotation? Although many metholological differences exist across studies, one trend is clear. In all studies in which updating performance was relatively poor, participants used a pointing response (e.g., Easton & Sholl, 1995; Farrell & Robertson, 1998; Klatzky et al., 1998; Presson & Montello, 1994; Rieser, 1989). In all studies in which performance was relatively good, participants used a verbal response (e.g., Creem, Wraga, & Proffitt, 2001; Wraga, 1998; Wraga et al., 2000; Wraga, Creem-Regehr, & Proffitt, 2002). Recent research suggests that pointing- and verbal-response measures may affect spatial-updating performance in different ways during imagined and physical self-movement (de Vega & Rodrigo, 2001). The present studies were designed to investigate this issue further.

It is difficult to resist the logic that sensorimotor information accounts for enhanced updating performance during self-movement. This idea is backed by many empirical studies (e.g., Farrell & Robertson, 1998; Klatzky et al., 1998; Presson & Montello, 1994; Rieser, 1989; Rieser, Garing, & Young, 1994; Rieser, Guth, & Hill, 1986). For example, Rieser (1989) found that blindfolded participants' ability to point to an object from a novel perspective was more accurate when they were physically rotated to the new perspective rather than when they simply imagined rotating to it. Pointing response times (RTs) in the imagined condition also increased with angular disparity, whereas RTs during physical movement were independent of the angular distance traversed. These findings suggest that participants in the imagined condition had relied on a cognitively effortful process such as mental rotation to realign the egocentric frame of the physical body with the projected egocentric frame corresponding to the new viewpoint. In contrast, updating during physical movement appeared to be "automatic," in that reference-frame alignment occurred in tandem with movement and required little or no additional cognitive effort (e.g., Farrell & Robertson, 1998; Presson, 1987). Rieser and others have posited that the continuous align-

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ment of an observer's egocentric reference frame with his or her current heading during physical movement is due to contributions of concurrent sensorimotor signals (Farrell & Robertson, 1998; Rieser, 1989). The automatic-updating hypothesis provides a default mechanism in which observers are always primarily oriented to their physical heading (e.g., Presson, 1987).

Farrell and Robertson (1998) provided a further characterization of the automaticity effect. They examined spatial updating and self-rotation within several contexts. In their updating condition, blindfolded participants used a pointer to locate objects in an array after rotating to a new position in the array; in the imagination condition, they updated object locations after imagining rotating to a new position in the array. In line with Rieser (1989), performance was expected to be superior in the updating condition compared with the imagined condition. The critical task was the ignoring condition, in which participants physically moved themselves to a new position in the array but then located objects as if from their initial starting point. Farrell and Robertson reasoned that if sensorimotor information available during physical movement rendered updating automatic in the sense that it was not under participants' volitional control, then performance in the ignoring condition would be akin to an imagination-only condition. In other words, participants in the ignoring condition would be obliged to mentally rotate the egocentric reference frame from their new view back to the initial starting point. The results bore out the authors' predictions. Participants' pointing responses were slower and less accurate in the imagination and ignoring conditions compared with a control. Moreover, response rates in both conditions increased as a function of rotation magnitude. In contrast, no difference in performance was found between updating and control conditions, and updating RTs showed only a weak rotation magnitude effect.

These findings notwithstanding, it is important to note that additional sources of sensorimotor information do not always result in enhanced spatial updating. For example, several recent studies have shown that efference copies of motor commands, available during active movement, do not improve updating performance compared with updating during passive movement, when such information is absent (e.g., Wang & Simons, 1999; Wraga, Creem-Regehr, & Proffitt, 2002; Yardley & Higgins, 1998). Wang and Simons (1999) found that participants who were passively rotated by the experimenter to a new view about an unseen array were as accurate at updating object locations as those who had actively rotated themselves. Yardley and Higgins (1998) found a similar result for a task in which participants reported which number they would face after passive rotation or active rotation of their bodies about the center of a large clock. Yardley and Higgins found performance to be equivalent across both types of movement for rotations in one direction. An updating advantage for active movement emerged only when the active–passive movement sequence consisted of a continuous series of two or three counterdirectional rotations.

There is also some evidence that updating during imagined self-rotation can be automatic. Much of this work has directly compared updating during imagined self-rotations about an array with imagined rotations of the array itself (e.g., Amorim & Stucchi, 1997; Huttenlocher & Presson, 1979; Presson, 1982; Wraga et al., 2000; Wraga, Creem-Regehr, & Proffitt, 2002). In these experiments, participants typically perform one or the other imagined rotation and then update the location of a given object in an array by verbally reporting its location (e.g., "right" or "left"). The results have consistently shown that updating performance is faster and more accurate during imagined rotations of the observer than of the array. This advantage persists regardless of whether the observer is immersed within the array or is separate from it (Wraga et al., 2000) or whether the array is replaced by a single object depicting a novel or highly overlearned configuration (Amorim & Stucchi, 1997; Huttenlocher & Presson, 1979; Wraga et al., 2000). Some studies have found a flat rotation function for imagined self-rotations beyond 0° that is consistent with automatic updating (Wraga et al., 2000; Wraga, Creem-Regehr, & Proffitt, 2002).

Moreover, some studies have shown that updating during imagined self-rotation may transcend physical laws (Creem, Wraga, & Proffitt, 2001; Wraga, 1998). For example, Creem, Wraga, and Proffitt (2001) found that updating performance during imagined self-rotation about an array was not affected when the array appeared in a physically impossible position (e.g., parallel to the wall). Nor was performance affected when participants' bodies were in a position prohibitive to physical self-movement (e.g., lying supine on the ground). The critical factor to maintaining relatively fast and accurate updating performance during imagined self-rotation was preservation of the orthogonal relationship between the array and the projected egocentric reference frame. In instances where this relationship was violated, such as when the plane of rotation was parallel to the participant's egocentric frame (e.g., an imagined cartwheel movement around four objects), updating performance dropped to that of imagined array rotations. These results collectively suggest that updating during imagined self-rotation may be more flexible than previously assumed. Wraga and colleagues have argued that the flexibility may be due to the ease in which the human cognitive system transforms the egocentric reference frame, independent of sensorimotor signals (Wraga et al., 2000).

How can one reconcile the seemingly disparate spatial-updating performance found in the studies described previously? Recent research indicates that the use of different response measures may hold the answer. In a series of studies designed to explore the relationship between language and spatial representation, de Vega and Rodrigo (2001) found that pointing- and verbal-response measures may affect spatial updating differently. In their first experiment, participants formulated a spatial configuration from a verbal description of a scene. They then either physically rotated themselves to a new position in the configuration or merely imagined rotating to a new position and then updated object locations by using computer arrow keys. Similar to Farrell and Robertson (1998) and Rieser (1989), participants were faster and more accurate at updating during physical rotation than during imagined rotation. In the second experiment, participants performed the same task in identical movement conditions but used verbal labels to update object locations. Within the verbal modality, de Vega and Rodrigo found similar updating performance across physical and imagined rotations. That is, the classic updating decrement found during imagined self-rotation with a pointing response disappeared when participants responded with verbal labels instead. de Vega and Rodrigo concluded that the differential pointing and verbal-labeling results indicated the presence of two separate updating mechanisms, associated with spatial and language processing, respectively. According to de Vega and Rodrigo's view, pointing is a type of first-order updating, which occurs during physical movement and relies strongly on sensorimotor information. In contrast, verbal labeling elicits a type of second-order updating, which is purely representational and can be independent of the physical body.

