Research Article

Use of Cognitive Versus Perceptual Heading During Imagined Locomotion Depends on the Response Mode

Marios N. Avraamides,[1] Roberta L. Klatzky,[2] Jack M. Loomis,[1] and Reginald G. Golledge[3]

[1]Department of Psychology, University of California at Santa Barbara; [2]Department of Psychology, Carnegie Mellon University; and [3]Department of Geography, University of California at Santa Barbara

ABSTRACT—*Three experiments investigated whether the systematic errors previously observed in a triangle-completion task were caused by failures to form and update a cognitive heading or by use of perceived heading (even though an updated cognitive heading was available) during the response. These errors were replicated when participants indicated the origin of triangular paths they had imagined walking by turning their bodies toward the origin, but not when they responded verbally. The results indicate that participants are capable of updating their cognitive heading using imagined movements and suggest that the systematic errors previously observed were a result of the strong attachment of responses such as turns to a perceptual representation of the physical body.*

Navigation relies on updating one's position and orientation with respect to the environment. The central nervous system makes use of many sources of information in performing spatial updating. For example, perceptual information about the position of landmarks in the immediate environment can be used to "fix" one's position (e.g., by triangulation). When landmarks are absent, navigation can be carried out by means of path integration (Loomis, Klatzky, Golledge, & Philbeck, 1999). In this case, information about one's translations and turns are used to determine heading and distance from the origin of travel; this information can be external (e.g., optic flow) or body based (e.g., proprioception).

The abundance of information available for spatial updating suggests that given corresponding sensory capabilities, navigators should have considerable capability to update their position and orientation while moving in space even without vision. Indeed, empirical findings suggest that this is the case (e.g., Loomis et al., 1999; Philbeck, Loomis, & Beall, 1997; Rieser, Guth, & Hill, 1986; Simons & Wang, 1998). For example, Philbeck et al. (1997) asked participants to walk with eyes closed to previously seen targets using direct or indirect paths that were specified after vision was occluded. Participants could perform the task very accurately regardless of the path taken, suggesting that they were able to update their position on the basis of information available from self-directed movement. Similarly, Rieser et al. (1986) had participants learn a layout of objects from one standpoint and then point to them, while blindfolded, from that standpoint or a novel one. Pointing latency did not differ between the standpoints, suggesting that participants were able to update the layout while moving (blindfolded) to the novel position.

Although successful updating occurs with physical movements, imagined movements typically lead to impaired performance, indicating failure to update equivalently (e.g., Farrell & Robertson, 1998; Presson & Montello, 1994; Rieser, 1989; but see Wraga, in press). For example, in a study by Rieser (1989), which paralleled that of Rieser et al. (1986) but with rotations, performance was slower for imagined rotations than for physical rotations, and response latencies increased as a function of the angular deviation of the target from the participant's physical facing direction. A possible explanation is that imagined movements lack any correlation with vestibular signals or afferent and efferent proprioception. As many researchers have posited (e.g., Rieser, 1989), without direct sensory cues, spatial updating requires effortful cognitive processing.

In light of the evidence for impaired performance with imagined movements, Klatzky, Loomis, Beall, Chance, and Golledge (1998) argued for a distinction between two internal representations of heading: Perceived heading refers to what one experiences to be one's facing direction,[1] whereas cognitive heading is any heading that one

Address correspondence to Marios N. Avraamides, Department of Psychology, University of California, Santa Barbara, CA 93106-9660; e-mail: avraamides@psych.ucsb.edu.

[1]In most cases, perceived heading is the same as a person's physical heading. However, there are ways to dissociate the two (e.g., by using virtual reality) so that a person feels he or she is facing a direction that is different from his or her actual facing direction.

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can adopt through imagination, including a heading adopted for purposes of a task that requires reasoning from a perspective other than one's own. Whereas perceived heading is updated by perceptual processes during physical movement, updating cognitive heading is believed to require effortful cognitive processing.

