Journal of Experimental Psychology:
Learning, Memory, and Cognition
2000, Vol. 26, No. 1, 169–186

0278-7393/00/$5.00 DOI: 10.1037//0278-7393.26.1.169

Path Integration While Ignoring Irrelevant Movement

Mark May
Universität der Bundeswehr Hamburg

Roberta L. Klatzky
Carnegie Mellon University

Participants attempted to return to the origin of travel after following an outbound path by locomotion on foot (Experiments 1–3) or in a virtual visual environment (Experiment 4). Critical conditions interrupted the outbound path with verbal distraction or irrelevant, to-be-ignored movements. Irrelevant movement, real or virtual, had greater effects than verbal or cognitive distraction, indicating inability to ignore displacement during path integration. Effects of the irrelevant movement's direction (backward vs. rightward) and location (1st vs. 2nd leg of path) indicated that participants encoded a configural representation of the pathway and then cognitively compensated for the movement, producing errors directly related to the demands of compensation. An encoding-error model fit to the data indicated that backward movement produced downward rescaling, whereas movement that led to implied rotation (rightward on 2nd leg) produced distortions of shape and scale.

In the past decade, there has been increasing interest in the ability of people to perform path integration—updating their position in space on the basis of proprioceptive (kinesthetic, vestibular) input in the absence of visual input (see Loomis, Klatzky, Golledge, & Philbeck, 1999). When movement is actively controlled, efferent commands also may play a role. Path integration is so called because it requires the integration of velocity signals, the double integration of acceleration signals, or both to update spatial position after rotational and translational movements (straight-line positional changes without rotation). For example, an organism that begins at position (0,0) in Cartesian coordinates (centimeter scale) and walks along the x-axis at 5 cm/s for 10 s can integrate velocity over time to determine the new position to be (50,0). Path integration is contrasted with navigation by landmarks or with respect to azimuthal references like the sun (Gallistel, 1990; Maurer & Séguinot, 1995).

Following previous research described below, the present studies tested the hypothesis that path integration is an automatic process, by the criterion that any perceptually signaled movement is incorporated into the representation of current spatial location and orientation. We propose that if navigators are asked to ignore some of the movements they make, they cannot simply exclude them by volition; instead, they must perform a cognitive process that attempts to compensate for the movements and adjust the underlying representation. The compensatory process is not, however, error-free. Not only does it affect overall accuracy, but it can introduce systematic sources of error. Our studies tested specific hypotheses about the representation that results from movement, the processes that must be performed to compensate for to-be-ignored movement, and the effects of such compensation on the path representation.

Prior Research on Path Integration

In humans and animals, path integration performance has been assessed with tasks like returning to the origin of travel of a path, typically consisting of a small number of linear segments (legs) and turns. The ability of humans to perform this task is limited, but responses are generally well above chance (e.g., Beritoff, 1965; Juurmaa & Suonio, 1975; Klatzky et al., 1990; Loomis et al., 1993; Passini, Proulx, & Rainville, 1990; Worchel, 1951). Path integration also is required in tasks in which navigators sight or hear a location in space and then walk toward it without vision. Over a range of about 20 m, people have been found to be highly accurate at walking without vision to previously seen targets, either directly or along a two-legged path (Loomis, Da Silva, Fujita, & Fukusima, 1992). In this case, they must use path integration to determine how far they have walked or turned during the response. When initial perception of target location is made difficult, for example, by reducing visual cues or by using auditory targets, people make errors in traveling to the target without sight; however, they arrive at the same response location whether they walk directly or by an indirect path. This commonality of location errors following direct and indirect response trajectories suggests that the erroneous response reflects a misperception of the target location and not errors in response execution, such as updating position in the absence of vision (Loomis, Klatzky, Philbeck, & Golledge, 1998; Philbeck & Loomis, 1997).

Studies of path integration assess people's ability to keep track of their position in space as they move, without optical flow or sight of landmarks. Another body of research deals

---

This research was supported by a grant from the Deutsche Forschungsgemeinschaft (ma-1515-2/1).

We gratefully acknowledge the assistance of Fredrik Wartenberg with data collection and programming of virtual environment experiments. We also thank Evelina Dineva, Birsen Kahraman, and Katja Werheid for their help with data collection and Tim Hubbard for very helpful comments on this article and the research issues.

Correspondence concerning this article should be addressed to Mark May, Institut für Kognitionsforschung, Universität der Bundeswehr Hamburg, Postfach, D-22039 Hamburg, Germany or to Roberta L. Klatzky, Department of Psychology, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213. Electronic mail may be sent to mark.may@unibw-hamburg.de or to klatzky@cmu.edu.

with the ability to keep track of position relative to a reference frame or landmarks during imagined movements through space. In contrast to the level of accuracy achieved with real movement, updating by imagination alone appears to be a slower and error-prone process. This has been attributed to a difference between the underlying processes that are used for path integration during real and imagined movement. Positional updating that occurs on the basis of perceptual inputs has been characterized as rapid and automatic, whereas imaginal updating has been suggested to require cognitive, attention-demanding processing (Klatzky, Loomis, Beall, Chance, & Golledge, 1998; May, in press; Rieser, 1989; Rieser, Guth, & Hill, 1986; Sholl & Nolin, 1997).

Other studies have tested the idea that path integration from perceptual inputs occurs automatically by assessing the ability to ignore physical movements. If physical (cf. imaginal) translations and rotations are automatically encoded at a perceptual level, ignoring the movements would require a process of cognitive adjustment. Farrell and Robertson (1998) found that participants who physically rotated without vision were able to update their orientation with respect to a learned set of landmarks (thus replicating Rieser, 1989), as indicated by rapid responses that were minimally affected by rotation angle. But participants who were asked to ignore the rotation in making their responses showed slower responses and a strong effect of rotation angle on response time. Farrell and Thomson (1998) examined the ability of participants to ignore a translational displacement to a second vantage point, from which they were to walk to objects seen from the first vantage point. Constant and variable errors were higher in the ignore condition than in the control conditions of do not ignore and no translation, again indicating that the movement could not be ignored.