Overview of the Experiments

We concur with de Vega and Rodrigo's (2001) characterization of separate updating mechanisms for pointing versus verbal responses; however, we suspected that the distinction underlying differences in performance occurs at a more general level than that of language versus spatial processing. In particular, we hypothesized that observers have difficulties updating object locations during imagined self-rotation when required to use a pointing response because traditional pointing response measures unnaturally anchor observers to their physical body. This anchoring effect tends to emphasize the spatial conflict between the egocentric reference frame of the physical body and the projected frame of the new viewpoint. The conflict thus interferes with observers' ability to move mentally to the location of the projected egocentric frame during imagined self-rotation. On the other hand, response measures such as verbal labels reduce the spatial conflict between the physical and projected egocentric frames, most likely because verbal responses are less dependent on the framework of the physical body. Thus, verbal responses allow observers to move mentally to the projected egocentric reference frame more readily. According to this view, spatial-updating performance is mediated by the presence or absence of reference-frame conflicts at the storage and/or output level, rather than on verbal versus spatial encoding per se.

In the present studies we tested the reference-frame-conflict hypothesis by varying the response measures used in a novel spatial-updating task, which participants performed under conditions of physical, imagined, and ignored self-rotation. The updating task was based on Farrell and Robertson's (1998) paradigm, with several notable changes. One potential problem of their design was that the duration of the RT event differed across experimental conditions. In their updating (physical-movement) condition, the RT event began after the participant had completed rotating: It included only the time to locate the object. However, in their imagined and ignoring conditions, the RT event included time to rotate and time to locate a given object. Given that one indication of updating automaticity is a flat RT rotation function, it is possible that inclusion of time-to-rotate in the imagined and ignoring RT events might have artificially inflated RTs in those conditions with increasing rotation magnitude, compared with the updating condition. Thus, automaticity effects in those conditions may have been concealed. To control for this possibility, we divided the entire spatial-updating event into rotation and location components, each of which was separately timed (following Wraga, Creem-Regehr, & Proffitt, 2002). Participants first were given the location of a target to rotate to within an array; once they had arrived at the new view, they then located another object in the array from that location. This technique rendered all movement conditions equivalent with respect to the critical location component of the task. It also eliminated the need for a control condition: Performance in the location component could be directly compared across movement conditions.

Other differences in our paradigm involved the makeup of the arrays and the range of trials tested. Farrell and Robertson's (1998) array contained seven objects separated at increments of 51.5°, and their trials included only a subset of possible rotation–location pairings. In the present experiment we used a six-object array with 60° increments because this arrangement was more adaptable to changes in response measures. We also paired all possible rotations of the array with all possible object locations (with the exception of 0° location) in order to test a broader range of trials.

We conducted three experiments on the reference-frame-conflict hypothesis using the novel updating task. Experiment 1 was designed to replicate Farrell and Robertson's (1998) finding of enhanced updating performance during physical self-rotation. We compared participants' updating performance during physical self-rotation, imagined self-rotation, and a rotation condition in which participants had to ignore superfluous sensorimotor signals. In all movement conditions, judgments were made using a pointing response. In line with Farrell and Robertson, we found performance in the physical-self-rotation task to be superior to that of the other conditions. In Experiment 2 we introduced a response measure designed to reduce the conflict between physical and projected egocentric reference frames. We used the same updating task and movement conditions as in Experiment 1, but participants responded by verbally locating objects rather than pointing to them. Similar to de Vega and Rodrigo (2001), we found an advantage for updating during imagined self-rotation using the verbal context. The third experiment demonstrated that verbal encoding was not the critical factor to improved updating. We tested performance during physical and imagined self-rotation only, using a pointing response that was designed to reduce participants' reliance on the coordinate systems of their bodies. Participants responded by pressing keys on a computer keyboard that contained spatial indicators offset from the egocentric frame of the physical body. Performance was again found to be superior in the imagined-self-rotation condition, indicating that it is not verbal encoding per se that improves performance, but rather a more general reduction of reference-frame conflicts.

Experiment 1

Experiment 1 was designed to replicate Farrell and Robertson's (1998) finding of superior updating performance during physical self-rotation, using a novel spatial-updating task. In the present experiment participants sat in a rotating chair in the center of a six-object array and used a pointer to locate the positions of unseen objects from novel perspectives. Participants' movement to the novel perspectives was dictated by the supposed movements of a cartoon character, Gumby. For each trial, participants heard a target location where Gumby had "traveled" to in the array (e.g., "Gumby is in blue"). After turning to face the target location (hereafter referred to as *the Gumby color*), participants then heard a second color and were required to locate it from their perspective facing the Gumby color. We tested three types of movement to the Gumby color. In the aligned condition, the experimenter physically rotated participants to the Gumby color; thus, participants' projected egocentric frame was aligned with the physical egocentric frame for the location component of the task (see Figure 1A). The aligned condition is similar to Farrell and Robertson's updating condition, except that participants' movement was passive

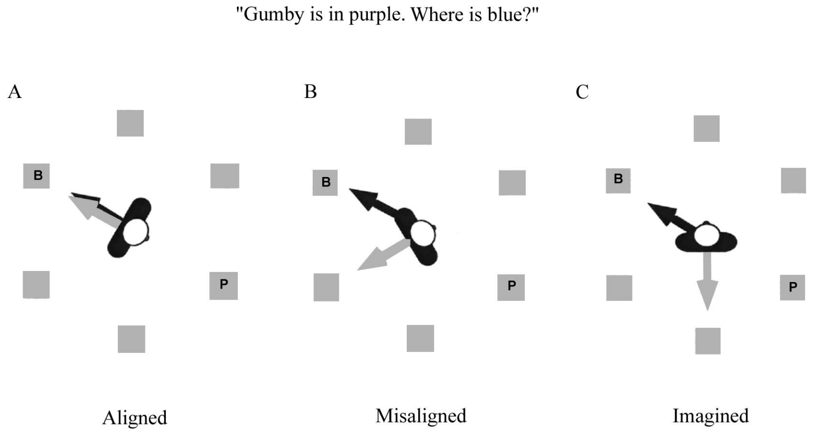

Figure 1. Overhead view of the array configuration used in Experiments 1–3, illustrating the relationship between physical (dark arrow) and projected (light arrow) egocentric reference frames in the three movement conditions during the location component of a hypothetical trial. A: In the aligned condition, the participant is turned to the Gumby color (P); his or her physical and projected reference frames are aligned with respect to B, the color to be located. B: In the misaligned condition, the participant is turned to a color other than P but updates B as if facing P; his or her physical and projected egocentric frames are misaligned. C: In the imagined condition, the participant imagines turning to P; his or her physical and projected reference frames are misaligned.

rather than active. We did not expect this to be problematic, as previous research has found no difference in updating performance for passive self-rotation and active self-rotation (e.g., Wang & Simons, 1999; Wraga, Creem-Regehr, & Proffitt, 2002). In the misaligned condition, participants were instructed to imagine rotating themselves to the Gumby color while the experimenter rotated them to another color; participants then located objects with respect to the Gumby color. Thus, a participant's projected egocentric frame was misaligned from that of his or her physical body for the location component of the task (see Figure 1B). The misaligned condition is similar to Farrell and Robertson's ignoring condition, in that participants were required to ignore sensorimotor signals received during movement to an incorrect location. In the imagined condition, participants mentally rotated themselves to the Gumby color; thus, their projected egocentric frames were again misaligned from those of their physical bodies during the location component (see Figure 1C). In all conditions, the location component of the task (i.e., location of the second color) was most critical to the analysis. In line with Farrell and Robertson, we predicted that updating performance would be superior in the aligned condition compared with the imagined and misaligned conditions.

