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OBSERVATIONS

Mental Rotation and the Automatic Updating of Body-Centered Spatial Relationships

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Blindfolded adult participants (7 male and 9 female) were asked to point to previously seen targets after a body rotation. In 1 condition, participants had to update their positions relative to the targets during rotation; in another condition, they had to ignore the rotation and to imagine that they were still in their initial orientation. In the updating condition, replicating research of J. J. Rieser (1989), response latencies were only slightly affected by the magnitude of the body rotation. In the ignoring condition, however, response latencies increased with the angular difference between the participants' new position and their original orientation, suggesting that the participants updated their positions and then retrospectively "undid" this updating to mentally reestablish their original orientation. The results are supportive of the idea that heading is updated automatically as a person moves so that she or he is always primarily oriented with respect to her or his actual position.

We can relate to the environment in terms of different spatial frames of reference, such as body-centered frames or environment-centered frames (Paillard, 1991). To successfully fit their actions to the world, people must correctly align the body-centered spatial framework with their actual positions relative to the task environment. If it is not aligned with the environment, or if a person's represented egocentric position is not the same as that required by the task, performance will be impaired. As a person moves around the world, however, egocentric spatial relationships change continuously, and so her or his egocentric reference frame has to be brought into alignment continuously with the new relationships. This article describes an experiment in which we investigated the means whereby the egocentric reference frame is updated to take account of these changes.

The difficulties that arise when participants' egocentric representations of themselves relative to the environment are not aligned with their true positions are demonstrated in misaligned map tasks (e.g., Levine, Jankovic, & Palij, 1982; Rossano & Warren, 1989). In these tasks, participants study a map of a path in a particular orientation and subsequently have to use this representation to make judgments about the directions of points in the real path. Difficulties arise when this real path and its representation on the map are misaligned with respect to one another (Levine et al., 1982), and in these situations the participants have to engage in supplementary processing to bring the two reference frames into alignment (Rossano & Warren, 1989).

Evidence suggests that such processing takes the form of a mental rotation. In a study by Rieser (1989), blindfolded participants stood in the center of a circular array of targets, and then they either rotated round to face another direction and pointed to targets from this new orientation or else imagined that they faced a different direction and pointed to the targets as if they actually occupied this imagined orientation. Rieser found that the participants took longer to respond and made more errors when they merely imagined facing a different orientation, compared with when they actually rotated so as to face this new orientation (see also Presson & Montello, 1994). Moreover, not only were the participants slower overall in the imagination task but their response latencies increased as the angular difference between their actual and imagined orientations increased. This finding has also been obtained by Easton and Sholl (1995). Though the Rieser study and Easton and Sholl study have slightly different interpretations of these results, both agreed that the processing in the imagination task seemed to involve an analog of the physical rotation that occurred when the participants actually did change their directional heading.

Similar findings were obtained by Shepard and Hurwitz (1984), who presented participants with schematically presented paths about which they had to make judgments about right and left turns. The time taken for the participants to make this decision increased with the disparity between their own body-centered axes and the imaginary point of view that they had to adopt to make the judgment. This result is consistent with the idea that the participants mentally rotated one of the frames of reference into alignment with the other

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(see also Boer, 1991; Hintzman, O'Dell, & Arndt, 1981; Péruch & Lapin, 1993).

When participants actually move to a new location, however, their egocentric frame of reference will also be out of alignment with the environment unless it is updated. This situation is formally similar to the imagination tasks just described but, in contrast, does not seem to require the same effortful and time-consuming mental rotation. In Rieser's (1989) study, there was no effect of the size of the rotation on the response latencies when the participants actually rotated without vision to face the new direction. It appears that the participants updated their changing headings relatively automatically as they moved.