Overview of the Present Research

The present article extends research on the ability to ignore movements during path integration. We were particularly interested in navigation without prior sight or sound of landmarks, which when present appear to facilitate updating of position during nonvisual locomotion (Loomis et al., 1992; Rieser, Frymire, & Berry, 1997). The methodology of our studies used the return-to-origin task, in which participants walked along an outbound path and then attempted to return to the origin of travel. Irrelevant verbalization along the path was used to prevent counting footsteps, which could provide a purely cognitive (cf. perceptual) basis for responding. In various conditions, the outbound path was interrupted with one of four types of distractor tasks: additional verbalizing (the control), counting backward, making a to-be-ignored movement that was directed backward along the path of travel, or making a to-be-ignored movement that was orthogonal (rightward) to the local direction of travel, without rotating the body.

Our overarching hypothesis was that participants construct a representation of the outbound path on the basis of proprioceptive cues and that this representation is always affected by movements, even when they are to be ignored. To comply with task demands and to "ignore" the irrelevant movements, the navigator cannot simply tune them out during performance but rather must cognitively compensate for them. Specific hypotheses then concerned the nature of the representation that is corrected and the effects of different types of to-be-ignored movement. Quantitative measures permitted us to assess not only how well the movements can be ignored but also whether and how the act of cognitively compensating for to-be-ignored movement introduces systematic sources of error.

More specifically, the novel contributions of this research are (a) the comparison of motoric distraction, in the form of irrelevant movements, with purely cognitive distraction, in the form of backward counting, to demonstrate that the nature of the to-be-ignored activity is critical; (b) testing the hypothesis that irrelevant movements are incorporated into a configural representation of the outbound path trajectory, rather than a "homing vector" that conveys only current distance and orientation relative to the origin; (c) evaluating whether a to-be-ignored rotation is difficult to compensate for, even when it is implicit (i.e., the participant does not physically rotate); and (d) quantitative modeling of effects on the representation of the outbound path that are attributable to the act of compensating for irrelevant movement. In addition, the studies included a visual virtual-reality task, which allowed us to evaluate the effects of irrelevant movement when path integration is performed on the basis of visual cues with exclusion of correlated vestibular cues. The subsequent sections of the introduction review prior work relevant to these issues and explain their importance.

Spatial and Nonspatial Distraction

An initial question asked in this research was whether the inability to ignore irrelevant movement during path integration reflects a process that is specific to spatial activity or whether it constitutes a general decrement due to cognitive distraction. To address this question, we compared simple verbalizing (the control condition), counting backward (which should introduce a cognitive load), and making a translational movement (real or virtual) along or orthogonal to the path. The hypothesis that all perceptually signaled movement is automatically incorporated into path integration predicts that, relative to the control, irrelevant movement should be more disruptive to performance than the counting task. Figure 1 illustrates what would be expected if participants were asked to duplicate the length of an outbound path after a pause with verbalization or an irrelevant movement backward (left and center panels, respectively). If participants cannot ignore the irrelevant movement backward during the outbound journey, they should shorten the return path accordingly; no such effect was expected in the counting condition, which served as an additional control. An effect of rightward movement (right panel of Figure 1) may or may not occur, depending on how easily people can adjust for displacement that is orthogonal to a simple path.

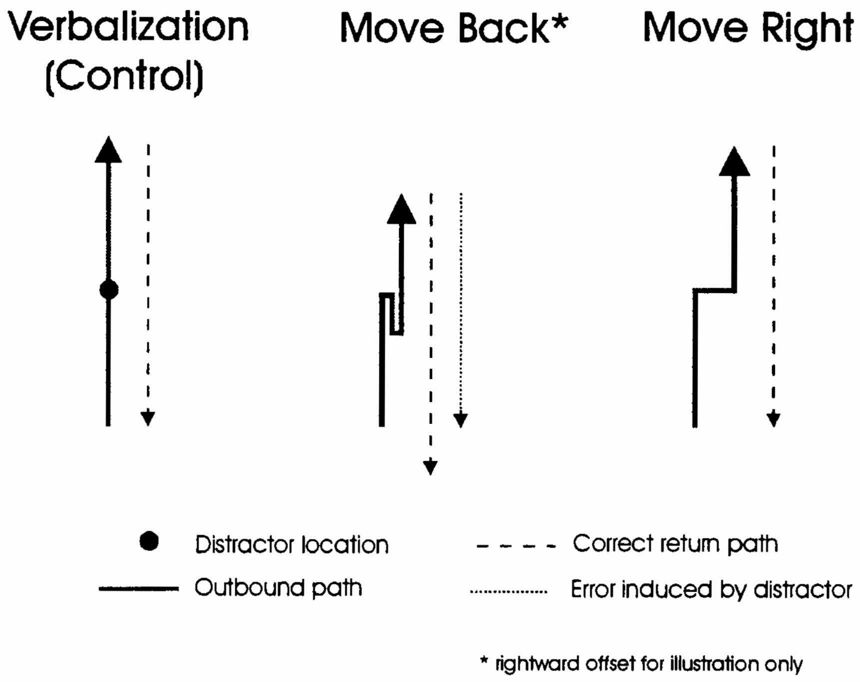

Figure 1. Simple (one-segment) return tasks with different distractor conditions.

Configural Coding Versus Maintaining a Homing Vector

One way in which irrelevant movements could affect performance on a return-to-origin task is for the resulting spatial displacements to be incorporated into a representation of the outbound trajectory, necessitating compensatory processing to correct the representation and comply with demands to ignore the movements. In previous research, two hypothesized types of representations have been contrasted: (a) a configural representation that retains geometric characteristics of the outbound path and (b) a history-free representation, consisting of a homing vector that indicates only the turn and distance required to reach the origin (see Fujita, Loomis, Klatzky, & Golledge, 1990). Evidence against a history-free representation (Loomis et al., 1993) includes the demonstrated ability of navigators to retrace a path on demand as well as complete it and the finding that the time required to initiate the completion leg (e.g., the third leg of a triangle) depends on the history of leg lengths and turns.

The present studies allowed a further test of the configural and history-free hypotheses by comparing backward and rightward movements on the second leg of a two-legged path. Figure 2 illustrates these conditions. Two terms that are important in understanding Figure 2 are *heading* and *bearing*. The heading of an object is its direction of orientation in space, relative to a reference direction. The bearing from one object to another is the direction of a line connecting them, relative to a reference direction (not shown in Figure 2). Figure 2 shows that relative to the verbalization control, in which no movement occurs, both movements introduce a change in the bearing of the physical origin from the participant's location at the end of the outbound path. If there were no instructions to ignore the movement on the second leg, the required turn would be equal to the angular difference between the person's final heading and the bearing of the origin. This turn is one of the parameters of the homing vector. If the change in bearing of the origin, due to the distractor movement, has automatically been incorporated into the homing vector, instructions to ignore the movement mean that the participant must adjust the turn parameter to compensate. A reasonable assumption is that errors in this process increase with the magnitude of the adjustment. The stimuli were designed, however, so that the change in turn induced by the irrelevant movement was the same for backward and rightward movements. Thus, there is no reason to expect a difference in error between the two conditions if the homing-vector hypothesis is correct.