Method

Participants

Nineteen Harvard University undergraduate students (10 women and 9 men) volunteered to participate in the experiment. All were right-handed. They were compensated $10 for their time. None of the participants knew of the hypothesis being tested.

Materials

Six wooden stands, 95 cm in height, were positioned to form a 183-cm diameter hexagonal array. Each stand was comprised of two 15 × 15 × 2 cm (Length × Width × Height) wooden squares, attached together with a 91-cm long, 2-cm diameter wooden dowel. Onto the center of each stand was placed a 5 × 24 cm piece of colored felt (red, purple, blue, white, gray, and yellow). For the pointer, we affixed a 0.5-cm diameter, 22-cm long black dowel with pointed tip to a 25 cm × 61 cm × 1 cm wooden board, painted white. The center of the dowel was attached to the board with a nail and several washers, which raised it 0.5 cm from the board. We attached a 1.5-cm high wooden peg to the top of the board a few degrees left of the 0° pointer position. This measure ensured that the pointer was aligned with the 0° position and that it could be turned in only a clockwise direction. To record pointing responses during the test trials, we inserted a 24-cm^2 diameter photo-reproduced compass, accurate to minutes of degree, on the board underneath the pointer. We created the experiment using PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993), run on a Macintosh G3 laptop. PsyScope controlled the auditory stimulus presentation and recorded RTs and errors.

Procedure

Participants first learned how to use the pointer. They were seated in a swivel chair centered within the array, which initially did not contain any color squares. The experimenter then placed the pointer (without the compass) onto the arms of the chair so that it was directly in front of the participant. Participants were instructed to turn the pointer using their dominant hand in a clockwise direction only. They were then given as much time as necessary to learn to use the pointer to locate the six array locations. The experimenter then tested them for the array locations. Participants closed their eyes, and the experimenter positioned the compass onto the pointer. The experimenter then tapped on each of the stands of the array, in a random order. Participants were instructed to point to each stand as quickly and as accurately as possible. They received verbal feedback on responses that were displaced off the target by amounts greater than ± 10° (e.g., "The target is actually more to your right or left"). Criteria for learning were met when participants could locate each stand within 5 s at an accuracy of ± 10°. Once participants had learned to use the pointer, the experimenter removed the compass. Participants opened their eyes, and the experimenter placed the colored felt pieces of a given array configuration on the stands. Participants then learned the configuration of colors. They were given as much time as necessary to memorize the color locations and to practice locating them with the pointer (most participants took about 5 min). After memorization, participants closed their eyes and the experimenter placed the compass onto the pointer. The experimenter then tested for the color locations by calling them out in a random order. The same criteria for learning to use the pointer were used in the array-configuration training. After training, the experimenter removed the compass for the rotation and location components of the task. The instructions were altered depending on the movement condition as follows.

Rotation component. For each trial, participants first heard a Gumby color (e.g., “Gumby is in red”). In the aligned condition, participants were asked to imagine turning clockwise in place on the chair to face the Gumby color and were informed that the experimenter would also physically turn them clockwise to the Gumby color. Immediately after the Gumby color was heard, the experimenter turned the participant in his or her chair to the correct location in the array. The experimenter said “stop” to indicate that participants had arrived at the Gumby color. In the misaligned condition, participants were asked to imagine turning clockwise in place on the chair to face the Gumby color and were informed that the experimenter would be turning them clockwise to a color other than the Gumby color. Once the Gumby color was heard, the experimenter turned the participant to a previously determined color, which was located either one or two colors before the Gumby color or one or two colors after the Gumby color (order of occurrence was randomized). The experimenter said “stop” to indicate that participants had arrived at the non-Gumby location. In the imagined condition, participants were asked to imagine turning clockwise in place on the chair to face the Gumby color. They were instructed to say “stop” aloud when they had arrived at the color in their imagination. Response latency (measured from the end of the presentation of the Gumby color to the onset of a “stop” response) was recorded using the computer’s timer, which the experimenter controlled. She pressed the computer mouse to initiate and end the timed event.

Location component. Once participants had “arrived” at the Gumby color in each movement condition, they heard a second color (e.g., “blue”). Their task was to locate this color from their new perspective by pointing to it as quickly and accurately as possible. When they were confident in the position of the pointer, participants said “okay.” The computer controlled presentation of the second color: It was delivered 100 ms after the end of the rotation event. Response latency for the location component was measured from the end of the presentation of the second color to the onset of an “okay” response, which the experimenter controlled by pressing the computer mouse.

Once participants understood the instructions, they put on a blindfold. They performed a practice trial that acclimated them to the auditory cues of the computer; it also ensured that they understood the task. They then performed the test trials. For each trial, the experimenter recorded RTs for turning and location components of the task as described previously. The experimenter recorded the magnitude of pointing responses separately on a sheet of paper and later entered these values into the computer. At the end of each condition, participants were allowed to remove the blindfold and take a short break. The experimenter then created the next array configuration and began training and instructions for the next condition.

Design

Participants performed in all movement conditions (aligned, imagined, and misaligned). We created three array configurations based on the following criteria: Across arrays, no color appeared at the same location, and no two of the same colors were adjacent to each other. Each of the six rotations of the array (0°, 60°, 120°, 180°, 240°, 300°) was matched with five locations (60°, 120°, 180°, 240°, 300°; with 0° excluded) for a total of 30 trials per condition. The Gumby target “appeared” randomly at the six rotation positions, and the location colors were also randomized. Orders of condition and array configurations were counterbalanced across participants.

Analyses

We recorded pointing responses and RTs for each condition. For analysis, we computed mean unsigned error by taking the absolute value of the difference between participant’s pointing response for a given trial and the canonical value for that trial. For the RT data, RTs greater than 2.5 times the condition means were trimmed; they were replaced with the condition means ($<2\%$ of the data). We performed a 6 (order of condition) × 3 (movement condition) × 6 (rotation magnitude) mixed design analysis of variance (ANOVA) on the mean unsigned error and RTs.

Results

Rotation RT

Table 1 shows mean RTs and standard errors for rotation in the aligned, misaligned, and imagined conditions. Because the method of rotation differed among movement conditions (e.g., passive physical vs. active imagined rotation), we did not perform parametric tests on these data.