Rieser and his colleagues (e.g. Rieser, Guth, & Hill, 1986; Rieser & Rider, 1991) have proposed that such updating in the absence of vision is based on the proprioceptive information that is generated by self-movement, and this idea could explain why performance is better on tasks in which the participants actually move to a new position, compared with tasks in which they merely imagine that they have moved to a new position. In the former task, the changes in spatial relationships that have occurred are specified to the participant by the proprioceptive information, whereas no such information is available in the imagination task. In addition, the greater difficulty of imagination tasks over locomotion tasks is consistent with the idea that spatial updating occurs automatically: When participants actually move, the proprioception ensures that their egocentric reference frame is in alignment with their new position, whereas in the imagination tasks, the absence of locomotor proprioception leaves the egocentric reference frame unchanged, thus creating a conflict between the unchanged egocentric reference frame and the demands of the task. Such automatic updating would mean that participants are always primarily oriented to their actual directional heading in the world, as proposed by Presson (1987). This automatic updating hypothesis, however, has not been directly tested in the aforementioned studies, and so we decided to investigate it in the present experiment.

If it is the case that participants are primarily oriented to their actual heading in the world by means of automatic updating but are asked to imagine themselves still to be in their initial orientation, their egocentric reference frame will be out of alignment with the orientation that is necessary for performing the task, that is, their previous orientation. In other words, the situation would be formally similar to that in the imagination task: The participants would have to bring their now updated frame of reference back into alignment with the task-relevant reference frame. We investigated this issue in the present experiment by having participants rotate on the spot so as to face a new direction but by asking them to ignore their rotation and to imagine that they were still facing in the same direction as they did at the start. If proprioception updates the participants' headings automatically, they should find it difficult to ignore their movement, and they would have to undo this updating before they could point to the targets. In this case, we would expect that response latency would be a function of the size of the rotation that the participants have performed because they would have to mentally rotate their updated body-centered reference frames back into their original orientations.

Method

Participants

Sixteen adult participants (7 male, 9 female; mean age = 45.7 years, SD = 7.6 years) from the Medical Research Council Applied Psychology Unit (Cambridge, United Kingdom) subject panel were tested and paid for their participation.

Apparatus and Layout of Experimental Space

The experiment was carried out in a room in which a 2.5 m × 2.5 m space had been cleared. Seven common household objects (book, cup, jar, shoe, plate, brush, box) with one syllable names were used as targets, and these also served to define the seven possible participant orientations. They were placed on wooden plinths 1 m high, which were spaced at 51.5° intervals to form a circle with a diameter of 2 m. The participant sat in a rotatable chair directly over the center of this circle and pointed to the targets with a 50-cm-long handheld pointer. While pointing, the participants wore a blindfold and listened through headphones to white noise played by a tape recorder attached to the back of the chair. The volume of the white noise was loud enough to mask any background sounds that could have acted as localization cues but still permitted the experimenter to be heard when giving instructions.

Design

Participants performed the pointing task under the four following conditions.

Updating. After viewing the targets, the participants rotated without vision to face another direction and had to point to the true position of the named target from this new orientation.

Imagination. The participants viewed the targets from the starting position and then were blindfolded. However, the participants did not move from this initial orientation but instead had to imagine that they were facing a new orientation and had to point to the named target as if they were actually facing in the imagined direction.

Ignoring. After blindfolding, the participants rotated to face a new direction but had to try to ignore this rotation and to imagine that they were still facing the initial direction. The participants thus had to point to the targets as if they were pointing to them from the starting position.

Control. In this condition, the participants rotated in one direction and then in the opposite direction so that they ended up facing in their original direction. The participants then pointed to the true location of the target.

Because use of all the permutations of different possible starting points, rotation sizes, and target objects would have made the experiment impracticable, the same trials were used in all four conditions. Thus, the amount of rotation that had to be updated, imagined, or ignored was the same in each condition, as were the target objects and correct responses. Any differences between the conditions, therefore, could not be a result of some responses being intrinsically more difficult or time consuming than others or of particular targets being remembered more easily than others. For each participant, a set of 8 trials was formulated, using each of the eight rotation magnitudes once. The direction of rotation (clockwise or counterclockwise) was decided randomly for each trial. Each trial was presented twice, in a random order, in each condition. Thus, the participant performed 16 trials in each condition. The conditions themselves were presented in a Latin square design.

