Research Report

SPATIAL UPDATING OF SELF-POSITION AND ORIENTATION DURING REAL, IMAGINED, AND VIRTUAL LOCOMOTION

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Abstract—*Two studies investigated updating of self-position and heading during real, imagined, and simulated locomotion. Subjects were exposed to a two-segment path with a turn between segments; they responded by turning to face the origin as they would if they had walked the path and were at the end of the second segment. The conditions of pathway exposure included physical walking, imagined walking from a verbal description, watching another person walk, and experiencing optic flow that simulated walking, with or without a physical turn between the path segments. If subjects failed to update an internal representation of heading, but did encode the pathway trajectory, they should have overturned by the magnitude of the turn between the path segments. Such systematic overturning was found in the description and watching conditions, but not with physical walking. Simulated optic flow was not by itself sufficient to induce spatial updating that supported correct turn responses.*

An important component of navigation is updating knowledge of one's spatial position and orientation. People navigating on foot receive multiple cues for updating. Vision signals self-motion by the changing positions of distal landmarks and by the optic flow field. Proprioception (including vestibular sensing as well as kinesthetic feedback from muscles, tendons, and joints) provides cues to the navigator's velocity and acceleration. In the research reported here, we asked how well people update their internal representation of location and orientation as they travel in space under conditions in which these cues are reduced or unavailable, including conditions in which they do not physically move at all. The conditions examined included walking without vision (proprioceptive cues), imagining oneself walking along a verbally described path (neither proprioceptive nor visual cues), watching someone else walk and trying to take that person's perspective (visual cues not coupled with self-locomotion), and watching optical flow fields generated by a virtual display to correspond to a physical walk (visual cues typically coupled with self-locomotion).

Past research indicated that updating of position and orientation is not equivalent across these conditions. When a subject moves physically along a pathway without vision, he or she can update by *path integration*, the process of monitoring one's position in space from velocity or acceleration signals provided by proprioception. Many lower organisms are capable of path integration from nonvisual cues (see Etienne, Maurer, & Séguinot, 1996; Gallistel, 1990; Maurer & Séguinot, 1995). Studies testing human path integration on simple pathways have indicated that responses such as pointing or returning to an origin of travel are performed well above chance. Similar measures indicate that after learning the locations of landmarks by visual exposure or nonvisually guided travel from a source location, individuals can update their position and orientation relative to those landmarks during locomotion without vision (Ivanenko, Grasso, Israel, & Berthoz, 1997; Loomis, Da Silva, Fujita, & Fukusima, 1992; Loomis et al., 1993; Mittelstaedt & Glasauer, 1991; Rieser, 1989; Rieser, Guth, & Hill, 1986; Sholl, 1989).

Updating position and orientation over the course of imagined movement, as is required when encoding from a verbal description, appears to be considerably more difficult than updating from proprioceptive cues. In one paradigm (Rieser et al., 1986; see also Loomis et al., 1993), subjects were exposed to a set of objects by walking to them from an initial position without vision. They were then asked to point to a target object after moving to a new location by either physical or imagined locomotion. Performance was worse in the imagination condition (particularly for sighted subjects). Rieser (1989; Rieser et al., 1986) has suggested that during physical translation or rotation, even without vision, updating of the distances and relative bearings of objects occurs through automatic perceptual processes. Updating after imagined rotations, and in at least some cases imagined translations (Easton & Sholl, 1995), in contrast, apparently requires effortful cognitive processing.

The difficulty of updating orientation through imagination is apparent when imagined rotations and translations are compared. Rotations produce relatively long response times, and errors tend to increase with the angular difference between the physical and imagined orientation (Easton & Sholl, 1995; Farrell & Robertson, 1998; May, 1996; Presson & Montello, 1994; Rieser, 1989). The cognitive effort involved in imagining rotation can also be seen from the difficulty people have when using a map that is not aligned with their orientation in space (Levine, Jankovic, & Palij, 1982; Presson & Hazelrigg, 1984; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998).