Location Accuracy

Figure 2 shows mean unsigned error and standard errors for each movement condition as a function of rotation magnitude. The principal finding was that updating performance was more accurate in the aligned condition ($M = 13.66°$) than in the misaligned ($M = 7.27°$) and imagined ($M = 22.12°$) conditions. The ANOVA performed on mean scores yielded a main effect of condition, $F(2, 26) = 6.05$, $p < .007$. Post hoc analyses of this effect revealed

Table 1
Rotation Latencies and Standard Errors (SEs) in Experiment 1

	Degree of rotation											
	0		60		120		180		240		300	
Condition	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Aligned	1.205	± .054	3.426	± .117	4.811	± .136	6.548	± .187	8.515	± .254	9.761	± .314
Misaligned	3.551	± .171	5.174	± .260	5.136	± .248	5.329	± .313	6.675	± .449	6.346	± .379
Imagined	1.529	± .174	2.269	± .186	2.074	± .197	1.871	± .168	2.401	± .268	2.202	± .211

Note. All values are in seconds. The experimenter controlled response times (RTs) in the aligned and misaligned conditions; the participant controlled RTs in the imagined condition.

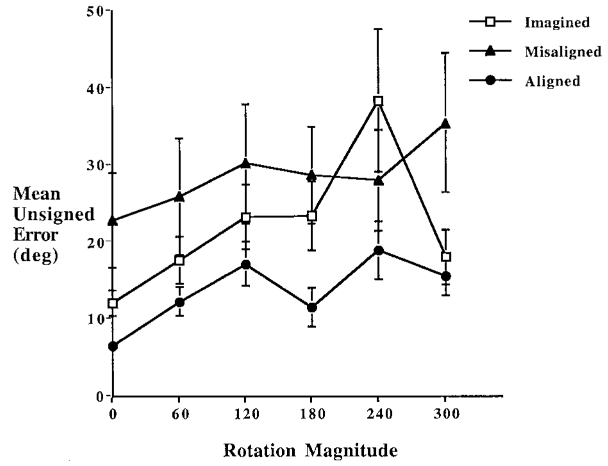

Figure 2. Mean unsigned pointing error and standard errors of Experiment 1, as a function of rotation magnitude. deg = degrees.

significant differences between aligned and misaligned conditions, $t(18) = -2.96$, $p < .008$, and between aligned and imagined conditions, $t(18) = -2.84$, $p < .011$, but no difference between misaligned and imagined conditions, $p > .05$. We also found a main effect of rotation magnitude, $F(5, 65) = 4.26$, $p < .002$, and a significant Condition × Rotation Magnitude interaction, $F(10, 130) = 1.98$, $p < .040$. Linear contrasts performed on the separate degree trials for each condition yielded the following patterns. For the aligned condition, RTs increased from 0° to 60° ($p < .006$) and remained constant between all other comparisons (*p*s > .05). For the misaligned condition, RTs remained constant across all comparisons (*p*s > .05). For the imagined condition, RTs increased from 0° to 60° ($p < .021$); remained constant between 60° and 120°, 120° and 180°, and 180° and 240° (*p*s > .05); and decreased from 240° to 300° ($p < .013$). The Order × Task × Rotation Magnitude interaction was also significant, $F(50, 130) = 1.50$, $p < .037$.

Location RT

Figure 3 shows mean response times and standard errors for each movement condition as a function of rotation magnitude. Consistent with the error patterns, updating performance was faster in the aligned condition ($M = 3.96$ s) than in the misaligned ($M = 5.10$ s) and imagined ($M = 4.72$ s) conditions. The ANOVA performed on mean scores yielded a main effect of condition, $F(2, 26) = 19.99$, $p < .0001$. Post hoc analyses of this effect yielded significant differences between aligned and misaligned conditions, $t(18) = -3.35$, $p = .004$, and between aligned and imagined conditions, $t(18) = -3.33$, $p = .004$, but no difference between the misaligned and imagined conditions ($p > .05$). We also found a main effect of rotation magnitude, $F(5, 65) = 6.72$, $p < .0001$, and a significant Condition × Rotation Magnitude interaction, $F(10, 130) = 5.65$, $p < .0001$. Linear contrasts performed on the separate degree trials for each condition yielded the following patterns. For the aligned condition, RTs increased from 0° to 60° ($p < .001$), increased from 60° to 120° ($p < .021$), decreased from 120° to 180° ($p = .003$), increased from 180° to 240° ($p > .05$), and remained constant between 240° and 300° ($p > .05$). For the misaligned condition, RTs increased from 0° to 60° ($p < .033$), increased from 60° to 120° ($p < .048$), and remained constant across all other comparisons ($p > .05$). For the imagined condition, RTs increased from 0° to 60° ($p < .0001$), remained constant between 60° and 120° and between 120° and 180° (*p*s > .05), increased from 180° to 240° ($p < .05$), and decreased from 240° to 300° ($p < .02$).

Discussion

As predicted, participants were faster and more accurate at locating objects with a pointer when they were physically turned to new perspectives in an array (aligned condition) compared with when they merely imagined turning to them (imagined condition) or when they had to ignore movement to an incorrect perspective (misaligned condition). In contrast, no difference in performance was found between the imagined and misaligned conditions. These results are in agreement with those of Farrell and Robertson (1998) and thus lend credence to the novel spatial-updating task that we used. However, some of Farrell and Robertson's findings did not replicate. For one, they found that pointing errors increased with larger rotation magnitudes in their updating (physical-movement) condition. Although errors in the present experiment showed an effect of degree over all conditions, the function for aligned errors was relatively flat. This is most likely because participants in the present experiment were given the location of their new heading (i.e., the Gumby color) at the onset of each trial, whereas participants in Farrell and Robertson's study were not. As those authors have previously noted, participants might use advance information of heading to correct any errors that may have accumulated during movement. Other updating experiments in which participants were given heading information at the onset of self-rotation have yielded a flat error function similar to that of the present study (Rieser, 1989).

We also failed to replicate Farrell and Robertson's (1998) automaticity effects. In their study, a clear dissocation was found between RT patterns for physical movement and those of imagined movement and ignored movement, with the former being less

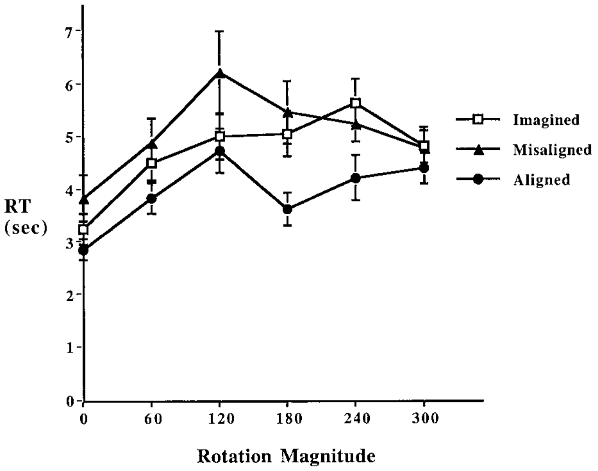

Figure 3. Mean response times (RTs) and standard errors of Experiment 1, as a function of rotation magnitude. sec = seconds.

influenced by rotation magnitude than the latter two. In the present study, RTs generally increased to 120° and peaked at 120° and 240°. Moreover, we found this pattern most strongly in the aligned condition and to lesser degrees in the misaligned and imagined conditions. This finding is striking for two reasons. First, it contradicts the notion that updating during physical movement occurs automatically. Second, it suggests that differences in updating automaticity across movement conditions are not as clear-cut as previously thought.