Procedure

The participants were seated in a rotating chair in the center of the circular array of target objects. They were told the names of the objects and instructed to look at them and to try to remember where they were. The participants were then tested on their memory for the target positions by pointing without vision at each of the target objects while facing each of the seven possible directions. Before each practice trial, the participants viewed the targets from the appropriate orientation, and after each practice trial, they were allowed to look to see how accurate the response was. It was emphasized to the participants that they should try to point directly at the target, not just in the correct general direction. At the end of this practice period, all of the participants were able to point correctly to each of the target objects; that is, their pointing responses fell within a sector of the experimental space 25.5° on either side of the target and thus were closer to the correct target than to any other target. All participants said that they were confident that they knew the layout of the targets, and none said that they wished any additional practice trials.

For the experimental trials, the participant was fitted with the blindfold and the headphones. In the updating condition, the participant looked at the targets while facing the object defining the starting orientation and was then blindfolded. We then touched the participant on one shoulder, and the participant then started to rotate around toward the side on which she or he had been touched (e.g., if touched on the right shoulder, the participant would rotate in a clockwise direction). When the participant had reached the new orientation, we told her or him to stop, and then we named the target to which the participant had to point and simultaneously started a stopwatch. The participant then pointed to the target, and we stopped the stopwatch as soon as the participant had pointed to the target. The participant was instructed to point as quickly and as accurately as possible and, to facilitate accurate timing of the responses, to point using a single decisive movement.

When the participant had pointed, a plumb line was dropped from the end of the pointer to the floor, and a marker was placed at this location. The participants were not allowed to see how well they had done during the experimental trials, and the presence of decoy markers on the floor from the start meant that the participants were unable to use the markers to gauge the accuracy of their responses. The participant was then rotated to the starting orientation for the next trial.

The same procedure was used in the imagination condition except that, in this case, the participant did not actually rotate to face the new orientation but was told to imagine that she or he was facing in a different direction. After viewing the targets and being blindfolded, the participant was instructed to "point to the [insert name of target object] as if facing the [insert name of orientation object]." In the ignoring condition, the participant rotated to a new orientation, as described above, but was told beforehand to try to ignore this rotation and to imagine that she or he was still facing in her or his initial direction. After rotating, the participant was instructed to "point to the [insert name of target object] as if still facing the [insert name of original orientation object]." In the control condition, the participant, after being blindfolded, was touched on the shoulder and started to rotate toward that side. When the participant had rotated through half of the angle used in the corresponding trial in the other conditions, we touched her or him on the other shoulder; the participant rotated back in the opposite direction and was told to stop once the initial orientation had been regained. The participant then pointed to the target that we named.

Results

One-way repeated measures analyses of variance were used to analyze the effects of condition on the mean absolute angular deviation from the target direction and mean response latency. Post hoc pairwise comparisons were carried out by using Tukey's honestly significant difference procedure.

There was a significant effect of condition on angular error, $F(3, 45) = 6.64$, $p < .01$. Post hoc comparisons showed that there were significant differences between the control condition and both the imagination and ignoring conditions ($p < .01$; see Figure 1A). There was, however, no difference between the control condition and the updating condition. The updating, imagination, and ignoring conditions did not differ significantly from one another, although 11 of the 16 participants were more accurate in the updating condition than in the ignoring condition. There was also a significant effect of condition on overall mean response latency, $F(3, 45) = 42.95$, $p < .01$. Post hoc pairwise comparisons indicated that responses in the control and updating conditions were significantly faster than those in the imagination and ignoring conditions ($p < .01$). The most important finding, that response latencies were longer in the ignoring condition that in the updating condition, was consistent between subjects: All 16 participants showed this pattern. There were, however, no significant differences between the control and updating conditions or between the imagination and ignoring conditions (see Figure 1B).