The story is different, however, according to the configural hypothesis, because backward and rightward translational movements have qualitatively different effects on the configural representation of the outbound path. As shown in Figure 2, a rightward deviation from the second leg induces a change in the bearing from the end of the first leg to the stopping point at the end of the second leg, whereas backward movement along the second leg leaves the corresponding bearing unchanged. In effect, the rightward deviation changes the magnitude of the first turn in the outbound two-legged configuration, requiring an implicit rotation to compensate for the movement. Below, we argue in detail that the implicit rotation required by the rightward movement makes it more difficult to "ignore" (i.e., cognitively compensate for) than the backward movement. According to the configural-coding hypothesis, then, there should be a difference in error between the two conditions.

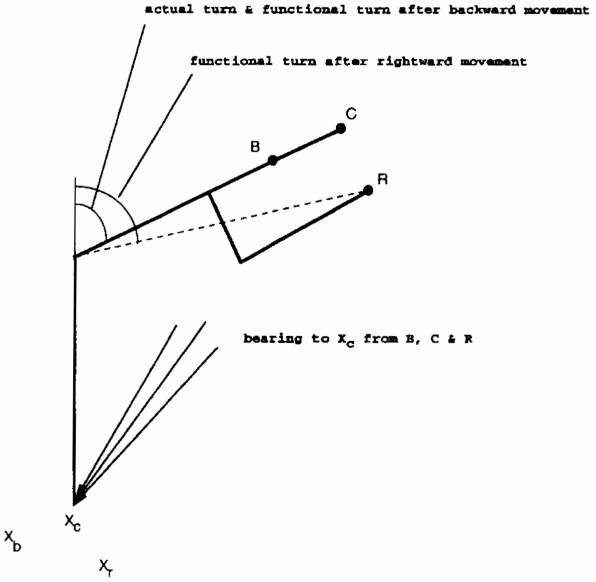

Figure 2. Effects of irrelevant movement on Leg 2. Bold lines indicate physical paths of travel in the control (C), moving-backward (B), and moving-rightward (R) conditions. C, B, and R are the respective ends of the outbound path, and X_c (true origin), X_b, and X_r are the corresponding correct-response endpoints in these conditions, respectively. Backward and rightward movements change the bearing to X_c (shown without the reference axis) from the end of the outbound path by equal amounts, but only rightward movement changes the functional value of the outbound turn.

Ignoring Rotation Versus Translation

If navigators cannot simply ignore irrelevant movements and must cognitively compensate for them, there is reason to believe that compensating for a to-be-ignored change in the magnitude of the turn in the outbound configuration should be particularly difficult. Changing the angle of the turn through imagination demands a mental rotation, and the process of rotation has been particularly implicated as cognitively difficult in imagined navigation tasks. In a seminal series of studies, Rieser (1989) contrasted rotation with translation. Participants in his experiment first learned about the disposition of objects relative to an initial position and orientation and then were asked to point to the objects after either an imagined rotation (without translation) or an imagined translation (without rotation). Translation was relatively easy, but pointing times and errors increased with the magnitude of the required angular change during rotation. Subsequently, these findings have been extended (e.g., Presson & Montello, 1994) and augmented. May (1996) showed that participants who were disengaged from a frame of reference anchored in the room, by being turned back and forth before responding, could point faster and made smaller errors than participants under normal imagining conditions but still showed decrements in performance indicative of additional cognitive processing. Easton and Sholl (1995) found that translation was made more difficult with irregular object arrays but that the response times and errors in the translation condition remained substantially less than those in the rotation condition, again indicating the cognitive demands of imagined rotation.

Another indication of the difficulty of imagined rotation is that people may fail to make changes in heading that they are instructed to imagine. Klatzky et al. (1998) found that when participants watched another person walk or imagined themselves walking along a two-legged pathway with a turn in it, they abstracted the shape of the walked pathway but did not incorporate into the representation the fact that the walker's body had rotated at the turning point. As a result, when asked to make the turn that would result in the walker facing back toward the origin, they turned the amount that a person still facing in the direction of the first outbound leg would have to turn. This resulted in an overturn error, the magnitude of which was equal to the magnitude of the turn between legs in the outbound path.

The comparison of rightward and backward movements on the second leg of a two-legged path, as shown in Figure 2, was used here to test whether it would be more difficult to ignore irrelevant movements when compensating for those movements required an imagined rotation, as occurs with the rightward movement. As we noted earlier, this would be consistent with the assumption of configural encoding. Comparison of the same movements on the first leg of the path, where neither introduced a demand for rotation, served as a further control. A methodological innovation here was that the movements that led to a need for compensation by imagined rotation were actually translational movements that involved no physical rotation. Thus, the required rotation induced by the rightward movement on the second leg was not signaled by an explicit turn. Even in the case in which the demand for rotation was implicit, we predicted that the condition that introduced rotational demands would lead to greater error than conditions that did not.

Quantitative Modeling of Effects of To-Be-Ignored Movement

One approach to quantifying the present results was to determine the extent to which participants' errors were predicted by their inability to ignore the irrelevant movement. An "ignorability index" was constructed to measure the match between the observed stopping point and the stopping point that would be expected on the basis of an inability to ignore. This measure corrected for other sources of error, as measured by the verbalization control.

To quantify further the effects of irrelevant movement and to describe the underlying processing, the present data were fit to the encoding-error model of Fujita, Klatzky, Loomis, and Golledge (1993). This model assumes that participants perform path completion through multiple processes: The first set of processes, collectively called "encoding," senses the pathway and builds an internal representation of leg lengths and turns. Subsequent processes use the representation to compute the trajectory to the origin and execute it. According to the model, all systematic errors can be accounted for by the first set of processes, or encoding. Fitting the model requires estimating the encoding functions, which convert objective stimulus values of leg length and turns into internalized representations of these stimulus values. The observed errors in both turn and distance are then accounted for with the derived encoding functions, providing a single mechanism to explain both types of errors. The model has proved to be useful in understanding path completion during movements of the whole body (Fujita et al., 1993; Klatzky, Beall, Loomis, Golledge, & Philbeck, 1999), in virtual visual navigation (Péruch, May, & Wartenberg, 1997; Wartenberg, May, & Péruch, 1998), and with haptically perceived paths (Klatzky, 1999).