There are several possible explanations for why Farrell and Robertson's (1998) automaticity effects did not replicate. In their study, they used only a subset of the total possible updating trials, repeated twice for a total of 16 trials. In the present study, we tested 30 trials, none of which were repeats. One possibility is that increased cognitive demands required to process a broader range of new trials in the present study diminished automaticity effects. This interpretation would imply that automatic updating is the result of practice; however, other studies using single-trial presentations have found automaticity effects (Wraga et al., 2000; Wraga, Creem-Regehr, and Proffitt, 2002). A more likely explanation is that the technique we used of separating the spatial-updating event into rotation and location components put all of the movement conditions on more equal footing. This technique thus allowed a more accurate assessment of differences in performance among aligned, misaligned, and imagined conditions.

Although the general RT function we found across movement conditions is not in accord with Farrell and Robertson's (1998) results, there is some precedent for it. Wraga, Creem-Regehr, & Proffitt (2002) also found that pointing RTs in a self-rotation task were greater for rotation magnitudes that were offset from the intrinsic axes of the human body. In the present experiment, RTs generally peaked at magnitudes of 120° and 240°—angles that are oblique to the major axes of the body and whose locations appear behind the observer and thus out of sight. These results are in line with Franklin and Tversky's (1990) spatial-framework model of space conceptualization, which posits that mental representations of space reflect the constraints of the physical body.

Experiment 2

The previous experiment established an advantage for spatial updating during physical self-rotation versus imagined self-rotation. Experiment 2 examined whether the reverse effect could occur. We used the same updating task in identical movement conditions as in Experiment 1, with one important exception: Participants in Experiment 2 indicated object locations verbally rather than by pointing to them. de Vega and Rodrigo (2001) found that merely changing the response measure in a spatial-updating task from pointing to verbal labeling resulted in improved performance during imagined self-rotation. We anticipated a similar result. Similar to Experiment 1, participants updated object locations in an array during aligned-, misaligned-, and imagined-movement conditions. On the basis of the results of de Vega and Rodrigo and on other studies showing excellent updating performance for imagined self-rotations using the verbal modality (e.g., Wraga et al., 2000; Wraga, Creem-Regehr, and Proffitt, 2002), we predicted that updating performance would be superior in the imagined condition compared with aligned and misaligned conditions.

Method

Participants

Nineteen Harvard University undergraduate students (9 women and 10 men) volunteered to participate in the experiment. All were right-handed. They were compensated $10 for their time. None of the participants knew of the hypothesis being tested.

Materials

The materials were identical to Experiment 1, except that no pointer was used.

Procedure

The procedure was identical to Experiment 1, except that participants did not undergo a pointer training session. Before performing the aligned, imagined, and misaligned conditions, participants first learned the locations of the array with respect to six verbal labels (*front, back, right–front, right–back, left–front, left–back*). They were then tested on their memory for the color configurations. Similar to Experiment 1, participants closed their eyes, and the experimenter then tested for the color locations by calling them out in a random order. Participants received verbal feedback on responses that were incorrect. Criteria for learning the array were met when participants could locate all colors of the array correctly within 1 s. Instructions for the rotation and location components of the array were identical to those of Experiment 1, except that in the latter, participants simply responded with the verbal label corresponding to the correct location of the second color. They were instructed to respond as quickly and as accurately as possible for all test trials.

Design

The design was identical to Experiment 1.

Analysis

The analysis was identical to Experiment 1, except that only trimmed RTs and mean errors were included.

Results

Rotation RT

Table 2 shows mean RTs and standard errors for rotation in the aligned-, misaligned-, and imagined-movement conditions. Because rotation was not equivalent across the three movement conditions, parametric tests were not performed on the data.

Location RT

Figure 4 shows mean response times and standard errors for each movement condition as a function of rotation magnitude. The principal finding was that participants were faster at updating in the imagined condition ($M = 2.27$ s) than in the aligned ($M = 2.59$ s) and misaligned ($M = 2.81$ s) conditions. The ANOVA performed on mean scores yielded a main effect of condition $F(2,26) = 4.97$, $p < .015$. Post hoc analyses of this effect yielded significant differences between imagined and aligned conditions, $t(18) = -2.29$, $p = .034$, and imagined and misaligned conditions, $t(18) = -5.86$, $p = .0001$, but no difference between the aligned and misaligned conditions ($p = .178$). We also found a main effect of rotation magnitude, $F(5, 65) = 6.45$, $p < .0001$, and a signif-

Table 2
Rotation Latencies and Standard Errors (SEs) in Experiment 2

	Degree of rotation											
	0		60		120		180		240		300	
Condition	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Aligned	0.951	± .054	3.169	± .120	4.659	± .169	5.778	± .292	6.909	± .404	7.842	± .460
Misaligned	4.032	± .176	5.540	± .218	5.247	± .154	5.336	± .213	6.751	± .298	6.275	± .244
Imagined	1.331	± .097	2.217	± .250	2.343	± .284	2.311	± .294	2.547	± .355	2.295	± .347

Note. All values are in seconds. The experimenter controlled response times (RTs) in the aligned and misaligned conditions; the participant controlled RTs in the imagined condition.

icant Condition × Rotation Magnitude interaction, $F(10, 130) = 3.58$, $p < .0001$. Linear contrasts performed for each degree condition yielded the following patterns. For the aligned condition, RTs remained constant between 0° and 60°, between 60° and 120°, between 120° and 180°, and between 180° and 240° ($ps > .05$); however, RTs decreased from 240° to 300° ($p < .018$). For the misaligned condition, RTs increased from 0° to 60° ($p < .009$) and remained constant for all other comparisons ($ps > .05$). For the imagined condition, RTs increased from 0° to 60° ($p < .041$), increased from 60° to 120° ($p < .043$), and remained constant for all other comparisons ($ps > .05$).

Location Accuracy

Figure 5 shows mean errors and standard errors for each condition as a function of rotation magnitude. Participants' responses were highly accurate in all tasks (aligned: $M = 0.13$ error; misaligned: $M = 0.12$ error; imagined: $M = 0.09$ error). The ANOVA performed on mean error scores produced a main effect of rotation magnitude only, $F(5, 65) = 4.81$, $p < .001$. Linear contrasts revealed that errors increased from 0° to 60° ($p < .031$), remained constant between 60° and 120° ($p > .05$), decreased from 120° to 180° ($p < .0001$), increased from 180° to 240° ($p < .043$), and remained constant between 240° and 300° ($p > .05$).