To determine how various conditions affect spatial updating, we used a phenomenon that can be demonstrated as follows. Suppose you ask a colleague to stand with eyes closed and take an imaginary walk that you describe—without physically moving. At the end of the walk, the colleague is immediately to make the physical turn that a real walker, having traveled along the same path, would make in order to face the initial origin of travel. The imagined pathway to be walked is as follows: "Go forward 3 m, turn clockwise 90°, then go forward 3 m. Now face the origin." (The reader is invited to take the imaginary walk and make the turn before reading further.) If your colleague is like the subjects described here (and like many colleagues we have induced to try our demonstration), he or she will make a turn of about 225°, or turn toward the southwest if the initial heading were north. The correct response, however, is a turn of 135°, or toward the southeast! As the experiments reported here demonstrate, a person who had physically walked the same pathway, without vision, would correctly turn 135°. The situation is illustrated in Figure 1.

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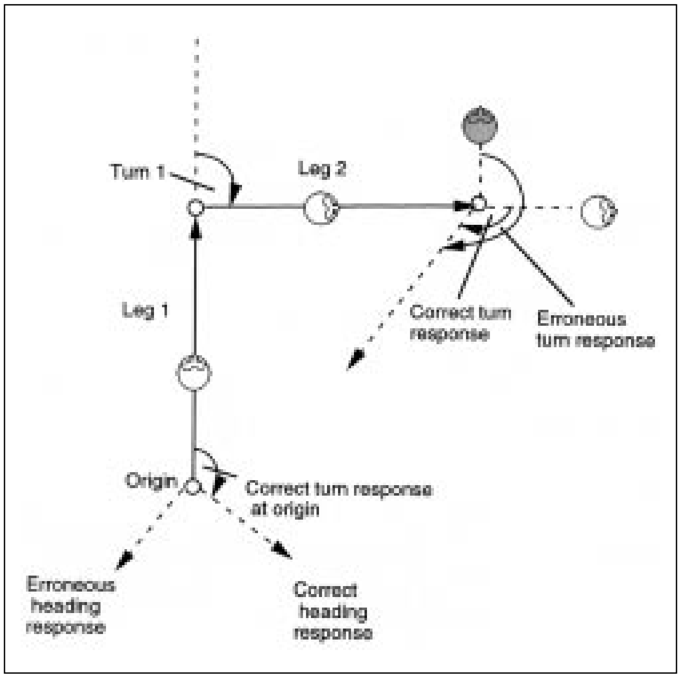

Fig. 1. Schematic of the triangle-completion task. The subject (indicated by unshaded head) is presented with the path consisting of Leg 1, Turn 1, Leg 2, and is then to turn and face the origin. Subjects who do not update heading (indicated by shaded head) will erroneously overturn by the value of Turn 1.

Further discussion requires defining terms used in describing spatial relations. The *bearing* from a navigator (or other object) to a target object is the angle between a reference direction (e.g., north) and a line originating at the navigator and directed toward the target. If an object has an angular orientation, as defined by an intrinsic axis such as the sagittal plane of humans, its *heading* is its direction of orientation relative to some reference direction. An object within the same space as a navigator has an *egocentric (or relative) bearing,* which is the direction of the object relative to the navigator's axis of orientation (equivalent to the difference between the navigator's heading and the bearing from the navigator to the object). If a navigator wishes to face an object, the required turn angle (i.e., degrees of rotation of the body) is equal to the value of the egocentric bearing.

An object's physical heading is what can be objectively measured with respect to the reference direction. People's movements in space, however, are governed by their internal representation of heading. The research described earlier indicates, in fact, a distinction between two internal representations. *Perceived heading* results from automatic processes (e.g., during physical locomotion) and is what one believes to be one's orientation in a space. In addition, one can use effortful cognitive processes to take an *imagined heading,* which may or may not be discrepant with the perceived heading. An important issue is whether taking an imagined heading results in updating of the perceived heading; if not, a person will be aware of any discrepancy.