In addition to examination of the overall mean errors and response latencies in each condition, regression analyses were used to see whether there were linear or curvilinear relationships between the magnitude of rotation and the mean errors and latencies in each condition. These were perhaps the more important analyses because they should be sensitive to differences between conditions that may have been masked when all rotation magnitudes were grouped together. In the control condition, there was a linear relationship between magnitude of rotation and angular error ($r^2 = .703$), $F(1, 6) = 14.20$, $p = .009$. Examination of Figure 2 shows that there was only a slight rise in error as rotation magnitude increased, indicating that angular error in the control condition was not greatly affected by the distance through which the participant had rotated. In the updating condition, however, there was a more marked linear increase in error as the angle through which the participants had rotated became larger. This was reflected in a significant linear relationship between magnitude of rotation and error ($r^2 = .934$), $F(1, 6) = 84.73$, $p < .001$. There was no linear relationship between magnitude of rotation and error in the imagination condition ($r^2 = .06$), $F(1, 6) = 0.39$, $p = .557$, but there was a strong curvilinear relationship ($r^2 = .909$), $F(2, 5) = 24.99$, $p = .002$. A similar pattern was found in the ignoring condition: There was again no linear relationship

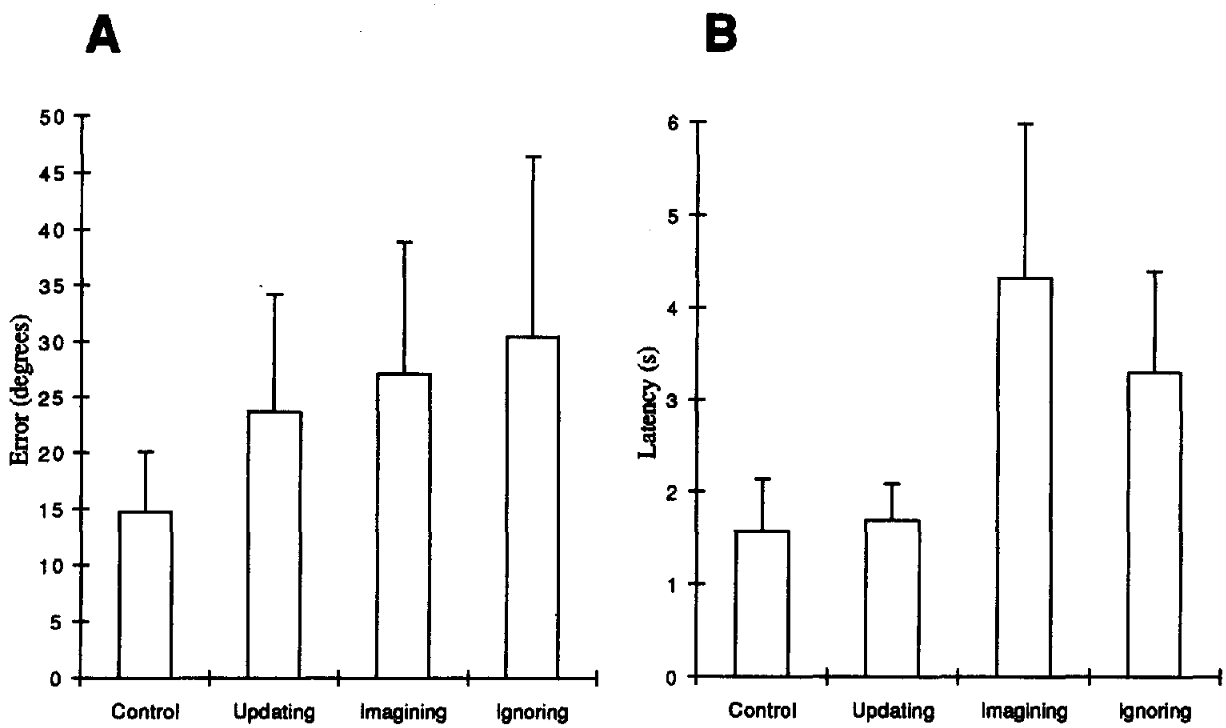

Figure 1. A: Mean angular error and standard deviations. B: Mean response latencies and standard deviations.

between the magnitude of rotation and error ($r^2 = .134$), $F(1, 6) = 0.93$, $p = .373$, but there was a significant curvilinear relationship ($r^2 = .805$), $F(2, 5) = 10.31$, $p = .017$. In both the imagining and ignoring conditions, therefore, a similar pattern was seen: Angular error increased with the disparity, in either direction, between the participants' actual orientation and the imagined orientation that they had to adopt to perform the task at hand.

