Perception, 1994, volume 23, pages 1447–1455

Updating after rotational and translational body movements: coordinate structure of perspective space

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Received 12 June 1994, in revised form 10 September 1994

Abstract. As people move through an environment, they typically change both their heading and their location relative to the surrounds. During such changes, people update their changing orientations with respect to surrounding objects. People can also update after only imagining such typical movements, but not as quickly or accurately as after actual movement. In the present study, blindfolded subjects pointed to objects after real and imagined walks. The role of rotational and translational components of movement were contrasted. The difficulty of imagined updating was found to be due to imagined rotation and not to imagined translation; updating after the latter was just as quick and accurate as updating after actual rotations and translations. Implications for understanding primary spatial orientation, the organization of spatial knowledge, and spatial-imagination processes are discussed.

1 Movement and orientation in surrounding and imaginal spaces

Mobile organisms must maintain orientation to a stable surrounding environment as they move. This ability to keep track of the changing spatial relations to objects and places as one moves is known as spatial updating (Pick and Rieser 1982). Humans also can imagine body movements and the consequences of movements on their relation to the surrounds. However, judgments about one's changed relation to the surrounds are easier to make (more accurate and faster) when actually moving than when only imagining the movements. The relative advantage for real movement as opposed to imagined movement has been demonstrated in two types of study. In studies of spatial updating, when people physically move to a new station point while blindfolded, they are nearly as fast and accurate in pointing to room objects as they are before moving (Rieser and Rider 1991; Rieser et al 1986). Rieser et al (1986) argued that movement provides proprioceptive information that allows people to update their changing relation to the surrounds in a relatively 'automatic' manner. When movement is only imagined, people must use a slower, more difficult computational strategy to figure out how to point.

A similar pattern has been shown in studies of spatial perspective taking. In those tasks, subjects imagine what an array of objects would look like to an observer at a different vantage point, and pick a picture or model to show the new appearance. This task is difficult for children (and even for adults), and they typically make many 'egocentric' errors, responding as if the observer would see just what the child currently sees (Piaget and Inhelder 1956). However, if children move to the new vantage point, they are able to anticipate what the covered array would look like, and do not make 'egocentric' errors (Huttenlocher and Presson 1979; Shantz and Watson 1971).

In both these procedures, the real and imagined movements to a new vantage point (like most complex movement) consist both of translational and of rotational components. That is, subjects move away from their original location and change the direction they were facing. Thus, it is not clear whether the rotational and translational components of movement contribute differentially to the difficulty of imagined updating.

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In the present study, we contrast separately the role of different components (rotation and translation) of movement in both real and imagined movement.

Differences between translation and rotation, if they exist, have implications for understanding how spatial information is coded in working memory during and/or after imaginary movement. From a purely computational approach, if the organization were based on a polar reference frame, then imagined updating after rotations would be easier than after translations. Such a frame encodes locational information in terms of straight-line distance and direction from an origin. After rotation, all distances would stay the same and all directions would change by the same amount, the angle of rotation. Updating after imagined translations, however, would be difficult. Object distances and directions as expressed in the polar frame would change differentially and in complex ways after translation, the extent of changes depending on object locations with respect to the origin.

Alternatively, if the organization of spatial working memory were based on a two-dimensional Cartesian reference frame, imagined updating after translation would be easier than after rotation. Such a frame encodes locations relative to front–back and left–right dimensions originating at a person's location. In a manner depending on the direction of the translation, position would be adjusted by shifting the origin along the front–back and/or left–right axes, and the coding of object locations would change uniformly along that axis. But much as is true for translational movements with a polar frame, updating after rotational movements would be complex given a Cartesian frame.

Rieser (1989) addressed this issue of the relative ease of updating after rotations and translations. He reported that subjects introspected that updating after imagined rotations was much harder than updating after imagined translations. He also compared the difficulty of pointing to array objects after real and imagined rotations. Response latency was greater after imagined movements, and it varied as a function of rotation angle much like familiar patterns of latency in image-rotation studies (eg Shepard and Cooper 1982). Accuracy was also less for imagined (as opposed to real) rotations. Finally, in a third experiment, six subjects updated after imagined rotations and translations. Latencies after imagined rotations were greater than after imagined translations. Pointing accuracy after imagined translations was greater than after imagined rotations, although this difference was not statistically significant ($p < 0.08$). Rieser (1989) interpreted these data as showing that spatial information was organized in terms of a Cartesian reference frame. These findings are important, and here we provide an independent, conceptual replication of Rieser's study.