In these terms, people who have imagined walking two legs of a triangle in our task should make a turn equal to the egocentric bearing from the end of the second leg to the origin, from the perspective of someone who has physically walked and hence has updated perceived heading at the initial turning point in the pathway. But instead of doing so, people typically make the turn necessary to face the imagined origin of travel from their current physical heading, as aligned with the first leg. People may appear to ignore the turn in the stimulus path, but this is clearly not the case, for the response turn varies predictably with that turn. This means that people have encoded the trajectory along the path. It appears, however, that the internal heading that governs the response at the end of the imagined path is not aligned with the second leg; it is instead the initial heading as defined by the first leg. Accordingly, people turn the egocentric bearing corresponding to their physical heading, thus overturning by the angle between the first two legs of the path (in our example, 90°).

We propose that the response in our task is governed by the automatically updated perceived heading rather than the cognitively effortful imagined heading, and furthermore, that people can encode the trajectory along the designated path without changing their perceived heading. This claim is consistent with the literature on navigation in lower organisms (especially rodents), which indicates the existence of distinct neural systems for updating position (e.g., O'Keefe, 1976; O'Keefe & Dostrovsky, 1971; O'Keefe & Nadel, 1978) and heading (e.g., Blair & Sharp, 1995; Taube, Muller, & Ranck, 1990a, 1990b). It is also consistent with theoretical proposals that navigating organisms have multiple reference systems potentially available for spatial updating (Gallistel, 1990; Hart & Moore, 1973; Levinson, 1996; Pick & Lockman, 1981). According to one frequently made distinction, an *egocentric* reference system represents the current distances and bearings of points in space relative to the navigator, and an *allocentric* reference system represents the relative positions of points in an environment external to the navigator. (These are akin to what Gibson, 1979, called perspective structure and invariant structure, respectively.)

MAIN EXPERIMENT

The main experiment compared performance across several conditions in the task described earlier. If subjects updated perceived heading during travel, they should have responded correctly; if they did not, they should have systematically overturned by the value of the turn between the two legs they traveled. From the literature reviewed (and as our demonstrations indicate), we predicted that listening to a described walk would not lead subjects to update perceived heading. We expected that watching someone else walk would have results similar to those of hearing a description, because watching provides information about the coordinates of the pathway and navigator from a single viewpoint. Viewpoint-dependent representations of navigable spaces appear to arise when observers are allowed only a small number of views (Shelton & McNamara, 1997; Diwadkar & McNamara, 1997; Sholl & Nolin, 1997). This condition would make it difficult to adopt a perspective from the end of the second leg, because the subject's viewpoint-specific representation would be in conflict with the field of view that the physical walker would have at the end of the pathway. In contrast, we predicted that the subject's own physical walking without vision would allow the subject to update perceived heading, and hence to correctly portray the egocentric bearing of the pathway origin from the end of the second leg.

We included two conditions to investigate whether simulated optical flow from a virtual display would induce updating of perceived heading. In one case, only optical flow was provided; in the other, the subject was physically rotated at the point of the turn in the pathway. Because the physical turn provided vestibular signals to change of heading, we predicted that subjects in this condition would update perceived heading. We did not know whether subjects with simulated flow from a turn, but without proprioceptive cues, would update similarly. We had previously found that subjects who remained stationary while viewing optic flow from a virtual display performed less well in a triangle-completion task than subjects who walked or were transported in a wheelchair, and hence had proprioceptive cues (Loomis, Beall, Klatzky, Golledge, & Philbeck, 1995; see also Chance, Gaunet, Beall, & Loomis, in press).

Method

Subjects

The subjects were 50 university students. Each was assigned to one of five exposure conditions, as defined by the way in which the initial pathway was presented. There were 10 subjects per condition.

Procedure

The subject's task was to receive information about the first two legs and turn within a triangular pathway and then make the turn someone who walked the pathway would make in order to face the origin. In the *describe* condition, blindfolded subjects heard a verbal description of the pathway, in which leg lengths were described in meters and turns were described in degrees. They were familiarized with the term *degrees* by demonstrations of six turns. In the *watch* condition, subjects viewed the experimenter walking the two initial legs, then closed their eyes before responding. In the *walk* condition, blindfolded subjects were led over the first leg, Turn 1, and the second leg, and then tapped on the shoulder at the end of Leg 2. The subjects in these first three conditions stood during the trials.