Klatzky et al. (1998) used a triangle-completion task to examine the updating of perceived heading under conditions of physical movement and imagined movement induced in various ways. On each trial, participants experienced a path consisting of two outbound legs (Leg 1 and Leg 2) and an intervening turn (Turn 1). At the end of the outbound path, participants were asked to produce, while standing, the turn that someone who walked the path would make in order to face the path's origin (Turn 2). This response measure was chosen because it makes use of the physical body, and was therefore believed to be governed by perceived heading. In a *describe* condition, blindfolded participants listened to descriptions specifying Legs 1 and 2 in meters and Turn 1 in degrees. In a *walk* condition, blindfolded participants were guided over the outbound path by the experimenter. In a *watch* condition, participants watched an experimenter walk the outbound path. Two additional conditions involved experiencing simulated movements (specified by optic flow in a virtual environment), accompanied by either real or simulated turns (*real-turn* and *visual-turn* conditions, respectively). Results revealed that only when real rotations were performed (i.e., walk and real-turn conditions) did participants perform Turn 2 accurately. In the remaining conditions, participants systematically overturned by the value of Turn 1. For example, if Turn 1 was 90° and the correct Turn 2 was 135°, participants tended to turn 225° instead.

Figure 1 demonstrates the task. Suppose a participant in the describe condition is standing at the origin with a perceived heading aligned with Leg 1 (which we designate as 0°) and then imagines walking three steps forward, turning 90° to the right, and walking another two steps. If the participant forms and updates a cognitive representation of heading, then after executing Turn 1, he or she should have a cognitive heading that differs in orientation from perceived heading by the value of Turn 1. In our example, cognitive heading is 90°.

To make a response, the participant needs to compute Turn 2, or the relative bearing, defined as follows:

$$\text{relative bearing} = \text{return bearing} - \text{current heading} \qquad (1)$$

(The return bearing and the current heading must be defined with respect to a common reference direction—in our example, aligned with Leg 1.) The return bearing is the direction of home from the end of Leg 2. The participant should have two current headings available, cognitive heading and perceived heading. In our example, the return bearing is 214°, and the current heading the participant is supposed to use in the computation is cognitive heading, or 90°; hence, the correct Turn 2 is 124°. The participant, however, incorrectly executes a turn of 214°, which is greater than the correct response by the value of Turn 1.

The tendency to overrespond by the value of Turn 1 indicates that Equation 1, using cognitive heading for the current heading, is not applied. If the cognitive heading has been formed, updated, and used in the computation, the error should not be observed. We consider two hypotheses that might account for the error pattern. First, there might be only one heading available, perceived heading, which must be used to compute the relative bearing and make the response turn. (A

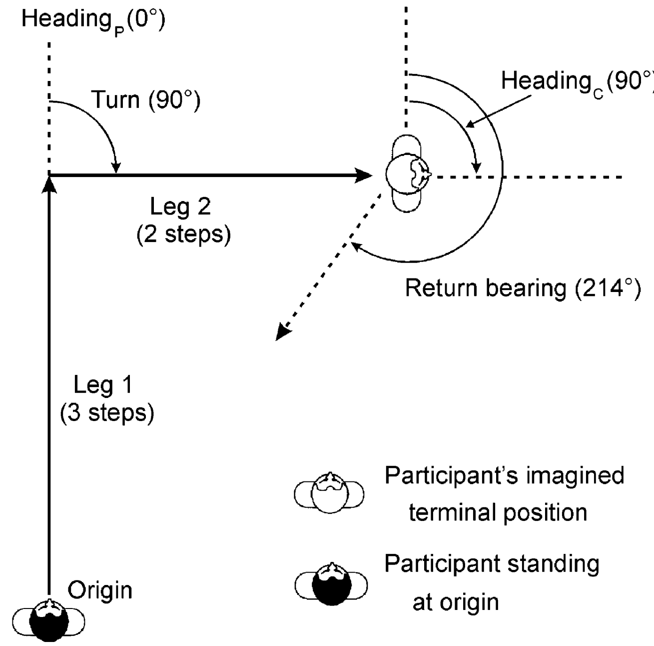

Fig. 1. Schematic representation of an example path. The participant is standing at the origin with a perceived heading (Heading$_P$) aligned with Leg 1 (designated as 0°) and then imagines walking three steps forward, turning 90° to the right, and walking another two steps. The task is to turn to face the direction in which the origin would be. Participants typically do not account for cognitive heading (Heading$_C$) in calculating their response, and consequently overshoot the correct response of a right turn of 124°.

computationally equivalent idea is that there is a second heading, cognitive heading, but it is updated only if the perceptual heading changes.) This hypothesis would predict the observed errors, but it is problematic given the evidence that people can—with cognitive effort—adopt a cognitive heading different from their physical one. A second hypothesis is that although participants have a cognitive heading and update it when experiencing the outbound path, they fail to take it into account when computing Turn 2. In terms of Equation 1, participants subtract the value of perceived heading, instead of that of cognitive heading, from the return bearing. We suspected that the body-referred nature of the response mode in the study by Klatzky et al. (1998) could have induced such an error.