Contrasting rotational and translational components of movement presents several problems in defining equivalence. For example, a small rotation changes the directional heading to targets more than does a small translation. Such concerns make it difficult to be certain that a difference is due to the movement type and not to other factors. Different solutions are possible. A particular strength of Rieser's task was that it included a large number of targets and specific movements, which created a large number of unique trials.

However, there are a number of reasons why conceptual replication of Rieser's study with different approaches to the question of equivalence is important. First, Rieser's procedure confounded the comparison between rotation and translation with the magnitude of directional change created by the movement. The mean change in angular heading to the targets after the rotational movements was 90°, whereas it was only 33.75° after the translational movements. Second, not only were the overall mean changes in direction to the targets different for the two types of movement, but also variances in the amounts of change between trials were different. The changes in the target heading from trial to trial was greater after rotational movements.

Third, after rotational change all targets were in orthogonal or perfect diagonal relations to the subject, whereas after translational change a variety of oblique headings occurred as well. These potential confounds in the comparison of rotations and translations, coupled with the fact that the observed difference for pointing accuracy between imagined rotation and translation was not statistically significant in Rieser's study, make further study of this question essential.

Our strategy in comparing the two movement types was in some ways simpler than Rieser's. We established more-constrained situations, for which there was a single target, and for which the two movements (forward translations and clockwise rotations) always changed the heading of the target by the same amount. Although this has the limitation of a smaller set of specific arrays and movements, it provided the most straightforward control for the amount of angular change in target location for the two movements. This procedure, like all others, does not equate rotations and translations in all ways, but they are equated in the present experiment in the ways discussed above.

2 Method

2.1 *Subjects*

Subjects were twenty-four females and sixteen males from introductory psychology classes, participating as part of a course requirement.

2.2 *Materials*

The experiment was conducted in a large (10.7 m × 11.7 m) room that was unfamiliar to subjects. Three styrofoam objects (a blue star, a red ball, and a green cube), each about 10 cm across, were placed in the room on stands (1 m tall) according to one of two floor plans, A or B (figure 1).

Subjects responded by using a 28 cm circular pointer that was placed on top of the circular seat of a stool. Degree gradations were marked along the perimeter of the back side of the pointer dial. A stopwatch was used by the experimenter to record response latencies.

2.3 *Procedure*

Subjects were tested individually, and wore a hood (a cap covered with opaque cloth) that blocked vision of the walls and objects in the experimental room, but allowed

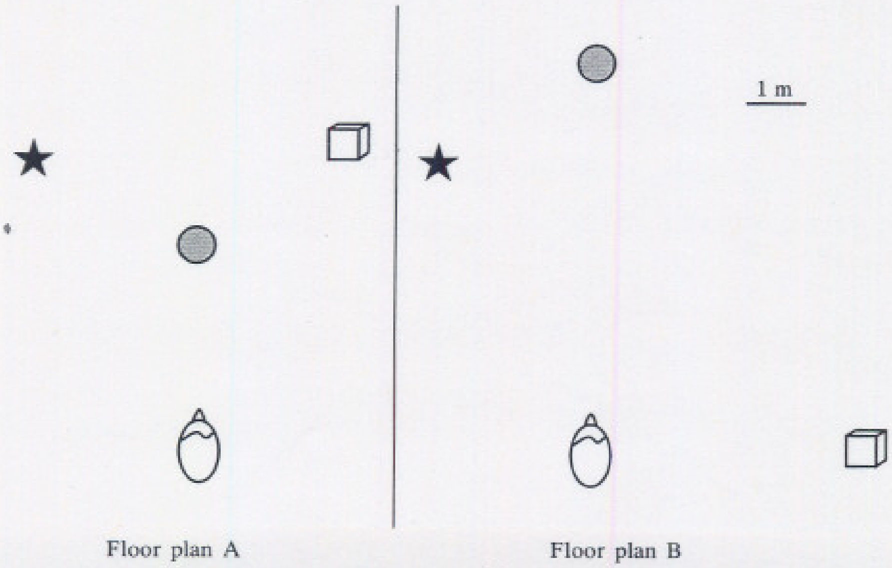

Figure 1. Floor plans A and B. Objects are not drawn to scale.

subjects enough visibility to see the pointer in front of them. They were led into the room and stood at a small red dot on the floor near one side of the room (which served as initial station point), facing the ball in front of them. The hood was removed, and the experimenter pointed to the red dot and the three objects, initially placed according to floor plan A for half the subjects and floor plan B for the other half. Subjects were told to memorize the locations of these objects because they would later be asked about them when blindfolded. The pointer was then demonstrated. Both accuracy and speed of response were stressed. The experimenter then replaced the hood over subjects' heads, and provided the movement instructions.