Applying the encoding-error model to the data leads to a specification of how irrelevant movements affect the internal representation of the path (assuming a configural representation is maintained and not just a homing vector). Because separate parameters are estimated for the internalized equivalents of leg lengths and turns, the model allows for discrimination between two potential types of effects of to-be-ignored movement. One effect is an internal rescaling that adjusts the size of the path and not its shape. In this case, the model should show misencoding of the lengths of legs but accurate encoding of turns. Note that because a common encoding function is fit to all legs in the path configuration, the model assumes that irrelevant movement on one leg affects the encoding of the others. A second effect corresponds to changing the internalized shape of the outbound configuration. In this case, turns are misencoded, which seems particularly likely when rotation is needed to compensate for an irrelevant movement.

Extension to Virtual Environments

A final study in this article extended the task of ignoring irrelevant movements to a virtual visual environment, in which progress along a path was signaled by optical flow. This study allowed us to determine whether movements are relatively easy to ignore if they are not signaled by vestibular cues. Most research on path integration emphasizes the importance of vestibular input to path integration mechanisms (Mittelstaedt & Mittelstaedt, 1982; Potegal, 1987). More recent work has indicated that path integration can be achieved to some degree on the basis of purely visual input, such as optical flow without landmark information (Cutting, 1996; Cutting, Vishton, Flückiger, Baumberger, & Gerndt, 1997). Using return-to-origin tasks in a virtual environment, Péruch et al. (1997) found that path integration based on optical flow alone exhibited severe systematic distortions in encoding of changes of heading (turns); encoding functions for distance were very similar to nonvisual navigation conditions. In a similar vein, Klatzky et al. (1998) found in one experiment that optical flow alone was not sufficient to induce a sense of change in heading but rather a physical turn was necessary; however, a second study in which participants were disoriented before experiencing the virtual environment yielded more ambiguous results. Thus far, it is unclear what mechanisms are essential to visually controlled navigation and whether the coding of spatial information in virtual visual environments is automatic in the absence of concurrent vestibular inputs. The present studies introduced virtual visual conditions to further explore the roles of visual and vestibular input in path integration.

Present Manipulations

Experiment 1 used a simple one-legged path to evaluate the effects of irrelevant movement on distance encoding. In Experiments 2 and 3, a more complex two-legged path was used. Experiment 2 examined the effects of movements along the second leg, which potentially introduce a compensatory rotation. Experiment 3 compared the effects of irrelevant movement on the first and second legs of a two-legged path. Finally, Experiment 4 replicated Experiment 1 with a virtual visual environment.

Experiment 1

Experiment 1 investigated how the different distractor tasks affected the accuracy of path completion for one-legged paths. Participants walked each path, either directly (with or without an additional cognitive task) or with an irrelevant movement, and then attempted to return to the origin as if the distractor had not occurred. This experiment allowed us to compare the effects of irrelevant movement with purely cognitive interruption and to evaluate the difference between backward and rightward irrelevant movement in a simple configuration. As noted above, rightward movement may be relatively easy to ignore when it is orthogonal to a single linear segment.

Method

The participants' task on each trial was to return to a starting point after having walked away from that point for a given distance (9, 12, 15, or 18 m; called the "requested distance," to differentiate it from the actual distance to the physical starting point, which could be changed under distractor conditions). The response thus constituted a locomotor distance estimate. The outbound pathway was interrupted at a random point for 6 s, during which participants had to perform one of four different tasks: continued verbalizing, counting backward in threes, moving rightward, or moving backward.

Participants. Seventeen participants (11 women and 6 men) with ages ranging from 23 to 44 years (M = 29.9 years, SD = 5.0 years) took part for a payment of DM 20 (US $12).

Materials and apparatus. The experiment took place on a sand-covered soccer field (120 m × 80 m). Colored tape marks on a plastic line indicated the different distances. To measure distance estimates, a measuring tape was placed parallel to the walking track. Participants' sight was occluded by black-taped swimming goggles that touched the surface of the skin around the complete perimeter of both eyes, preventing central as well as peripheral vision. Hearing was attenuated by having participants wear a pair of headphones, eliminating background noise but allowing participants to understand loudly spoken commands (see key words below) from short distances (<1 m). Participants held a stick (30 cm long and 4 cm thick) at one end, and the experimenter led them by holding the other end and walking.

Procedure. All experiments were conducted by two experimenters: one taking responsibility for leading the participants and the other for indicating the experimental conditions and measuring and recording the responses. At the beginning of the experiment, participants were introduced to a number of standardized instructional key words (e.g., "start," "stop," "turn around") to be used by the first experimenter. The participants then took part in a small number of practice trials with unobstructed sight and hearing. Next, they were asked to put on the goggles and the headphones, and they performed another series of practice trials consisting of two trials with each distractor task at two different randomly chosen pathway lengths (one short and one long relative to the range of distances tested). Three blocks of trials followed, with a break between each block. Practice and experimental trials were performed in different locations on the soccer field (about 80 m apart), so that participants never directly saw the layout of the experimental pathway. Practice and experimental tracks had different headings and were rearranged for each participant; this procedure was used to avoid systematic influences of any external landmarks that could have helped participants to navigate under imaginal conditions (see Rieser et al., 1997).

Participants were told to use their normal walking speed (between 1.0 and 1.5 m/s) and were asked to keep their speed constant during and across trials. At the beginning of each trial, participants were led to the starting point by a circuitous route and oriented so that they were facing in the direction of the endpoint of the pathway. To prevent counting footsteps, participants were told to verbalize nonsense syllables ("aja-beja") during the entire outward movement (including the distractor interval); for the counting-backward condition, verbalization of nonsense syllables was replaced by verbalization of numbers. Given the key word "start" (German "los"), the experimenter and the participant started walking with a constant velocity. On the outbound path, the first experimenter enforced the verbal instructions (e.g., "start," "stop") by nonverbally indicating movement requirements with the help of the leading stick.