Discussion

By simply changing the response measure from pointing to verbal labeling, we found spatial updating to be superior during imagined self-rotation, despite the absence of sensorimotor information specifying self-movement in that condition. Participants were faster at locating colors in the imagined condition than in the aligned and misaligned conditions. Nor was there a decrement in accuracy in the imagined condition compared with the aligned and misaligned conditions. These findings surpass those of de Vega and Rodrigo (2001), who found comparable updating performance during imagined and physical self-rotation for a task in which participants used verbal labels to update objects in a spatial configuration. In that study, participants initially constructed the spatial configuration from a verbal description of a scene. The results of the present study demonstrate that updating during imagined self-rotation can be advantageous even in situations in which spatial configurations are encoded from perceptual information.

In addition to the imagined-self-rotation updating advantage, the results of the present study differ from Farrell and Robertson's (1998) in several important ways. Within the verbal modality, we continued to see inconsistent automaticity effects across movement conditions. RTs increased with rotation magnitude in an overall pattern of results similar to that of Experiment 1. RTs

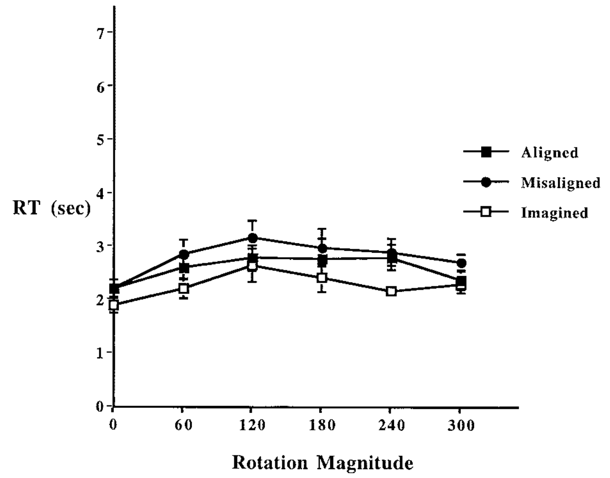

Figure 4. Mean response times (RTs) and standard errors of Experiment 2, as a function of rotation magnitude. sec = seconds.

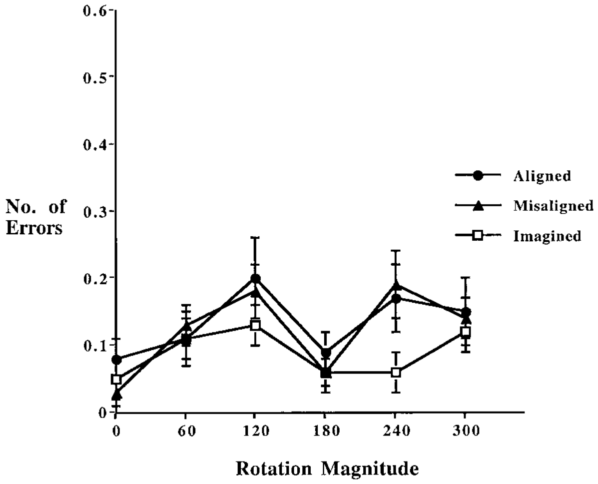

Figure 5. Mean errors (out of a possible 30) and standard errors of Experiment 2, as a function of rotation magnitude.

increased to the oblique axis of 120°, although this time they remained constant to 240°, showing greater automaticity. However, the effect differed somewhat across individual movement conditions in ways that are difficult to interpret. For example, we found a strong automaticity effect in the misaligned condition, where RTs remained constant beyond the 0° rotation. This finding is in contrast to previous assertions that conditions in which sensorimotor information must be ignored require processing akin to mental rotation (Farrell & Robertson, 1998). More evidence against the mental-rotation assertion is found in comparing updating performance between aligned and misaligned conditions. As assessed by both RT and accuracy, performance in these conditions was virtually identical. If updating in the misaligned condition requires mental rotation, one would be forced to argue for similar processing in the aligned condition. A more likely explanation is that performance in these conditions was equally affected by some other cognitive process. In debriefing, most participants claimed that they found movement in both aligned and misaligned conditions to be distracting, in the sense that it focused attention away from where they were trying to move mentally. Thus, the physical movement in these conditions may have created a type of interference effect. This issue warrants further empirical investigation.

Although the imagined-self-rotation updating advantage we found using a verbal-response measure is in line with our reference-frame-conflict hypothesis, it could also be explained using de Vega and Rodrigo's (2001) proposal that spatial updating is subserved by separate spatial- and language-processing mechanisms. A more direct test of the reference-frame-conflict hypothesis would show an imagined-self-rotation updating advantage using a response measure that was not verbal. We attempted this in Experiment 3.

Experiment 3

In Experiment 3 we investigated whether the updating advantage found with imagined self-movement in the previous experiment would hold up in a task that did not require verbal responses. According to our hypothesis, the critical factor to enhanced spatial-updating performance during imagined self-rotation is a response measure that does not anchor the observer to the coordinate system of the physical body. In Experiment 3 participants updated object locations by pressing arrow keys on a computer keyboard. The arrows were positioned in such a way that they were deliberately offset from the reference frame of the participant's body (see Figure 6). This created a counterintuitive arrangement that required some training to master. Nevertheless, we expected that this manipulation would allow participants to better ignore the reference frame of the physical body. As a consequence of the task difficulty, participants performed in the aligned- and imagined-movement conditions only. We predicted that updating performance would be superior in the imagined condition compared with the aligned condition.

Method

Participants

Sixteen Harvard University undergraduate students (8 women and 8 men) volunteered to participate in the experiment. All were right-handed. They were compensated $10 for their time. The data of 2 additional participants were eliminated from analysis for having more than 50% errors (1 in the aligned condition; 1 in the imagined condition). None of the participants knew of the hypothesis being tested.

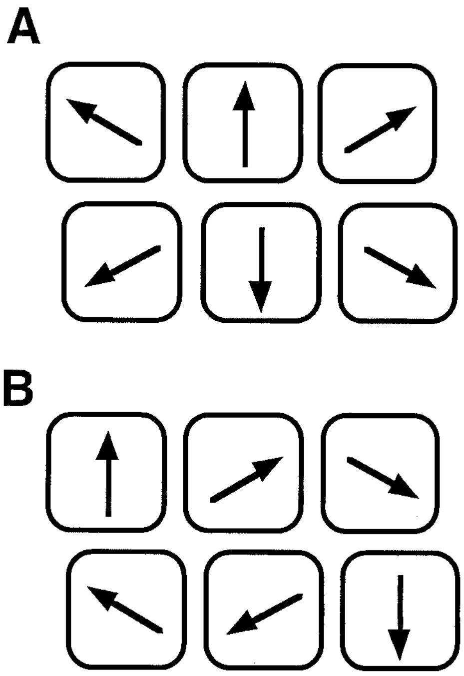

Figure 6. A contrast of pointing response schematics. A: A traditional pointing response, in which the arrows are aligned with the observer's egocentric frame. B: The set of arrows used in Experiment 3, which were offset from the observer's egocentric frame.