Half the subjects performed actual movements (translations and rotations), and the other half imagined those movements. Within each group, either the two translations (one for each floor plan) or the two rotations were performed first, in counterbalanced orders. For real (and imagined) translations, subjects were told to "(pretend to) walk straight to where the ball is, without turning your body either right or left. Stop when you are (imagine yourself) standing right in front of the ball". For real (and imagined) rotations, subjects were told to "(pretend to) turn your body without stepping off the red dot, until you are (imagine yourself) facing directly towards the cube". Subjects typically were accurate in their real movements. If they began to deviate substantially, they were lightly (and briefly) touched on the arm to correct the movement. Most subjects needed no correction.

After subjects moved or imagined moving, the pointer was placed in front of them on a stool, visible from underneath the hood, with the radius pointed directly toward the subject. Subjects who had actually moved were asked to "point quickly in the direction of the star". Subjects who had imagined movements were told to "quickly point in the direction the star would be if you were at the ball (or facing the cube)".

Response directions and latencies were recorded. Subjects in the real-movement conditions were then returned to the starting position. The experimenter placed the ball and cube for the next conditions, and the entire procedure was repeated. The experimental session lasted about 15 min.

3 Results

Performance on the pointing tasks was analyzed in terms of response latency and angular accuracy (mean deviation, or absolue value of pointing error). The order of task performance (rotation first or translation first) had no effect either on accuracy or on latencies and is not considered further (for all, $F < 1.0$). The two dependent variables were analyzed in two four-way, mixed-model ANOVAs: movement conditions (real vs imagined) and subject sex were between-subjects factors; movement type (translation vs rotation) and floor plan (A vs B) were within-subjects factors. Two outlying response latencies (1.2% of 160 responses) more than 3 standard deviations greater than the means of their conditions were replaced with the next highest response-latency score. It can be seen from figure 2 that accuracy suffered after imagined rotations but was equivalent for the other three types of movements. Statistical tests confirm this: mean accuracy differed as a function of the interaction of movement condition and movement type ($F_{1,36} = 13.73$, $p < 0.001$). Accuracy did not differ for translations in the real and imagined conditions ($F_{1,36} = 0.65$). However, accuracy was less after imagined rotations than after real rotations ($F_{1,36} = 14.95$, $p < 0.001$). In terms of rotation versus translation, subjects pointed with equal accuracy after real movements of either type ($F_{1,36} = 0.01$), but they were less accurate after imagined rotations than after imagined translations ($F_{1,36} = 30.05$, $p < 0.001$). None of the higher-order interactions approached significance (for all, $F < 1.0$), nor was subject sex significantly related to pointing accuracy as a main effect or in interaction with the other factors (for all, $F < 1.0$).

Pointing accuracy did differ as a function of the interaction of movement condition and floor plan ($F_{1,36} = 6.28$, $p < 0.05$). Accuracy after real and imagined movements did not differ on floor plan A ($F_{1,36} = 0.66$), but was less after imagined movements on floor plan B ($F_{1,36} = 11.73$, $p < 0.01$). Differences between translational and rotational movement also depended on floor plan ($F_{1,36} = 6.62$, $p < 0.01$). Accuracy after rotations was less than after translations on floor plan A ($F_{1,36} = 23.43$, $p < 0.001$), but was equivalent for the two types of movement on floor plan B ($F_{1,36} = 2.16$, ns).

As an additional check for order effects, pointing accuracy was examined separately for subjects' first and then second judgments alone (a single data point contributed by each subject in each of two completely between-subjects designs). The central finding of an interaction between movement type and movement condition was replicated both for first and for second judgments ($F_{1,32} = 3.27$, $p < 0.08$; and $F_{1,32} = 5.63$, $p < 0.05$, for first and second judgments, respectively). In both cases, accuracy was worse after imagined rotations than after the other three types of movement, as in the overall analysis described above.