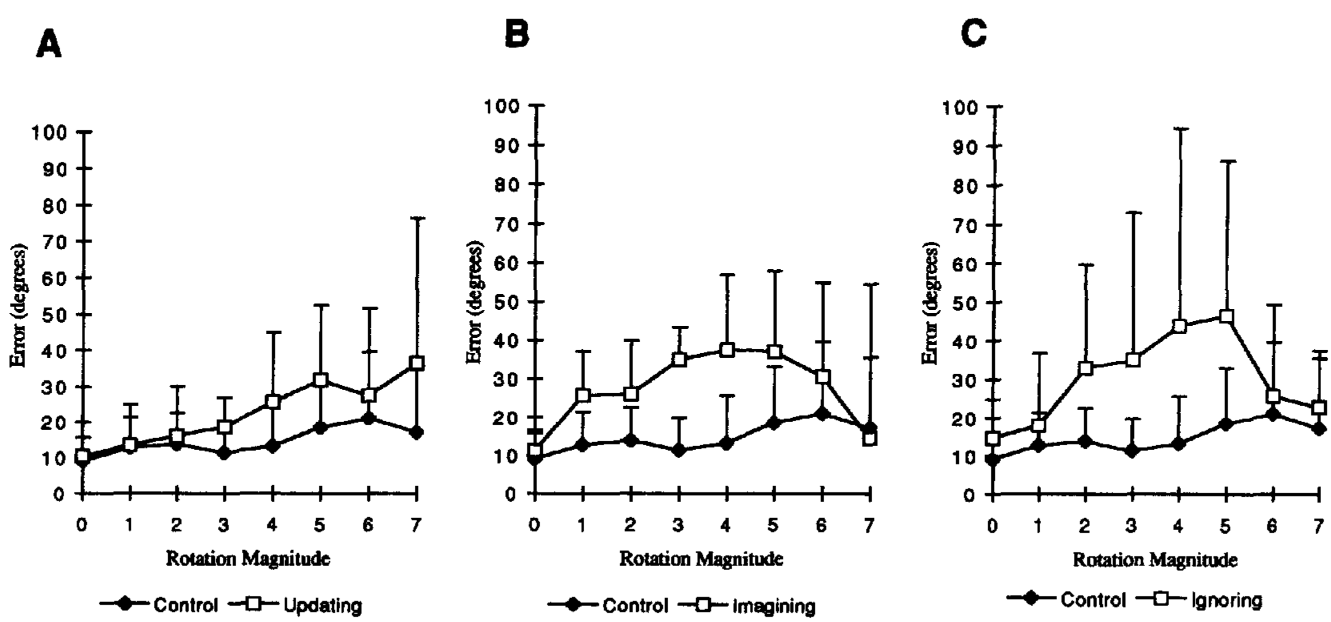

Figure 2. Mean angular errors and standard deviations as a function of rotation magnitude for (A) updating and control conditions, (B) imagining and control conditions, and (C) ignoring and control conditions.

In the control and updating conditions, there were significant linear relationships between response latency and magnitude of rotation; for control ($r^2 = .652$), $F(1, 6) = 11.25$, $p = .015$; for updating ($r^2 = .715$), $F(1, 6) = 15.02$, $p = .008$ (see Figure 3). In both cases, there was a slight rise in response latency with increasing rotation magnitude. However, in the imagination condition, although there was no linear relationship ($r^2 = .012$), $F(1, 6) = 0.07$, $p = .797$, there was a strong curvilinear relationship ($r^2 = .953$), $F(2, 5) = 50.50$, $p <$ 001, between response latency and magnitude of rotation. In the ignoring condition, there was also a significant curvilinear relationship between magnitude of rotation and response latency ($r^2 = .944$), $F(2, 5) = 42.23$, $p = .001$. Thus, in both the imagining and ignoring conditions, the participants' response latencies increased markedly with the angular disparity, in either direction, between their actual orientation and the imagined orientation that they had to adopt to perform the task correctly.