In the simulated conditions, subjects sat on a rotating stool, wearing a head-mounted display (HMD) that was part of a virtual-display system, which produced binocular stimulation appropriate to the simulated motion through space. (For a detailed description of the system, see Chance et al., in press.) The virtual environment depicted a field of vertical posts resting on the ground plane. The posts were spaced irregularly to avoid patterns that might convey azimuthal information; the average distance between posts was 1.5 m. The HMD field of view was 44° wide and 33° high, with 100% binocular overlap. Before the first trial, the subjects were allowed to see how the visual stimulation would change under head movements. On each trial, optical flow patterns that would be produced by translating along Leg 1 were projected, followed by an auditory cue. In the *real-turn* condition, the experimenter then turned the subject by the amount of Turn 1 (following markings on the floor below the stool), causing the commensurate rotational flow pattern to be displayed, following which the flow pattern that would arise from the translation forward along Leg 2 was initiated. The turn rate was approximately 90°/s. In the *visual-turn* condition, the flow patterns for the rotation and translation along Leg 2 (calculated assuming an average rate of turn approximating that in the real-turn condition, and accelerating and decelerating at the beginning and end of the simulated turn period) were initiated directly after Leg 1, without physical rotation of the subject. In both simulated conditions, the HMD was turned off at the end of Leg 2.

Subjects were asked to turn and face the origin immediately at the end of Leg 2. In the describe, watch, and simulated conditions, this instruction was elaborated to indicate that they should make the turn they would have to make if they had actually walked the path, were standing at the end of it, and were trying to point back toward the origin, "so that if you started walking in a straight line, you would end up back at the origin where you started." After the response, the subject's heading was measured with an electronic compass.

Each subject took part in five trials, using leftward Turn 1 values of 10°, 50°, 90°, 130°, and 170°, in random order. In all trials, Leg 1 was 3 m and Leg 2 was 2 m. Throughout the trials, subjects wore earphones receiving sounds from an omnidirectional microphone, precluding auditory azimuthal cues.

Results and Discussion

The dependent variable of interest was signed heading error, defined as the angular difference between the heading that the subject should have assumed in order to face home and the heading that the subject actually assumed. The heading errors were used to construct linear functions relating heading error to Turn 1; the slopes and intercepts of those functions were the data for our statistical analysis. (Being based only on turn and not distance, our measure is insensitive to errors of misjudging the scale of the translational movements.)

The signs of the heading errors were determined by a curve-fitting routine. Recall that our hypothesis predicted, in critical conditions, that there would be heading errors in the amount of Turn 1. However, there is an intrinsic ambiguity in whether the heading errors should be signed positively or negatively. One cannot simply hold the absolute value of error within 180° and sign errors according to the sign associated with the lesser absolute value. Suppose, for example, that an individual assumes a heading that is 190° counterclockwise of the correct value, when a counterclockwise error of 170° is predicted. Should the observed error be signed positively (i.e., +190°), in which case it is close to the predicted value, or negatively (i.e., –170°), in which case it is far from the predicted value? Observation of the turn direction does not disambiguate matters, because we consider it irrelevant whether the subject turned left or right to arrive at a final orientation in space.

To determine the signs of the errors, we used a method based on our prediction that the heading errors would match Turn 1 values. The method used circular statistics to fit a linear function relating the observed heading error to Turn 1 for each subject individually, using the five observations for that subject. First, the heading errors and Turn 1 values for the five pathways were represented as angular positions around a circle. Parameters of the linear function relating heading error to Turn 1 were then computed by aligning the circular positions representing the heading error and Turn 1 for each pathway as well as possible, subject to two transformations: The heading errors could all be multiplied by a single constant, or a single constant could be added to each. These operations move the heading errors around the circle by rescaling them or rotating them, respectively. Thus, the multiplicative operation represents a slope and the additive operation represents an intercept in the underlying linear function relating heading error to Turn 1. With these transformations allowed, the squared angular distance between heading errors and Turn 1, summed across the five pathways, was minimized. An additional constraint, adopted to preclude spurious slope and intercept values, was that no point was allowed to rotate more than 360° under the combined transformations.