At a randomly chosen point for every pathway (graphically marked on a protocol sheet for the experimenter and at least 1 m from the starting point and endpoint of the path), the participant was told to stop (German key word "stopp") and then was given a key word for one of the distractor tasks. Distinguishable key words were used to indicate the different tasks: (a) verbalizing (key word: "weitersprechen")—the participant remained in place and continuously verbalized the nonsense syllables, (b) counting (key word was a seed number between 40 and 99)—the participant remained in place and counted backward in steps of three from the seed number given, (c) move rightward (key word: "rechts")—the participant remained facing forward and moved 2 m rightward by making shuffling foot movements, and (d) move backward (key word "zurück")—the participant remained facing forward and moved 2 m backward by making shuffling foot movements. The speed of the shuffling foot movements was chosen to allow for rightward or backward displacements of 2 m within the distractor interval of 6 s. The experimenter leading the participant controlled the size of the distractor movement by telling him or her to stop after 2 m (key word: "stop"). After 6 s, the distractor interval was ended by a command to continue with walking (German "weiter"), and the participant completed the remaining segment of the outward bound pathway. Distractor conditions are illustrated in Figure 1.

At the end of the outbound path, the experimenter instructed the participants to stop (German key word: "halt") and to make a full turn (180°), thus reversing direction relative to the start of the outbound path; if necessary, the turn was corrected to 180° (nonverbally with the help of the stick). The participants had to make the locomotor distance estimate, that is, had to walk a distance that would result in returning to the starting point had the distractor task not occurred. Participants were instructed to ignore any spatial changes resulting from movements during the distractor interval. They were informed that the experiment examined their ability to make accurate spatial judgments, and they were explicitly told that the physical endpoints of their locomotor estimations and the original starting points did not coincide under conditions of moving rightward or backward during the distractor interval.

During the response phase, the experimenter passively led the participants in a straight line to avoid veering tendencies (Guth & LaDuke, 1994). Participants were free to stop at any point along the homebound trajectory. The point at which they actually stopped constituted their locomotor distance estimate. While the participants stood in the final position, the second experimenter measured the locomotor estimation to the nearest 10-cm mark on the measuring tape. The participants were then led by a circuitous route to the starting point, where the next trial started. One experimental session lasted between 90 and 120 min.

Design. The experiment constituted a complete within-subject design, with four requested distances (9, 12, 15, or 18 m) crossed with four distractor tasks (verbalizing, counting backward, moving rightward, or moving backward), each replicated three times. Each participant took part in three blocks of trials, in each of which all combinations of distance and distractor conditions were presented once in random order. To prevent participants from generating hypotheses about the distribution of the pathway lengths tested in the experiment, 4 dummy trials (1 for each distractor condition), having a randomly chosen distance between 6 and 20 m, were interspersed in each experimental block, producing a total of 20 trials per block. The dummy trials were recorded but not evaluated. The dependent variable was constant error (CE; arithmetic mean over three repetitions, with positive values indicating overshooting) of the locomotor distance estimates.

Results and Discussion

In this and subsequent *Results* sections, we report two types of analyses: analyses of variance (ANOVAs) on the CEs for distance (all experiments) and turn (Experiments 2–3 only) and an analysis involving a derived measure of the extent to which irrelevant movement can be ignored. For all analyses, we used a significance level of .05 to indicate reliability of effects.

Constant error. The mean response distances are shown in Figure 3 by requested distance; deviation from the

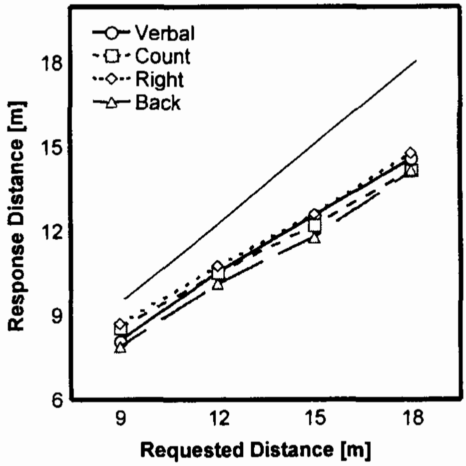

Figure 3. Observed walked distances for distractor conditions and requested distances in Experiment 1. Verbal = verbalizing; Count = counting backward; Right = moving rightward; Back = moving backward.

diagonal constitutes CE. The slopes of the linear functions relating response distance and requested distance were 0.72, 0.61, 0.67, and 0.68 in the verbalizing, counting, moving-backward, and moving-rightward conditions, respectively; all slopes were significantly less than 1.00. An ANOVA revealed significant main effects of requested distance, $F(3, 48) = 34.57$, $MSE = 9.70$, and distractor condition, $F(3, 48) = 3.46$, $MSE = 5.31$, on CE. The interaction was not significant, $F(9, 144) = 0.59$, $MSE = 3.55$. Figure 4 depicts the deviation of each distractor condition mean (averaged across requested distance) from a zero baseline defined by the verbalizing condition; the vertical bars mark the 95% confidence interval around the condition mean (i.e., these are the error bars when the various distances in Figure 3 were pooled). Only the moving-backward condition had a 95% confidence interval that did not include the mean for the verbalizing condition.[1]

Ignoring irrelevant movements. The downward arrow in Figure 4 indicates the CE that would have been expected if the participants had been completely unable to ignore the distractor. To quantify the extent to which the distractor movement was ignored, we used the following ignorability index (*I*; measured in percentage units):

$$I = \{1.0 - [(\text{Observed CE} - \text{Observed CE Verbalization})/\text{Predicted Error}]\} \times 100.$$

This formula measures the observed CE relative to the error that is predicted if participants did not ignore the distractor. It initially adjusts the observed CE by subtracting the error in the verbalization control. Thus, the index represents the additional error induced by the irrelevant movement as a percentage of the error expected by an inability to ignore the movement. The lower the score, the less the participants were able to ignore the distractor movement.