Discussion

In the imagination and ignoring conditions, the participants were less accurate than in the control condition, whereas in the updating condition, there was no significant difference with the control condition in terms of accuracy. With respect to response latency, the participants were significantly slower in the imagination and ignoring conditions than they were in the updating and control conditions. The results from the imagination condition confirm those of Rieser (1989) and of Presson and Montello (1994), but in addition, the difficulty experienced by the participants in the ignoring task indicates that they found it easier to update their orientations than to imagine that they had not moved.

Examination of the response latencies as a function of rotation magnitude suggests that, in the imagination and ignoring conditions, the participants performed mental rotations intended to bring the actual and imagined reference frames into alignment: in both conditions, the participants took more time to imagine themselves facing a particular heading the greater its angular distance (in either direction) from their actual heading. The imagination condition findings replicate those of Rieser (1989) and of Easton and Sholl (1995). The finding that in the ignoring condition, the participants required more time to imagine themselves in their original orientation as the angular distance that they had moved from it increased, supports the idea that they updated their positions automatically in the ignoring condition and then had to undo this updating retrospectively to reimagine themselves facing their original orientation. It did not appear to be the case that they could simply refrain from updating their positions from the outset, though this is what they were requested to do. In the updating condition, however, and in agreement with Rieser (1989), the response latencies were not greatly affected by the magnitude of rotation. This finding suggests that in the updating condition, there was little supplementary processing necessary after the movement had been performed: All the updating seems to have taken place during the movement itself.

The linear increase of errors as a function of rotation magnitude in the updating conditions is what one would expect if nonvisual updating takes place on the basis of visually calibrated proprioceptive information, as proposed

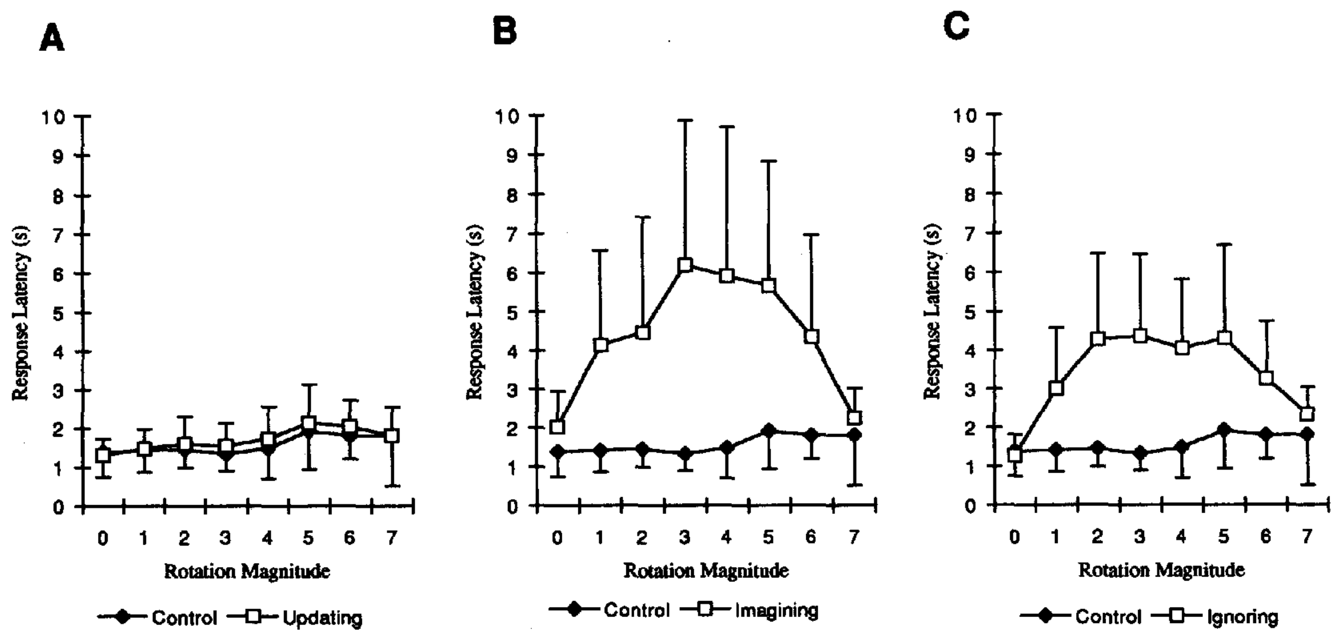

Figure 3. Mean response latencies and standard deviations as a function of rotation magnitude for (A) updating and control conditions, (B) imagining and control conditions, and (C) ignoring and control conditions.