Computed for each subject separately, the output of this method was a slope and intercept corresponding to the best fitting linear function relating the subject's heading error to Turn 1, across the five pathways. These parameters were used to disambiguate the signing of heading errors for individual trials, as follows. There exists a unique assignment of signs to the heading errors from individual trials that produces the same parameter values when response error is fit to Turn 1 by conventional least squares regression as when the circular method is used. Therefore, the heading errors were signed so that when regressed against the Turn 1 values by conventional regression, the function had the same parameters as were produced by the circular method. Most heading errors were signed as they would have been if we had required the absolute values to be less than 180°. The most common exceptions were on trials with Turn 1 values of 170°. We had predicted that the errors in these cases would be close to +170°, and by our method, some were given positive values greater than +180° rather than being signed with negative values greater than –180° (e.g., +190° rather than –170°).

Note that although the circular method is based on a model that heading error is related to Turn 1, it was applied to the results of all conditions, even those for which we predicted that heading error would be independent of Turn 1 (e.g., the walk condition). It could not impose a relationship where none existed (as is shown by the results), but it revealed a relationship where one did exist by allowing us to sign heading errors appropriately.

Figure 2 shows that, on average, as predicted, heading errors were directly related to Turn 1 values in the watch, describe, and visual-turn groups. Linear regression produced slopes close to 1.0 in those conditions, and those slopes were significantly greater than zero, $t(9) = 5.52$, 4.26, and 7.02, respectively, ps < .01. In the conditions involving physical turns, walk and real-turn, slopes did not differ significantly from zero. Analysis of variance confirmed that the slopes of the functions differed significantly across exposure conditions, $F(4, 45) = 7.30$, $p < .0001$, and post hoc Newman-Keuls tests with alpha = .05 showed that the effect reflected the partitioning of the slopes into those near 1.0 (the watch, describe, and visual-turn groups) and those near zero (the walk and real-turn groups). The intercepts did not differ significantly, $p > .25$. Figure 3 indicates the mean slope and standard error of the mean for each condition in the main experiment and a supplementary manipulation described next.

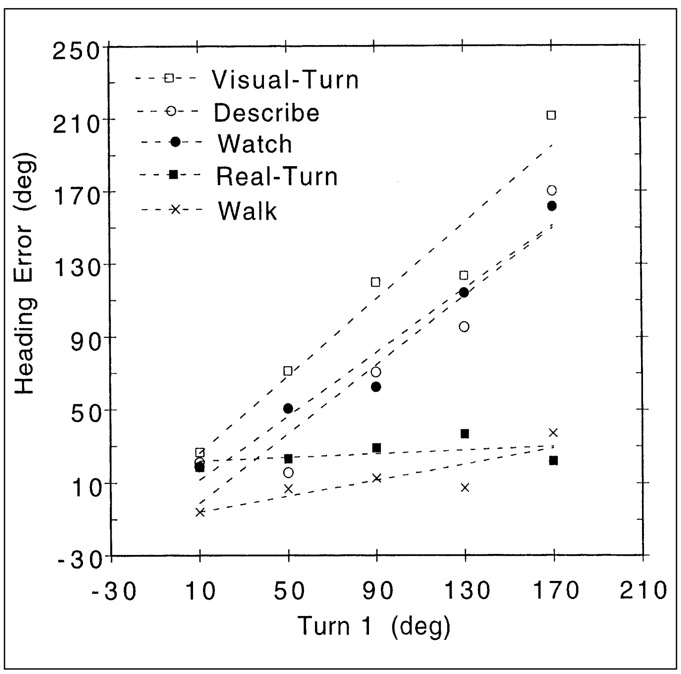

Fig. 2. Mean heading error as a function of Turn 1 for each condition in the main experiment, with linear functions fit to the data.