Although subjects pointed with varying accuracy in different conditions, examination of mean estimated directions indicate that this was not due to a systematic tendency of subjects to point in the original direction of the star, ie to point as if they had not moved. Analysis of estimated directions revealed that in all conditions subjects significantly pointed in a different direction from the original direction to the star. Also, except for the real translators on floor plan B, subjects did not significantly point away from the correct direction towards the direction that would have been correct had they not moved. In particular, on neither floor plan did imagined rotators significantly point in the original direction of the star.

Mean latencies differed as a function of the interaction of movement condition and movement type in much the same way as mean error had (see figure 3). However, this pattern did interact with sex ($F_{1,36} = 4.09$, $p < 0.05$). The two-way interaction reached significance for males ($F_{1,36} = 10.38$, $p < 0.01$), but not for females ($F_{1,36} = 0.56$). The pattern of response latencies for males exactly matched the

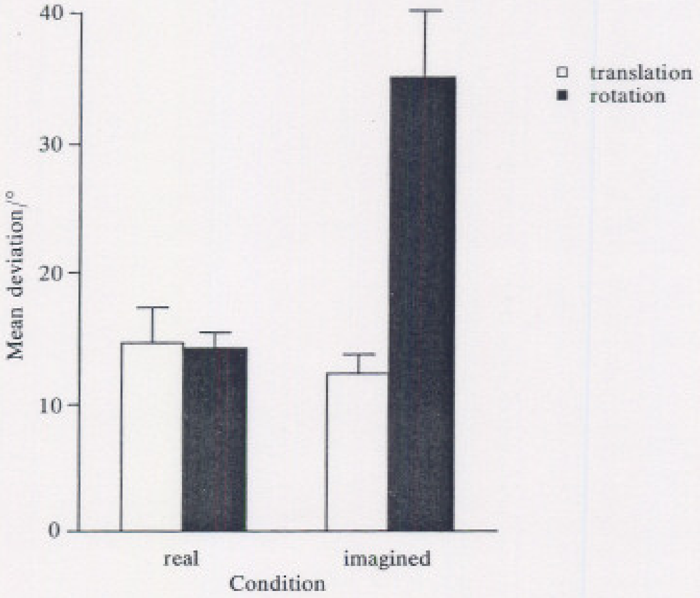

Figure 2. Mean angular deviation as a function of movement type and movement condition (error bars are 1 standard error).

accuracy pattern found for both sexes. That is, responses were slower after rotational movements in the imagined condition than in the real condition ($F_{1,36} = 11.34$, $p < 0.01$). Response latencies did not differ for translational movements in the real and imagined conditions ($F_{1,36} = 0.04$). In parallel to the accuracy results, males responded with equal speed after real translations and rotations ($F_{1,36} = 0.37$), but they were slower after imagined rotations than after imagined translations ($F_{1,36} = 15.61$, $p < 0.001$). Females did respond more slowly after imagined movement than after real movement ($F_{1,36} = 4.19$, $p < 0.05$), and they were marginally slower after rotational movements than after translational movements ($F_{1,36} = 3.78$, $p < 0.06$). None of the other higher-order interactions reached significance.

Latency of pointing also differed as a function of the interaction of movement condition and floor plan ($F_{1,36} = 3.98$, $p < 0.05$). Responses were faster after real movements than after imagined movements, with a larger difference for floor plan B ($F_{1,36} = 13.48$, $p < 0.001$) than for floor plan A ($F_{1,36} = 3.27$, $p < 0.08$). Response latency also differed as a function of the interaction of subject sex and floor plan ($F_{1,36} = 5.69$, $p < 0.05$). The sex difference was not significant for either floor plan, though there was some tendency for females to respond more slowly than males on floor plan A ($F_{1,36} = 2.43$) but no differently on floor plan B ($F_{1,36} = 0.28$).