Materials

The array was identical to that used in Experiment 1. We affixed a MacIntosh G3 laptop computer to a 35 cm × 61 cm × 1 cm wooden board, painted white. The board fit over the arms of the swivel chair. A 9.5 cm × 27 cm piece of foam core with a 3.5 cm × 6 cm opening was affixed over the computer keyboard in such a way that only the *U, I, O* and *J, K, L* keys were exposed. Onto these keys we placed round yellow stickers (1.3 cm diameter) containing directional arrows varying in orientation from 0° to 300° in 60° increments (see Figure 6B). An additional 2 × 10 cm cutout in the foam core over the spacebar permitted access to that key.

Procedure

The procedure was identical to Experiment 1, except that participants went through a computer-training phase rather than a pointer-training phase. The experimenter placed the computer on the arms of the participant's chair and showed the participant how to rest his or her dominant hand on the keyboard. Participants were told that they would be using the arrow keys to locate objects in the array. They were given time to practice pressing the keys with their eyes open to become acclimated with the directional sequence. They then closed their eyes, and the experimenter ran a practice script on the computer. The script was a random sequence of the directional keys programmed to produce auditory feedback if an incorrect key was pressed. The experimenter followed a paper copy of the same sequence while tapping on the stands. The participants used the keys to "point" to the correct position in the array. They received auditory feedback from the computer for incorrect responses. The criteria for learning were met if participants could locate all positions correctly within 1 s. If participants had not met these criteria by the end of the script, the experimenter ran it again. Participants usually learned the key positions in about 5 min. The experimenter then placed the colors for a given array configuration on the stands, and participants were tested for location of the colors. Participants closed their eyes, and the experimenter ran a script on the computer that presented the colors auditorially, one at a time in a random order. Participants pressed the arrow keys corresponding to the correct color locations. Criteria for learning the array were met when participants could correctly locate all colors consecutively within 1 s. Instructions for the rotation and location components of the task were identical to those of Experiment 1, except that in the location component, participants responded by pressing the key corresponding to the correct location of the second color. They were instructed to respond as quickly and as accurately as possible for all test trials.

Design

Participants performed in both movement conditions (imagined and aligned). Two of the three array configurations from Experiment 1 were used. Order of condition and array were counterbalanced across participants.

Statistical Analysis

We used the same statistical analysis from Experiment 1, except that only trimmed RTs and mean errors were used.

Results

Rotation RT

Table 3 shows mean RTs and standard errors for rotation in the aligned and imagined conditions. Because rotation was not equivalent across the two movement conditions, parametric tests were not performed on the data.

Location RT

Figure 7 shows mean response times and standard errors for both tasks as a function of rotation magnitude. The principal finding was that participants were faster at updating in the imagined condition ($M = 2.40$ s) than they were in the aligned condition ($M = 3.22$ s). The ANOVA performed on mean scores yielded main effects of condition, $F(1, 14) = 10.67$, $p < .006$, and rotation magnitude, $F(5, 70) = 11.22$, $p < .0001$, as well as a significant Condition × Rotation Magnitude interaction, $F(5, 70) = 2.54$, $p < .036$. Linear contrasts performed on the rotation magnitude effect for each condition yielded the following patterns. For the aligned condition, RTs remained constant between 0° and 60°, between 60° and 120°, and between 120° and 180° (ps $> .05$); increased from 180° to 240° ($p < .002$); and decreased from 240° to 300° ($p < .002$). For the imagined condition, RTs remained constant between 0° and 60° ($p > .05$), increased from 60° to 120° ($p < .039$), remained constant between 120° and 180° and between 180° and 240° (ps $> .05$), and decreased from 240° to 300° ($p < .0001$).

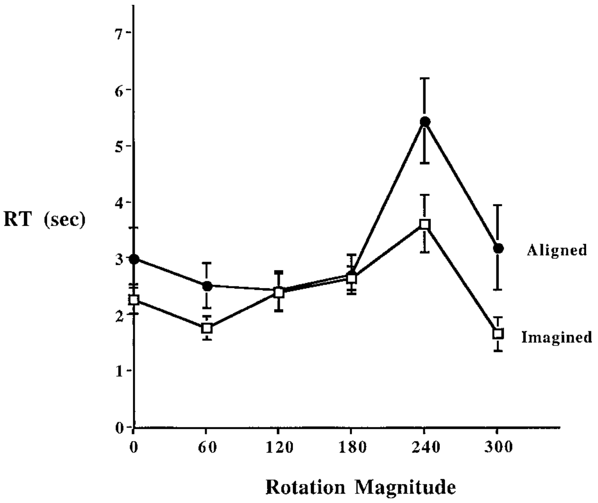

Figure 7. Mean response times (RTs) and standard errors of Experiment 3, as a function of rotation magnitude. sec = seconds.

Location Accuracy

Figure 8 shows mean errors and standard errors for each condition as a function of rotation magnitude. Participants' responses were very accurate in both movement conditions (aligned: $M = 0.22$ err; imagined: $M = 0.30$ err). The ANOVA performed on mean error scores produced a main effect of rotation magnitude only, $F(5, 70) = 9.87$, $p < .0001$. Linear contrasts revealed that errors remained constant between 0° and 60°, 60° and 120°, and 120° and 180° (ps $> .05$); increased from 180° to 240° ($p < .005$); and decreased between 240° and 300° ($p < .0001$).

Discussion

Performance was faster in the imagined condition compared with the aligned condition, and we found no difference in accuracy

Table 3
Rotation Latencies and Standard Errors (SEs) in Experiment 3

	Degree of rotation											
	0		60		120		180		240		300	
Condition	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Aligned	1.675	± .709	3.656	± .214	6.227	± .506	7.459	± .314	10.039	± .534	11.277	± .662
Imagined	1.194	± .135	2.548	± .596	3.109	± .589	3.286	± .727	2.580	± .457	2.802	± .539

Note. All values are in seconds. The experimenter controlled response times (RTs) in the aligned condition; the participant controlled RTs in the imagined condition.

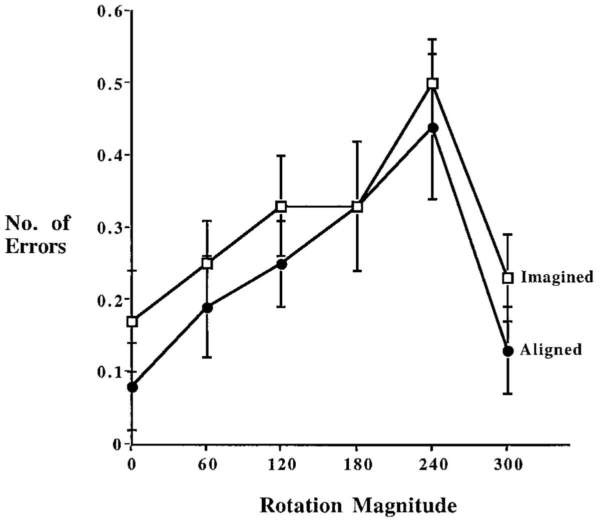

Figure 8. Mean errors (out of a possible 30) and standard errors of Experiment 3, as a function of rotation magnitude.

across conditions. Thus, a spatial-updating advantage for imagined self-rotations persisted for a situation in which participants used a response measure that did not involve verbal encoding. Instead, they located objects in the array by “pointing” with arrow keys that were offset from the coordinate system of the physical body. This finding supports the reference-frame-conflict hypothesis. An advantage for spatial updating during imagined self-rotation emerged when we used a response measure that reduced the conflict between the participant’s physical and projected egocentric reference frames.