by Rieser and his colleagues (e.g., Rieser et al., 1986). It seems likely that there would be noise present in this calibration, which would lead to an accumulation of this error as the participant had to update over greater distances. The linear increase in error as rotation magnitude increased is consistent with studies in which participants had to walk without vision to previously seen targets (e.g., Loomis, Da Silva, Fujita, & Fukusima, 1992; Rieser, Ashmead, Talor, & Youngquist, 1990), which also demonstrate a linear increase in error as the distance over which the participants have walked without vision becomes greater.

In the updating condition of Rieser's (1989) experiment, however, there was no increase in error with the distance covered. This may have been because the participants in Rieser's experiment were told which object they were facing in the updating condition after they had actually moved to face it, whereas participants in the present experiment were not told their new orientation, but only which target to point to. Thus, they were forced to rely solely on their nonvisual updating. Rieser's participants may have been able to use knowledge of their new heading to correct any errors that may have accumulated in the nonvisual updating itself. This question of whether participants can use allocentric spatial knowledge to infer new egocentric spatial relationships is an interesting one, but in the present experiment we decided not to inform the participants of their new orientation after rotation because this provided the most rigorous test of the updating hypothesis.

Another aspect of this procedure is that participants may have been able to start processing earlier in the imagination and ignoring conditions than in the updating condition (i.e., as soon as they knew the target name). Again, however, this procedure is actually somewhat conservative in that it would tend to militate against the predicted differences and thus again provides the most rigorous test of the updating hypothesis.

The error pattern in the imagination condition was a curvilinear function of the distance through which the participants had imagined themselves rotating. This has also been found by Rieser (1989) and by Easton and Sholl (1995) and has been interpreted in terms of the same accumulation of error that is seen during actual rotation of the participants. The pattern of errors in the ignoring condition also showed a curvilinear pattern, which is again consistent with the idea that the participants updated their positions automatically and then had to undo this updating to imagine themselves back at their starting orientation. In the imagination and ignoring conditions, cumulative error was manifested in a curvilinear rather than in a linear trend because the participants were not constrained by rotation in one particular direction, as in the updating task, but could imagine themselves rotating in either direction so as to take the shorter imaginary route between their actual orientations and the imagined orientation that they had to adopt.

There are, of course, limitations to the current findings. In particular, it has been demonstrated that automatic updating applies only to rotational movements with respect to targets in near space. It is possible that the updating demonstrated in the present experiment will not generalize to other movements and spaces. Nevertheless, Easton and Sholl (1995) have demonstrated that the effect of increasing response latency with increasing distance of imagined movement also exists for whole body translations and for imagined movements in far space. Thus, given the similarities between the imagined movement task and the ignored movement task in the present experiments, we would perhaps expect that some form of automatic updating may apply to other movements and functional spaces.

A further caveat applies to the term *automatic,* which has several specific senses, such as referring to processes that require little or no attentional resources or to processes that are not under volitional control. It is this latter sense of the term that is most appropriate to the present experiment: Despite having been instructed to ignore their movement to the new orientation in the ignoring condition, the participants seemed to find this difficult or impossible to do. The extent to which nonvisual updating of position is automatic in the sense of requiring little in the way of effortful processing remains to be seen. This possibility could be investigated by pairing visuospatial working-memory tasks with spatial updating.

In conclusion, then, the present experiment supports the notion that participants automatically update their changing spatial relationships as a result of self-movement, and it is also consistent with the idea that this can be done nonvisually on the basis of locomotor proprioception. Such a mechanism would serve to keep participants always in touch with their actual orientation in the world. When a task requires them to perform in a way not consistent with their actual spatial orientation, this proves to be difficult and can be accomplished only by engaging in mental rotation that overrides the automatic updating process.

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