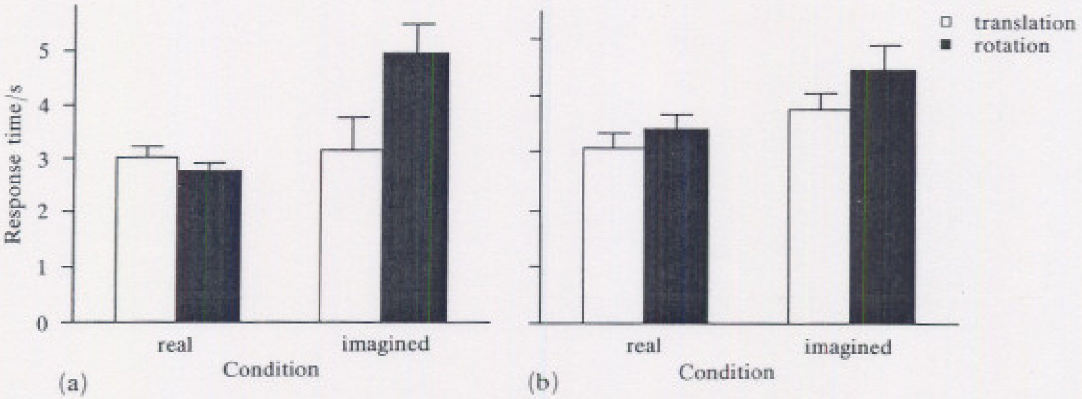

Figure 3. Mean response time as a function of subject sex, movement type, and movement condition (error bars are 1 standard error): (a) males, (b) females.

4 Discussion

In the present experiment we contrasted real and imagined updating (while subjects were blindfolded) after rotational and translational movements. Updating was more accurate after real movement than after imagined movement, but only in the case of rotations. Updating after imagined translation was as accurate as updating after real movements of either type. Further, the latency data of male subjects showed the same pattern of relative difficulty as did accuracy data. Thus, the simplest answer to our main question is that the difficulty of updating after imagined movements (as is found in studies of updating or perspective taking) is due primarily to the difficulty of the rotational component of the movement. These findings, based on a different design and further controls, parallel and complement the findings of Rieser (1989). In the present study we used a single experimental design to compare both real and imagined translations with real and imagined rotations, and equated the rotations and translations in terms of mean change in direction after movement, variance in changes in directions to targets after movement, and the new directions to the targets themselves.

Rieser (1989) interpreted his results in terms of his more extensive account of the nature of spatial updating, which is focused on perceptual mechanisms that underlie spatial orientation and updating. When a blindfolded person moves, the movement provides nonvisual, efferent, and proprioceptive information about the extent and direction of body movement, which supports a process of 'perceptual' updating. When people only imagine the result of a movement, they must use a slower, more difficult computational strategy to point as if from novel places. This general characterization fits with our rotation data and is consistent with subjects' reports in tasks that involve imagined movement (Rieser 1989; Rieser et al 1986).

Rieser's model does not make an a priori prediction of differences for rotational and translational movement, except insofar as differences would reflect the computational difficulties due to alternative geometries. The fact that updating after imagined translation is easier than updating after imagined rotation (both in the current study and in Rieser 1989) suggests that the ego-centered space coded in working memory is organized around a Cartesian frame rather than a polar frame. Such a conclusion would be consistent with previous theory and research indicating organization of spatial knowledge around a pair of orthogonal, ego-centered axes projecting front–back and left–right (Franklin and Tversky 1990; Sadalla and Montello 1989; Shepard and Hurwitz 1984). Such results are not consistent with an organization of working-memory space around a polar frame (eg Byrne and Salter 1983; Gallistel 1990).

Consideration of alternative coding systems does not readily account for all the results, however. In particular, Rieser's (1989) finding that pointing after imagined translations was no more difficult than baseline judgments led him to two additional conclusions (as does our finding that real and imagined translations are equally easy). First, subjects have direct access to object-to-object relations in memory, rather than needing to compute all relations through an origin (on the basis only of self–object relations). In this model, the location of self likely would be represented as an object among all others. Second, Rieser also concluded that subjects have a simplifying strategy for the imagined-translation judgments. They read the direction from the imagined station point to the target object and respond by pointing parallel to that direction. This would shortcut the need for additional computation.

An alternative, but not incompatible, account of our findings is suggested by earlier work (Presson 1987; Presson and Somerville 1985) contrasting primary and secondary spatial frames of reference. In this view, people maintain an ongoing, primary orientation to their immediate surrounds. People use their immediate, direct relation to the surrounds as a primary frame of reference, which affects more-abstract spatial problem solving (as in spatial perspective-taking and map-reading tasks). This primary frame of reference serves to structure spatial working memory and it has a favored status in spatial problem solving. A spatial-imagination or inference task requires an alternative, secondary, frame of reference to be constructed. Whenever this secondary frame of reference uses axes that conflict with the primary frame of reference, the task will be difficult if information about the same spatial environment must be related to both.