Within the offset keyboard response modality, we continued to find a weak automaticity effect. RTs in the imagined condition peaked at rotations of 120° and 240°; RTs in the aligned condition were flatter but peaked for 240° rotation trials. When compared with the values of Experiment 2, RTs for the 240° condition in Experiment 3 were markedly longer. We have no clear explanation for this difference, although the fact that it occurs for both imagined and aligned conditions suggests an individual difference effect. This finding warrants further empirical investigation.

General Discussion

These studies examined the effect of different response measures on spatial updating during physical and imagined-self-rotation conditions. In Experiment 1 participants used a pointer to locate unseen objects from novel perspectives within an array. Movement to the novel perspectives occurred by physical rotation to a correct perspective (aligned condition), physical rotation to an incorrect perspective in which sensorimotor information was ignored (misaligned condition), or imagined rotation to a correct perspective (imagined condition). Using the pointing modality, participants’ updating performance was superior in the aligned condition compared with the misaligned and imagined conditions. In Experiment 2 participants performed the same updating task in identical movement conditions but located objects in the array by using a verbal response rather than by pointing. Performance was found to be superior in the imagined condition compared with the aligned and misaligned conditions. In Experiment 3 we tested updating performance using a variation of a pointing task in which the location indicators were offset from the coordinate system of the participant’s physical body. Updating was again found to be superior during the imagined-self-rotation condition compared with the physical-self-rotation condition.

In the past, researchers have proposed a differentiation of the mechanism underlying spatial updating based on either automatic versus cognitively effortful processing (e.g., Farrell & Robertson, 1998; Rieser, 1989) or spatial versus verbal processing (de Vega & Rodrigo, 2001). The results of the present study suggest that neither of these proposals is quite accurate. We found that updating performance during imagined self-rotation, a task requiring cognitive effort, could actually surpass that of physical self-rotation, despite the absence of sensorimotor information that presumably enhances the updating process (Farrell & Robertson, 1998; Rieser, 1989). Nor was the imagined-self-rotation advantage due to an increase in automaticity within that movement condition, as indicated by the RT functions of Experiment 2. The updating advantage occurred when we changed the response modality from pointing to verbal labeling, a context that is arguably more cognitive. With regard to dissociations of spatial versus verbal processing, Experiment 3 demonstrated that the imagined-self-rotation updating advantage was not limited to the verbal modality per se. Performance was also superior during imagined self-rotation when we used a pointing task in which the spatial indicators were offset from the reference frame of the participant’s body. These results suggest that the critical factor to superior updating performance is a context in which the observer is not unnaturally anchored to the coordinate system of the physical body. Verbal responses and offset pointing responses meet this criterion; traditional pointing responses do not. The corollary to this argument is that the former modalities—in which the conflict between physical and projected reference frames is reduced—reflect the most natural, advantageous state for spatial updating. In recent years a trend in spatial-cognition research has been to focus on perceptual contributions to the spatial-updating mechanism (e.g., Farrell & Robertson, 1998; Klatzky et al., 1998; Rieser, 1989). On the basis of the present findings, we are arguing for greater emphasis on contributions of cognitive processing in its own right to the spatial-updating mechanism (see Wraga et al., 2000, for similar comments).

There is some support for this idea in the neuroimaging literature when one contrasts neural activation found in motor-imagery tasks with that of tasks involving imagined-whole-body transformations. Studies of motor-imagery tasks, in which participants imagine performing an action, generally have found neural activation in motor areas such as premotor cortex, primary motor cortex (M1), or both (e.g., Decety et al., 1994; Ganis, Keenan, Kosslyn, & Pascual-Leone, 2000; Kosslyn, DiGirolamo, Thompson, & Alpert, 1998; Kosslyn, Thompson, Wraga, & Alpert, 2001; Parsons et al., 1995). For example, Kosslyn et al. (1998) had participants view pairs of hands, one of which appeared at a different orientation with respect to the other. Their task was to decide whether the hand pairs were identical or mirror images. Kosslyn et al. found M1 activation during this task, despite the fact that participants had performed no physical movement. Evidently participants had imagined rotating their own hands into the depicted stimuli in order to solve the task, and such imagined movements elicited activation similar to that of physical movement. Interestingly, recent neuroimaging studies of imagined self-rotation have not yielded similar motor activation, despite the fact that participants imagine performing a rotation of the body (Creem, Hirsch Downs, et al., 2001; Wraga, Inati, Church, Shephard, & Kosslyn, 2002). Creem, Hirsch Downs, et al. (2001) found activation in supplementary motor areas but not M1 for a task in which participants updated an array during imagined self-rotation. Wraga, Inati, et al. (2002) found a similar result when activation for an imagined-self-rotation task was directly compared with that of an imagined-object-rotation task. These researchers have argued that imagined-whole-body transformations may not adhere to physical motor constraints in the same manner as mental transformations of individual body parts. More important to the present study, these findings suggest that the mechanism underlying spatial updating during imagined self-rotation is one in which the role of the physical body is minimized.

By highlighting the role of cognitive processing in spatial updating, we do not mean to imply that constraints of the physical world are completely absent. Indeed, the findings of the present study and others, showing greater RTs for object locations offset from the orthogonal axes of the egocentric reference frame, indicate that some aspects of the physical body factor into spatial representations (Wraga et al., 2000; Wraga, Creem-Regehr, & Proffitt, 2002; see also Creem, Wraga, & Proffitt, 2001, for evidence of other physical constraints). The challenge for spatial-cognition researchers is to provide a full and accurate characterization of the mechanisms underlying spatial updating, using both behavioral and neuroimaging techniques.

A final issue raised by our findings is the practicality of using singular measures to assess automaticity effects in spatial updating. Farrell and Robertson (1998) cited similarities in performance rates and RT functions found in their imagined and ignored conditions as evidence of participants' reliance on comparable cognitive processes. In particular, it was thought that participants in these conditions had used cognitively effortful processes akin to mental rotation. In contrast, the superior performance and flatter RT function found in their updating condition was interpreted as evidence for automatic updating. However, we found that the issue became more complex in the present study with the use of multiple response measures. Performance similarities varied among aligned-, misaligned-, and imagined-movement conditions depending on which response modality we used. In Experiment 1 in which participants updated locations by pointing, performance in the aligned condition was differentiated from that of imagined and misaligned conditions, the latter of which were nearly identical. However, within the verbal modality of Experiment 2, performance in the imagined condition became differentiated, and aligned and misaligned conditions were most similar. The precarious nature of these findings with respect to the automaticity issue makes a strong case for the use of multiple measures in future research.

In summary, the present research reveals an advantage for spatial updating during imagined self-rotation when measures other than traditional pointing responses are used. The critical factor to enhanced updating performance appears to be a context in which the spatial conflict between the reference frame of the physical body and the projected egocentric frame is minimized. These findings suggest that cognitive aspects of the spatial-updating mechanism may play a more critical role than has previously been thought.

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