Recent evidence (Wraga, in press) indicates that body-referred responses, particularly manual pointing, are difficult to use from imagined perspectives. The coupling of the response mode in Klatzky et al. (1998) with the physical body could have induced participants to use perceived heading to compute Turn 2. In order to assess this possibility, in the present study we repeated two conditions of Klatzky et al. (1998) while using a response measure that we believe relies less strongly on perceived heading. Specifically, we had participants respond verbally, by indicating the direction of Turn 2 and its extent in degrees, after performing the task as in the watch and describe conditions of Klatzky et al. It appears that spatial language (i.e., verbal report) can be used more flexibly from imagined perspectives than body-referred responses can be because it is not bound to the physical body (De Vega & Rodrigo, 2001; Wraga, in press; see also Avraamides, in press). In everyday life, people often use spatial language from perspectives other than their own (e.g., when giving directions to others).

If the systematic errors reported by Klatzky et al. (1998) were induced by the motor response, and do not reflect the lack of an updated cognitive heading, then no such errors would be expected with verbal responses. In contrast, if the errors were due to participants' failure to form and develop a cognitive heading, then systematic errors would be present with both body turns and verbal responses.

MAIN EXPERIMENT

The experiment involved watch and describe conditions, both of which were shown by Klatzky et al. (1998) to produce systematic overturns. In both exposure conditions, if people made the previously observed systematic errors only with the body responses, this would indicate that they were able to successfully update their cognitive heading during the imagined movements, and that they used that heading to compute the response turn with verbal responses but not body turns.

Method

Participants

Sixteen students (3 female) from introductory psychology classes at the University of California, Santa Barbara, participated in exchange for course credit. Eight participants were randomly assigned to each of the conditions. Response mode (body turns vs. verbal responses) was manipulated within participants.

Procedure

Participants in the describe condition stood blindfolded at the origin of the path (called *home*) and listened to an experimenter describe the values of Leg 1, Turn 1, and Leg 2, in that order. Unlike Klatzky et al. (1998), who described paths using meters, we specified them in walking steps. For example, participants listened to descriptions such as "You move three steps forward, you turn left 45°, and you walk another two steps." (As scale does not affect the turn errors, variations in individuals' steps are not of consequence.) The experimenter paused for a few seconds after describing each segment of the path, to allow participants time to perform the imagined movement. When responding with body turns, participants were asked to make the turn they would have made if they had actually walked the path and wanted to face home. When responding verbally, they were asked to indicate the direction (left or right) and the number of degrees they would have to turn in order to face home. Participants in the watch condition performed the same task except that instead of hearing verbal description of the paths, they watched an experimenter walk them.

Each participant performed six trials with body-turn responses and six with verbal responses, in that order. Six angles, presented in a random order for each response-mode condition of each participant, were used for Turn 1: −135°, −90°, −45°, 45°, 90°, and 135° (minus signs indicate turns to the left). Values of two, three, and four steps were randomly sampled for each leg of a path with the only constraint being that the same path did not appear in the two response-mode conditions.

Before the experiment proper, participants had training in estimating angles in degrees. They stood in the middle of the room facing a randomly determined direction not aligned with a wall. Then, for each of six objects located around them, they verbally estimated the object's angle relative to their facing direction by specifying the nearer direction (left or right) and degrees (0–180). After each verbal response, participants pointed to the object with a pointer superimposed on a protractor and looked at the value on the protractor to obtain feedback regarding the verbal estimate. This procedure was repeated until participants had estimated the relative directions of the six objects from three different facing orientations. Never during this training phase did participants estimate angles from imagined headings. Next, participants performed three filler tasks intended to prevent the previous training from priming a verbal strategy throughout the experiment, even when the body-turn response was called for. For the same reason, the body-turn responses always preceded the verbal responses in the experiment proper.[2] The three filler tasks consisted of estimating egocentric and exocentric (i.e., interobject) distances, and executing blind turns toward objects in the room.