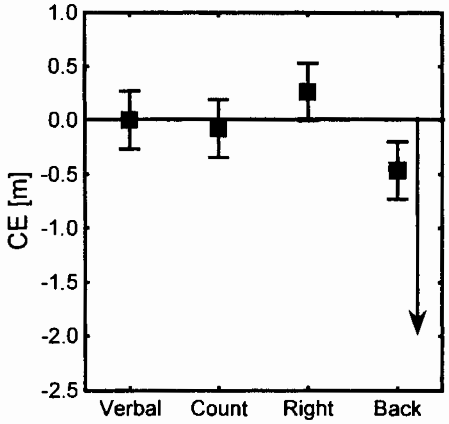

Figure 4. Effects of intermediate tasks in relation to the control condition (verbalization [verbal]) in Experiment 1. Error bars indicate 95% confidence intervals (see Loftus & Masson, 1994). The tip of the arrow shows the expected error, assuming that participants were unable to ignore the irrelevant movement. CE = constant error; Count = counting backward; Right = moving rightward; Back = moving backward.

Failure to ignore the distractor means that participants attempted to compensate for movements during that period and to return to the original starting point, rather than returning to an origin that was displaced in its physical location by virtue of the irrelevant movement. In the moving-backward condition, they would compensate by adjusting for the distance moved. For example, if the target path was 9 m long and a participant moved backward 2 m during the distractor period, failing to ignore the movement means a return on a leg of 7 m (reaching the initial location of the origin) rather than the requested distance of 9 m (2 m beyond the initial origin).

Table 1 reports the *I* values by condition for each experiment and classifies performance as to whether participants were able to ignore the irrelevant movement, according to the criterion that the 95% confidence interval around the mean *I* value included 100%. In the moving-backward condition, the confidence interval just reached 100%. Thus, it could be argued that participants were marginally able to ignore the movement during the distractor interval; however, lower *I* values in this condition in subsequent studies support the conclusion that they were unable to entirely ignore the movement. In the moving-rightward condition, the predicted error was zero because the irrelevant movement was orthogonal to the path and participants turned 180° at the response point (precluding error in the rightward direction). Thus, the index was not defined for this condition, but as expected, participants' moving-rightward error was not significantly different from their verbalizing error, making the numerator of the index equal to zero. We do not report ANOVAs on the ignorability index because the use of the CE from the verbalization control in calculating *I* precluded including the control in an ANOVA on *I* values. Given that *I* was not defined for the moving-rightward condition and was not of interest in the counting-backward condition, there were no conditions to compare in this experiment or Experiment 4. Comparisons between *I* values for moving-rightward and moving-backward conditions in Experiments 2 and 3 are given in terms of confidence intervals in Table 1.

Experiment 2

In Experiment 1, only in the moving-backward condition were participants unable (at least marginally) to ignore the movement taking place during the distractor interval. They behaved as if they could ignore a rightward movement that lay orthogonal to the path of travel, which suggests that decomposing such movements from the outbound trajectory imposes low computational load. To further investigate effects of distraction, Experiment 2 required participants to complete a triangle while ignoring irrelevant movements on the second leg. Thus, it examined the effect of rightward movements that were not orthogonal to the overall direction of travel (i.e., bearing from the origin). The distractor

---

[1] We used this test in preference to contrasts based on ANOVA because the contrast error term incorporates interactions involving conditions other than those being compared (see Keppel, 1973). Note also that, in most cases, formal contrasts gave the same results.

Table 1
Summary of Ignorability Index Across Experiments

Distractor location	Response measure	Experiment	Move rightward	Move backward
Leg 1	Turn	3	**95**	**83**
Leg 1	Distance	1, 3, 4	**(100), 97, (100)**	77, 48, 16
Leg 2	Turn	2, 3	8, 11	**112, 118**
Leg 2	Distance	2, 3	28, 42	24, 53

Note. Values in boldface (>80) have a 95% confidence interval including 100%, indicating ability to ignore; the value of 77 is marginal. Parentheses indicate that it was not possible to compute the ignorability index for move rightward in Experiments 1 and 4 because the predicted error was zero; in these cases, error was not significantly different from the control.

conditions were the same as those used in Experiment 1, including a verbal suppression control, counting backward, and irrelevant backward and rightward movements. If it is critical in compensating for a rightward movement that it be orthogonal to the overall direction of travel, the results of a moving-rightward condition on the second leg of a triangle should now show errors. Moreover, if the moving-rightward distractor induces a need to compensate through mental rotation, errors should be higher than in the moving-backward condition. This study also allowed a between-subjects comparison of the magnitude of ignorability in the moving-backward condition, relative to the one-segment pathways of Experiment 1; a within-subject comparison is provided in Experiment 3.

Method

Participants. Twelve participants (10 men and 2 women) with ages ranging from 21 to 42 years ($M = 28.2$ years, $SD = 6.4$ years) took part for a payment of DM 20 (US $12).

Stimuli. The participants' task on each trial was to return to a starting point (constituting a locomotor distance and turn estimate) after having walked the first two legs (Leg 1 and Leg 2) of a triangle with a turn of variable size in between. Triangles were isosceles with Leg 1 and Leg 2 length always equal to 8.0 m and angles between Leg 1 and Leg 2 of 60°, 90°, 120°, and 150°. (The turn made between Leg 1 and Leg 2 was the complement of the inner angle, so that the corresponding outbound turns were 120°, 90°, 60°, and 30°, respectively.) These configurations produced requested response angles (turns to the assumed starting point; i.e., complements of the inner angle at the response turning point) at the end of Leg 2 of 120°, 135°, 150°, and 165°, respectively. Distractor intervals were placed randomly along Leg 2. Four dummy trials with lengths of 8 m for Leg 1 and Leg 2 and outbound turns of randomly chosen values between 10° and 170° were interspersed in each experimental block (one for each distractor condition). These were intended to prevent participants from forming hypotheses about the distribution of outbound turns; data from the dummy trials were not analyzed.

Materials and apparatus. The experiment took place on the same field as that used in Experiment 1. The different triangular pathways were indicated by cardboard markers. Measurement was achieved by determining the polar coordinates of the endpoints of the participants' locomotor responses, using a tape for measuring distance and a fabricated measuring device indicating angle. These coordinates were the basis for calculating observed turn and distance responses. The rest of the technical equipment was the same as that used in Experiment 1.

Procedure. The experimental setting and the procedure, including the types of distractor, were generally the same as those used in Experiment 1 with some minor differences resulting from changes in the spatial task. Locomotor estimates were made by having participants first make an unguided turn in the direction of the assumed origin and then a passively guided forward walking movement that would reach the origin if any spatial changes resulting from the distractor movement were ignored. They were explicitly told that the correct endpoints of their homing attempt and the physical endpoints would not coincide under conditions of moving rightward or moving backward during the distractor interval but that their task was to ignore these discrepancies in making their locomotor estimates. Experimental sessions lasted between 90 and 120 min.