These results indicate that without a physical turn, subjects failed to update their perceived heading. It might be argued that the subjects failed to understand the instructions; however, it was clearly stated that the subjects should adopt the perspective of the traveler. Moreover, a "failure to understand" should not be taken as simply a matter of semantics; it directly reflects the failure to update heading. Our colleagues often say, after making the typical error, "I can't believe I did that."

SUPPLEMENTARY MANIPULATION

In the first five conditions, subjects had sight of the room before beginning the experimental trials. Possibly, those who remained stationary during the path presentation maintained a memory-based, viewpoint-specific representation of their true self-position relative to the room, which interfered with their ability to adopt an imagined perspective from within the path (May, 1996; Presson, 1987). May (1996) found that subjects who were disoriented, by being turned back and forth, before taking part in an imaginal updating task performed better than those who were not disoriented (although worse than subjects

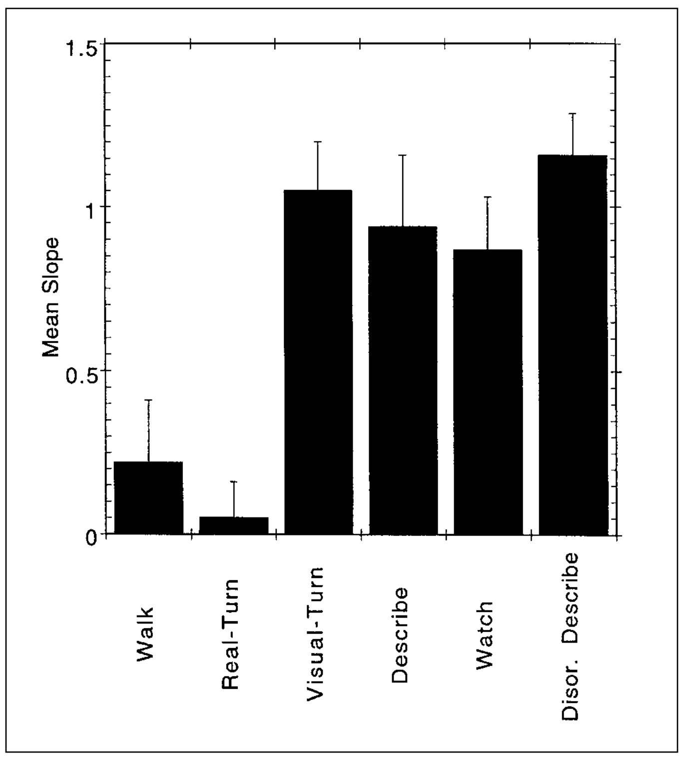

Fig. 3. Mean slope and standard error of the mean for each group in the main experiment (left five bars) and the supplementary, disoriented describe group (right-most bar).

who updated by physically moving). He attributed the positive effect of disorientation to the reduction of interference from viewpoint-specific memory. Accordingly, we disoriented subjects and repeated the describe condition; this should have facilitated correct responding if memory for the room made it difficult to update perceived heading during nonphysical travel in the main experiment.

Ten university students took part in a modified describe condition. To disorient them before they began the five trials, the experimenter turned them back and forth for a total of 10 direction changes, with the angular movement varying between approximately 30° and 200°.