Results and Discussion

The dependent measure of primary interest was signed heading error, defined as the angular difference between the correct response (i.e., the heading that the participant should have assumed or reported) and the actual response made. Separate repeated measures analyses of variance (ANOVAs) were performed for body-turn and verbal responses using Turn 1 and exposure condition (watch vs. describe) as factors.

Body Turns

To measure body-turn responses, we computed the extent of Turn 2 as the angular difference between pre- and postturn readings from a KVH (Middletown, Rhode Island) Azimuth 100 digital compass that was mounted with a belt on the back of the participants. Participants did not necessarily turn in the direction that would result in the shorter turn, but by observing the participant's direction of turn during each trial we determined which of the two possible turns was attempted. A 2 × 2 chi-square analysis on the direction of Turn 2 revealed the participants' preference for turning toward their right, $\chi^2(1, N = 96) = 4.38$, $p < .5$.

Given the results of Klatzky et al. (1998), we expected that participants would overshoot the correct responses by the value of Turn 1. Indeed, responses were very close to the predicted values, which allowed us to assign signs to errors without ambiguity by using the overshoot value (e.g., +60° rather than −300°).

Signed heading error did not differ as a function of the direction of Turn 1. Therefore, data from left and right Turn 1 values of equal magnitudes were pooled for subsequent analyses. Signed heading error, after averaging across the three Turn 1 values, did not differ significantly between the watch condition (86.9°) and the describe condition (93.7°). As expected, the amount of error was different for the three values of Turn 1, $F(2, 28) = 177.28$, $MSE = 141.26$, $p < .001$, $\eta^2 = .93$. The error pattern replicated the systematic errors observed by Klatzky et al. (1998): Participants' responses were greater than the correct ones by approximately the value of Turn 1; average signed errors for turns of 45°, 90°, and 135° were 49.19°, 93.72°, and 128.09°, respectively. This pattern did not differ between the two

[2] A pilot experiment without the three filler training tasks revealed that participants' performance of the body-turn task was verbally mediated. That is, they first calculated the turn in degrees and then executed the corresponding Turn 2. As indicated by postexperimental interviews, none of the participants used this strategy when the filler tasks were included.