Design. The experiment constituted a complete within-subject design with four triangles, defined by the requested response turns (120°, 135°, 150°, or 165°), crossed with four distractor conditions (verbalizing, counting backward, moving rightward, or moving backward). Each of three 20-trial blocks consisted of 16 trials (4 turns × 4 distractor conditions) plus 4 dummy trials, in random order. Dependent variables were CE of the observed locomotor turn and distance estimates (arithmetic mean over three repetitions, with positive values of turn CE indicating overturning).

Results

Turn constant error. The turn and distance responses are shown in Figure 5; as before, deviation from the diagonal represents CE. The slopes of the functions for turn responses were 0.52, 0.43, 0.58, and 0.61 in the verbalizing, counting-backward, moving-backward, and moving-rightward conditions, respectively; all slopes were significantly less than 1.00. Figure 6 shows the mean CE made in each condition in relation to the baseline defined by verbalization error, along with the 95% confidence interval. Again, the arrows indicate the predicted CE if the participants could not ignore the distractor.

The observed CEs indicate that the requested response turn was generally overestimated but less so the larger the requested value. An ANOVA revealed significant main effects of turn angle, $F(3, 33) = 32.77$, $MSE = 373.51$, and distractor condition, $F(3, 33) = 17.12$, $MSE = 161.14$, on turn CE. The interaction was not significant, $F(9, 99) = 1.27$, $MSE = 213.63$. The mean for verbalizing was outside of the 95% confidence interval around the means of both counting backward and moving rightward.

Distance constant error. The slopes of the functions for distance responses were 0.27, 0.17, 0.22, and 0.13 in the verbalizing, counting-backward, moving-backward, and moving-rightward conditions, respectively; all slopes were significantly less than 1.00. The observed CEs reflect a tendency for distance responses to move from overestimation to increasing underestimation as requested distance increased, a regression to the mean that has been observed in other triangle-completion studies (Loomis et al., 1993). The ANOVA revealed significant main effects of requested

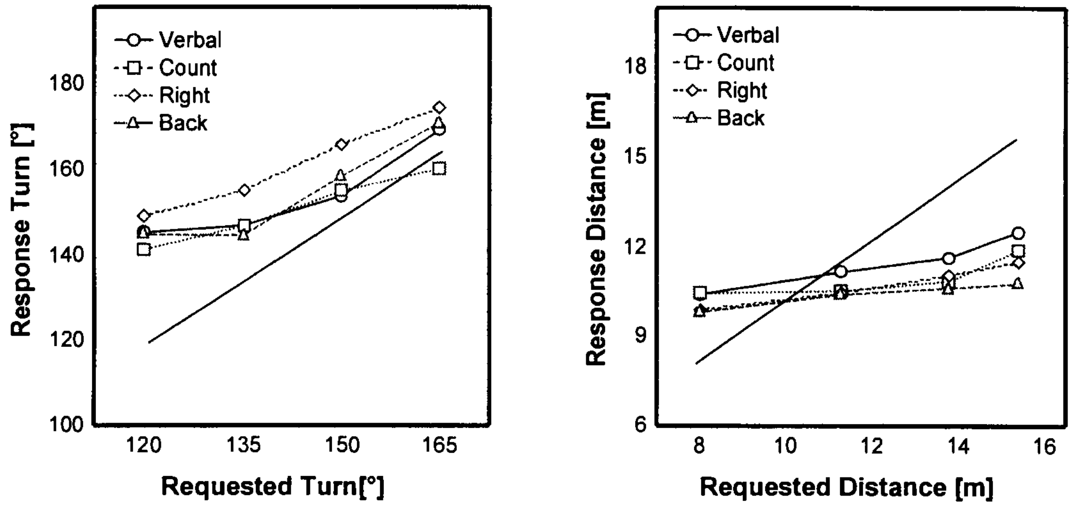

Figure 5. Observed turns (left panel) and distances (right panel) for distractor conditions and pathways in Experiment 2. Verbal = verbalizing; Count = counting backward; Right = moving rightward; Back = moving backward.

response turn, *F*(3, 33) = 101.49, *MSE* = 9.53, and distractor condition, *F*(3, 33) = 7.22, *MSE* = 3.83, on distance CE. The interaction was not significant, *F*(9, 99) = 1.01, *MSE* = 2.57. The 95% confidence intervals for counting backward, moving rightward, and moving backward all excluded the mean for verbalizing.

Ignoring irrelevant movements. The extent to which the CE matched what was predicted by inability to ignore the distractor movement (as shown by the arrows in Figure 6) was again indicated by the ignorability percentage, *I*, which was greater the more the distractor movement could be ignored. Only the moving-backward *I* value indicated an ability to ignore the movement. (The mean *I* in this condition slightly exceeded 100% because the error was actually less than the error in the verbalization control.)

Discussion

As expected, introducing rightward irrelevant movement on the second leg of the pathway induced a high level of error. In contrast to Experiment 1, in which rightward movement on Leg 1 was completely ignored, the same movement along Leg 2 in Experiment 2 essentially could not be ignored at all. This finding suggests that new computational complexity was introduced by the distractor location. Moreover, the higher error for moving rightward than

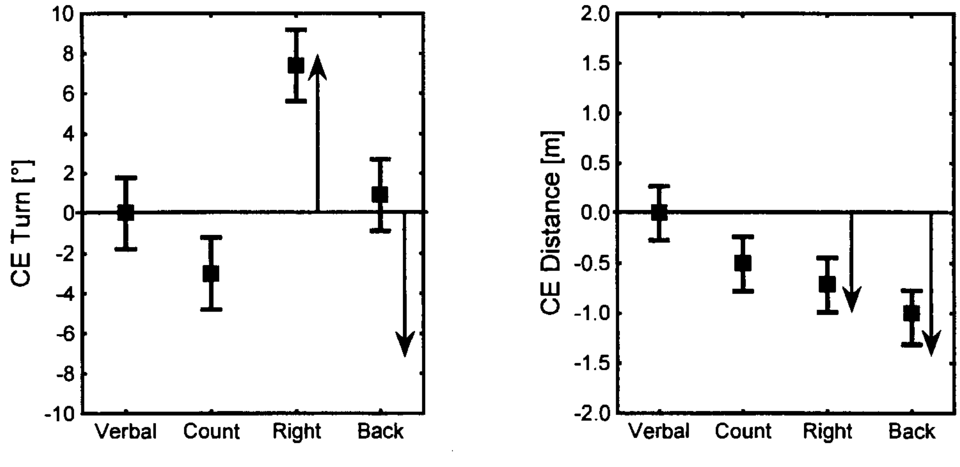

Figure 6. Effects of intermediate tasks in relation to the control condition (verbalization [verbal]) in Experiment 2. Error bars indicate 95% confidence intervals (see Loftus & Masson, 1994). The tips of the arrows show the expected errors, assuming that participants were unable to ignore the irrelevant movement. CE = constant error; Count = counting backward; Right = moving rightward; Back = moving backward.