An analysis in terms of conflicting frames of reference links the relative difficulty of imagined rotation to the literature on perspective taking and map use. The patterns of task difficulty as well as characteristic error patterns in these classic spatial tasks can be accounted for in terms of conflict between primary and secondary frames of reference (Presson 1987). In these tasks, when the to-be-imagined frame of reference conflicts with the subject's direct relation to the spatial surrounds (eg when reading a misaligned map or picking pictures in a perspective task), then map and perspective tasks are relatively difficult. However, when the axes of primary and secondary frames of reference do not conflict, then those tasks are much easier.

According to the conflicting-frames model, updating after real movement is easy not only because of nonvisual perceptual information but also because one can point to objects according to the orientation of the primary frame of reference. This theory suggests that we have a strong tendency to coordinate our behavior with respect to our actual location and position in the environment (our canonical orientation). Being forced to behave as if oriented from some alternative spatial perspective can result in a conflict between the heading of the coordinate axes in the imagined space and our actual heading in the environment.

This conflict increases the difficulty of imagined updating and results in decreased accuracy, response speed, or both. This is exactly the conflict situation that arises in the imagined-rotation condition, and it is imagined rotation that is more difficult than imagined translation.

One way in which a conflict between current and imagined orientations might be evidenced would be for subjects to have pointed directly at the target after imagined rotations. Such 'egocentric' responses, which use the primary frame of reference only, have been shown for children in perspective tasks (Hardwick et al 1976; Piaget and Inhelder 1956). However, even though relative task difficulty for adults is the same as for children and adults report the same conflicts, adults do not tend to make such errors (Presson 1982). Instead, adults typically catch themselves before such errors and often overcorrect for them. It is consistent with this that nine subjects in the imagined-rotation condition (vs only one in imagined-translation and none in the real-movement groups) expressed some confusion during debriefing about how they should have pointed after the transformation. Such confusion is consistent with the conflicting-frames-of-reference model, although subjects did not simply point in the actual direction of the star after imagined rotations.

Updating was no more difficult after imagined translation than after real translations. This result and Rieser's (1989) data suggest that subjects have direct access to object-to-object relations (see also Neisser 1987). If so, then the relative direction from the new location to the target can be directly identified; the correct response is a line parallel to that heading. In terms of the frames-of-reference model, of course, these lines are parallel because the axes of the primary frame of reference are aligned parallel with the axes of the imagined station point. Thus, it is the alignment of primary and secondary frames of reference that provides the 'shortcut'.

The present results are also consistent with Rieser's (1989) data in that differences in the ease of updating after real and imagined movements depended in part on the extent of the movement subjects made. Pointing responses were slower and less accurate after imagined movement than after real movement for movements that produced 90° (floor plan B) but not 30° (floor plan A) changes in the directions to objects. Also, the extent of movement, whether real or imagined, influenced differences in the ease of updating after rotational and translational movements. Pointing was significantly less accurate after rotations than after translations for movements that produced 30° changes only. The organization of the spatial information around Cartesian axes may make 90° rotational change something of a special case. If so, any potential difference between rotations and translations would be harder to detect for floor plan B. In spite of these differences, however, the interaction of movement type and condition discussed above did not significantly depend on the extent of subjects' movements.

In summary, our results converge with those of Rieser (1989) in demonstrating that updating after imagined movements is quite difficult when the movements are body rotations but quite easy when the imagined movements are body translations. These findings suggest that spatial long-term memory is not coded in a viewpoint-specific way and that spatial working memory is coded around viewer-centered Cartesian axes (as opposed to a polar frame). Our results were obtained by using a different methodology from Rieser's. Our study controlled for some problems of geometric nonequivalence between rotations and translations that Rieser's methodology did not.

Acknowledgements. This research was supported by NIH grant HD 20666. Portions of these data were presented at the meeting of the American Psychological Society, Alexandria, VA, June 1989. The authors thank Herb Pick, Nora Newcombe, and the Spatial Cognition Research Group (Paul Cregut, Carrie Fox, Jodie Simon, Kathy Tjas, and Brian Young) for general discussions of spatial cognition and for help with data collecting and coding.

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