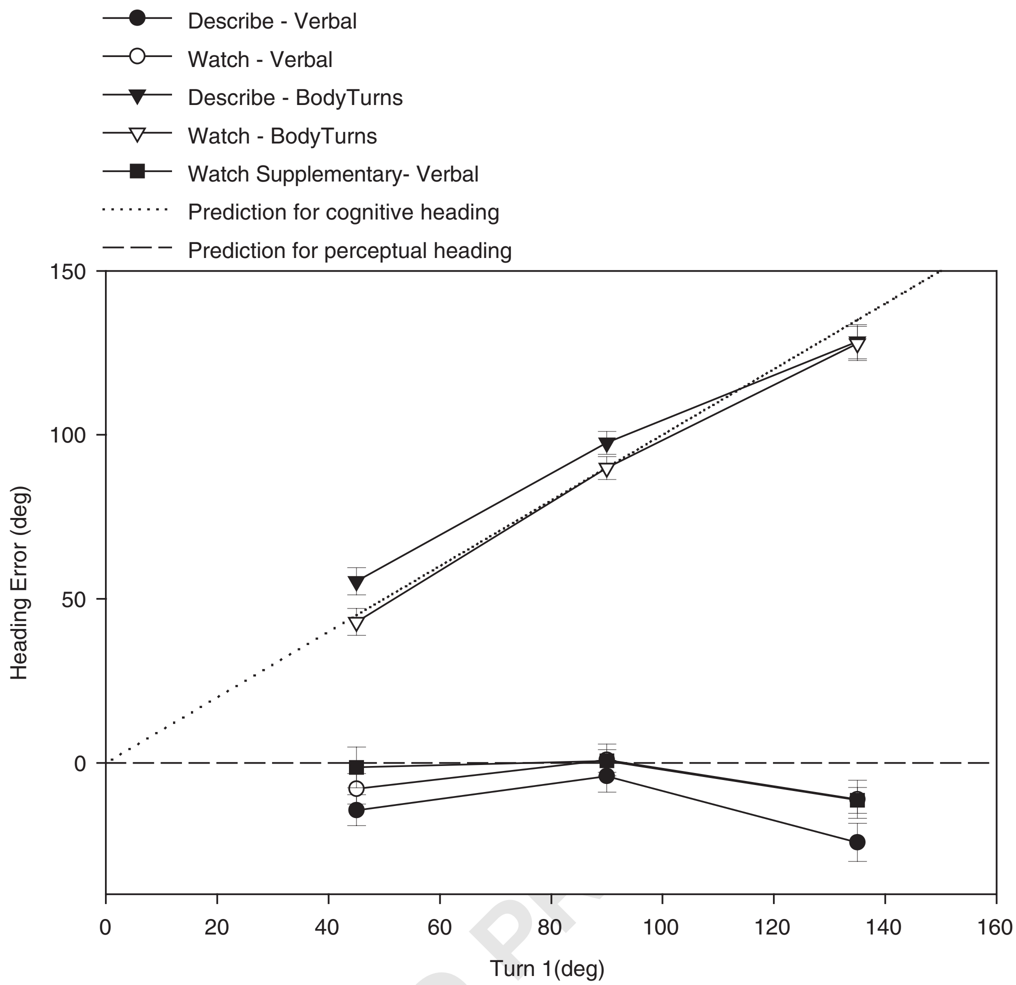

Fig. 2. Mean signed heading error as a function of Turn 1 in the main experiment and Supplementary Experiment 1. Error bars represent standard errors of the means.

conditions, as evidenced by a nonsignificant Turn 1 × Exposure Condition interaction (Fig. 2).

Verbal Responses

Verbal responses were limited to 0 to 180°, and participants were asked to indicate the direction of the turn needed to face the origin. The direction of turns can provide an indication of whether participants responded on the basis of an updated cognitive heading. That is, if participants updated their cognitive heading during Turn 1, then Turn 2 responses would be expected to be in the same direction as Turn 1 (e.g., both left). The opposite would be expected if cognitive heading was not updated. An analysis of turn directions revealed that every response matched the direction of Turn 1. This provided a first indication that participants had successfully updated their cognitive heading. A more definitive answer, however, was expected from the analysis of signed heading errors.

Overall signed error was again smaller in the watch than in the describe condition (–6.0° and –14.2°, respectively), but again, the difference fell short of being significant. As shown in Figure 2, the pattern of heading errors was substantially different from that observed with body-turns both in the present experiment and in the study by Klatzky et al. (1998). First, heading errors were extremely small compared with those computed for body turns. Second, the errors were negative; that is, participants tended to underestimate the extent of the correct Turn 2. Most important, mean signed heading error did not increase as a function of Turn 1. Average signed heading error was smallest (–1.53°) when Turn 1 was 90°, intermediate (–11.13°) when Turn 1 was 45°, and greatest (–17.63°) when Turn 1 was 135°, $F(2, 28) = 6.22$, $MSE = 168.60$, $p < .01$, $\eta^2 = .31$. Pair-wise *t* tests revealed that the differences between 90° and 45° and between 90° and 135° were statistically significant, $t(15) = -2.52$, $p < .05$, and $t(15) = 2.93$, $p < .01$, respectively. No significant Turn 1 × Exposure Condition interaction was obtained.

In summary, the very accurate performance of our participants when using verbal responses suggests that they had successfully updated their cognitive heading and had used it when computing their responses. It seems, then, that the systematic errors reported by Klatzky et al. (1998) and obtained in the body-turn responses in the present experiment do not occur when responses are verbal.

SUPPLEMENTARY EXPERIMENT 1

In the main experiment, participants always performed the body-turn responses before the verbal responses; this order was intended to avoid inducing a bias toward verbal mediation. To assess whether the accurate verbal-response performance depended on prior experience with body turns, we conducted an additional experiment with 4 participants (3 female) performing the watch condition with verbal responses only. Training was the same as in the main experiment. As shown in Figure 2, the pattern of signed heading error replicated that observed in the watch condition of the main experiment, indicating that performance with verbal responses in the main experiment did not depend on the preceding body-turn task.

SUPPLEMENTARY EXPERIMENT 2

The results from Klatzky et al. (1998) and our main experiment show that people systematically fail to incorporate an imagined turn into body-turn responses in our task. In contrast, in other studies with similar motoric pointing responses (e.g., Shelton & McNamara, 1997), responses from imagined new perspectives have generally been responsive to instructed changes in heading, although less accurate than responses from physically changed perspectives. However, the tasks used in these other studies had an implicit demand that responses vary systematically with an imagined change in bearing of the target object. An important feature of our task is that translation along one leg and then another is sufficient, by itself, to cause a systematic change in the bearing of the origin, even if the subject's heading is unchanged. Subjects therefore can comply with the implicit demand to vary their response turns without invoking cognitive heading.