Figure 4 shows the resulting heading errors in relation to Turn 1 value, derived as in the main experiment. The slope of the least squares function was near 1.0 (i.e., 1.2) and differed significantly from zero, $t(9) = 8.72$, $p < .01$. It did not differ significantly from the slope of the initial describe condition. Thus, the failure to update perceived heading appears not to reflect interference from viewpoint-specific memory for the original room.[1]

GENERAL DISCUSSION

The data indicate that when proprioceptive cues to change in heading are lacking, people fail to update the heading representation that governs the response turn. We have proposed that the operative representation is at a perceptual level, and that people may represent changes of location without updating perceived heading. (It is possible that subjects also have an imagined heading that is updated but does not govern their response.) Optic flow without proprioception, at least for the limited field of view of our virtual-display system, appears not to be effective for the updating of heading (see also Chance et al., in press; Chance & Loomis, 1997). Constructing a representation of the pathway layout appears, in contrast, not to require proprioceptive cues to the change in heading. The systematic tendency to overturn in the amount of Turn 1 indicates that from imagined, watched, or simulated movement, people can form a representation of a triangular path of travel, which allows bearings between points on the pathway to be computed.

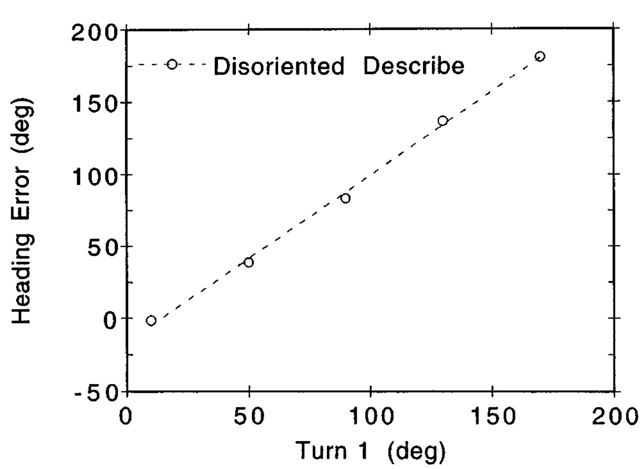

Fig. 4. Mean heading error as a function of Turn 1 for the disoriented describe group, with a linear function fit to the data.

The failure of subjects to update heading in three of the conditions of our experiment is a novel result. Other studies (e.g., Easton & Sholl, 1995; Farrell & Robertson, 1998; May, 1996; Presson & Montello, 1994; Rieser, 1989) have shown that although physical rotations of the body result in much faster and more accurate responses than do imagined rotations, subjects nevertheless do respond in accordance with imagined heading changes. The slowing of responses and increased error have been taken to suggest that imagined rotation involves a more cognitive process than the automatic, obligatory process invoked by physical rotation. Because the imagined rotations occur in isolation in studies patterned after Rieser's (1989) task (i.e., there is no translation on the rotation trials), subjects know that updating of heading is required and presumably attempt to invoke the requisite cognitive process (although young children may fail even to understand that updating of heading is required—see Rieser, Garing, & Young, 1994). In the current study, in contrast, the translations along the legs produced a change in the bearing of the origin, whether or not the subjects represented the heading change invoked by the turn. Because the change in bearing by itself required rotation at the response location, subjects who did not physically rotate during the outbound path may have failed to notice that heading had to be updated as well. That is, they may have felt they were complying with task demands by responding to the bearing change and hence failed to invoke the cognitive process needed to update heading.

It is possible that given sufficient time and experience with the present task, subjects would come to form a cognitive representation that could guide their turn responses. Indeed, our instructions specified rapid responding, and we used few trials, in order to preclude such cognitively based responses and assess the subjects' perceived spatial orientation. It is a representation of heading at this perceptual level that appears not to be updated in the absence of physical rotation.

1. We also conducted disoriented versions of the virtual-environment conditions. The results departed from the previous pattern in three respects: (a) Best fitting linear functions accounted for somewhat less variance than was found previously. (b) Although the slope for the visual-turn subjects was greater than zero (0.39), as before, it was significantly less than the corresponding slope in the main experiment (1.05). (c) The slope for the real-turn condition (0.44) was marginally greater than the corresponding slope in the main experiment (0.05). Thus, the visual-turn group was facilitated by the disorientation, and the real-turn group was somewhat impaired. Further work is needed to determine the reason for these results, but it is possible that updating from a real turn benefited from memory for the context of the room (see Rieser, Frymire, & Berry, 1997), whereas the same context interfered with forming a representation from optical flow alone.

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