If this reasoning is correct, subjects in our task should use cognitive heading even during body-turn responses if the change in bearing to the origin is entirely due to an imagined heading change (rather than translation). We asked 8 new participants to perform the body-turn task after watching the experimenter walk single-leg paths (e.g., move three steps forward and turn 90° to the left). A single-leg translation does not change the bearing to the origin. Each participant performed two trials with single-leg paths, one with a 90° and one with a 45° turn. We predicted that no systematic errors would be observed in these single-leg trials—participants would use cognitive heading because using perceived heading would lead to an invariant response turn of 180°. Furthermore, we expected that performing single-leg trials would prime participants to use cognitive heading in any subsequent task as well. We tested this possibility after participants completed the two single-leg trials by asking them to perform two trials with regular two-leg paths. All task instructions were identical to those of the main experiment and were given prior to the experiment; there was no reference to the two types of paths.

Results for the single-leg trials were as expected. Participants showed no systematic errors; average signed errors were −3.62° and −0.38° for the 45° and 90° turns, respectively. Surprisingly, performing the single-leg trials correctly did not lead our participants to use cognitive heading in the subsequent two-leg paths. The pattern of errors replicated previous results; average signed errors with two-leg paths were 49.63° and 93.25° for the 45° and 90° turns, respectively. Perhaps completing more single-leg trials would induce participants to perform two-leg trials correctly.

These results show that the systematic errors produced with body turns are not due to difficulty comprehending the instructions. With the same instructions, participants performed the single-leg trials correctly. The results further suggest that the observed systematic errors should not be expected with simple imagined movements, when use of perceptual heading will lead to an obviously invalid response. An example of such a task is pure imagined rotation; subjects who persisted in using perceptual heading would exhibit a complete failure to update.

GENERAL DISCUSSION

Replicating the results of Klatzky et al. (1998), the data from the body-turn responses show that people systematically overshot the correct turns. However, when participants made verbal responses, they were highly accurate. The accuracy of verbal responses indicates that participants were successful at updating their cognitive heading. The discrepancy between the two kinds of responses indicates, however, that cognitive heading was not always used in computing the turn toward the origin. Instead, the error pattern indicates that perceived heading was used for the computation of body-turn responses.

We propose that the apparent inability to separate perceived heading from body turns arises from the coupling between perceptual representations and motor responses. Wraga (in press) has suggested that the strong attachment of a manual pointing response to the body creates reference-frame conflicts at the output level when imagined reorientation is induced. These conflicts impair performance or confuse participants as to how to execute the response. Such confusion was directly noted by Presson and Montello (1994) in their study using a pointing task with imagined transformations of the body. In contrast, people use verbal responses from imagined perspectives repeatedly in the course of their everyday lives. For this reason, language could be a more appropriate response mode than body-referred responses for examining the spatial updating of cognitive heading (unless the spatial terms are themselves body referred; e.g., Avraamides, in press; Avraamides & Carlson, 2003).

We have described the determination of the response turn as involving a computation of the difference between the current heading (cognitive or perceived) and the return bearing, that is, the direction of the origin from the response location. An issue that bears further discussion is how these parameters become available. One mechanism is directly perceptual, as in the current watch condition, in which the participant can see the experimenter trace out the path. From the observed trajectory, it is possible to determine the experimenter's final heading (i.e., the participant's cognitive heading) and the return bearing, relative to some reference axis such as the participant's facing direction. The similarity of the describe condition to the watch condition suggests that a similar process may function when a path of travel is imagined; for example, the relevant parameters could be "read out" of a spatial image.

We note that a number of highly interesting questions about updating during imagined travel cannot be answered from these data. We cannot, for example, specify whether the representation formed in the describe condition is a visuospatial image or more abstract. If it is visuospatial, we do not know the imagined perspective—be it a bird's-eye or a walker's-eye view. Nor do we know whether the relative bearing toward home is updated moment to moment, as the outbound path unfolds, or only after the path has been completed. We do not know whether the errors observed with body turns reflect the use of the wrong heading in computing the response turn, or whether the correct turn is computed but somehow overshadowed by the perceived heading when the response is executed. These and other questions await further study. An important implication of the present study is that the nature of the response—verbal or body mediated—is likely to qualify the answers that are obtained.

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