moving backward suggests that participants represented their spatial position relative to the path configuration and did not just update a homing vector to the origin. As described above, the change in bearing introduced by the distractor, which would need to be monitored to correct the homing vector, was virtually identical for the moving-rightward and moving-backward conditions (8.0° and 7.2°, respectively). Thus, equivalent performance would be expected if error were proportional to the magnitude of the homing-vector correction. The observation of enhanced error after a move rightward is instead consistent with the assumption that participants must mentally rotate to compensate for a configural change. It appears that backward movement on Leg 2 led to lower ignorability than on Leg 1 (Experiment 1). Experiment 3 compared these conditions within participants.

Experiment 3

Because the distractor task in Experiment 2 was on the second leg of the path, the irrelevant rightward movement was no longer orthogonal to the overall path of travel. However, the greater error with positioning of the distractor on the second leg also might reflect greater complexity of the outbound pathway in Experiment 2 than in Experiment 1. To determine whether the greater error in Experiment 2 reflected the relative complexity of the pathway or whether the position of the distractor on the second leg was critical, Experiment 3 varied whether the distractor task occurred on the first or the second leg of a two-legged outbound pathway. This experiment also allowed a further test of the effects of a move-rightward distractor on Leg 1 because unlike Experiment 1, in which participants' turns were corrected by the experimenter, the turn toward the origin was free to vary and hence to incorporate error attributable to the distractor.

Method

Participants. Sixteen participants (13 men and 3 women) with ages ranging from 21 to 35 years ($M = 26.2$ years, $SD = 4.0$ years) took part for a payment of DM 20 (US $12).

Stimuli. As in Experiment 2, the participants' task on each trial was to return to the origin (locomotor distance and direction estimation) after having walked the first two legs of a triangle with a turn of variable size in between. Triangles were isosceles with Legs 1 and 2 equal to 8.0 m and angles between Leg 1 and Leg 2 equal to 60°, 100°, 140°, and 180° (in the last case, the two outbound legs formed a straight line), producing requested turn responses at the end of Leg 2 of 120°, 140°, 160°, and 180° (in the last case, participants were to reverse direction), respectively. In contrast to Experiment 2, distractors could be on Leg 1 or Leg 2. Distractor conditions were verbalizing, moving backward, and moving rightward. The stimuli produced approximately equal changes in bearing to the origin from the stopping point following a move rightward versus a move backward on Leg 2; the values were 7.9° and 5.9°, respectively. The counting-backward condition as well as the dummy trials were dropped to reduce the number of trials and the total duration of the experiment.

Materials and apparatus. The experiment took place on the same field as that used in Experiments 1 and 2. Marking of pathways and measurement of responses were the same as those used in Experiment 2. In the case of an angle of 180° between Leg 1 and Leg 2, the participants stopped between legs as they did in the other conditions, but there was no change in heading (i.e., 0° turn) before the command to continue.

Procedure. The experimental setting and the procedure were the same as those used in Experiment 2. Experimental sessions lasted between 100 and 130 min.

Design. The experiment constituted a complete within-subject design with four triangles, defined by the requested response turns (120°, 140°, 160°, or 180°), crossed with three distractor conditions (verbalizing, moving rightward or moving backward), and two distractor placements (Leg 1 vs. Leg 2), each repeated in random order within each of three consecutive blocks. Dependent variables were CE in turn and distance, defined as before.

Results

Turn constant error. Figure 7 shows the responses for turn and distance. The slopes of the functions relating response to requested value for turn responses were 0.57, 0.68, and 0.57 with distractors on Leg 1 and 0.71, 0.59, and 0.67 with distractors on Leg 2 in the verbalizing, moving-backward, and moving-rightward conditions, respectively; all slopes were significantly less than 1.00. Figure 8 shows the CEs relative to the verbalization control, as well as confidence intervals and predicted CE under the assumption of inability to ignore the distractor. The observed responses indicate turn angles to be generally overestimated, with overestimation becoming less pronounced the larger the requested turns. An ANOVA revealed significant main effects of requested turn angle, $F(3, 45) = 18.76$, $MSE = 1{,}712.87$, and distractor condition, $F(2, 30) = 5.48$, $MSE = 246.82$, on turn CE. The main effect of distractor placement (Leg 1 vs. Leg 2) was not significant, $F(1, 15) = 1.31$, $MSE = 269.18$. Neither the interaction between turn angle and distractor condition, $F(6, 90) = 0.48$, $MSE = 200.09$, nor the interaction between turn angle and distractor placement, $F(3, 45) = 1.96$, $MSE = 218.05$, was significant. The interaction between distractor placement and condition approached significance, $F(2, 30) = 2.84$, $MSE = 495.21$. The three-way interaction was not significant, $F(6, 90) = 1.82$, $MSE = 255.76$. The only mean with a confidence interval excluding the verbalization control was moving rightward on Leg 2.

Distance constant error. The slopes of the functions in Figure 7 for distance responses were 0.18, 0.15, and 0.24 for Leg 1 and 0.31, 0.19, and 0.23 for Leg 2 in the verbalizing, moving-backward, and moving-rightward conditions, respectively; all slopes were significantly less than 1.00. The distance responses reflect overestimation of the smaller requested distances and underestimation of the larger requested distances; however, the functions were not monotonic, in contrast to those in Experiments 1 and 2. An ANOVA revealed significant main effects of requested turn angle, $F(3, 45) = 101.08$, $MSE = 24.34$, and distractor condition, $F(2, 30) = 7.40$, $MSE = 7.52$. The main effect of distractor placement was not significant, $F(1, 15) = 1.01$, $MSE = 5.88$. None of the two-way interactions were

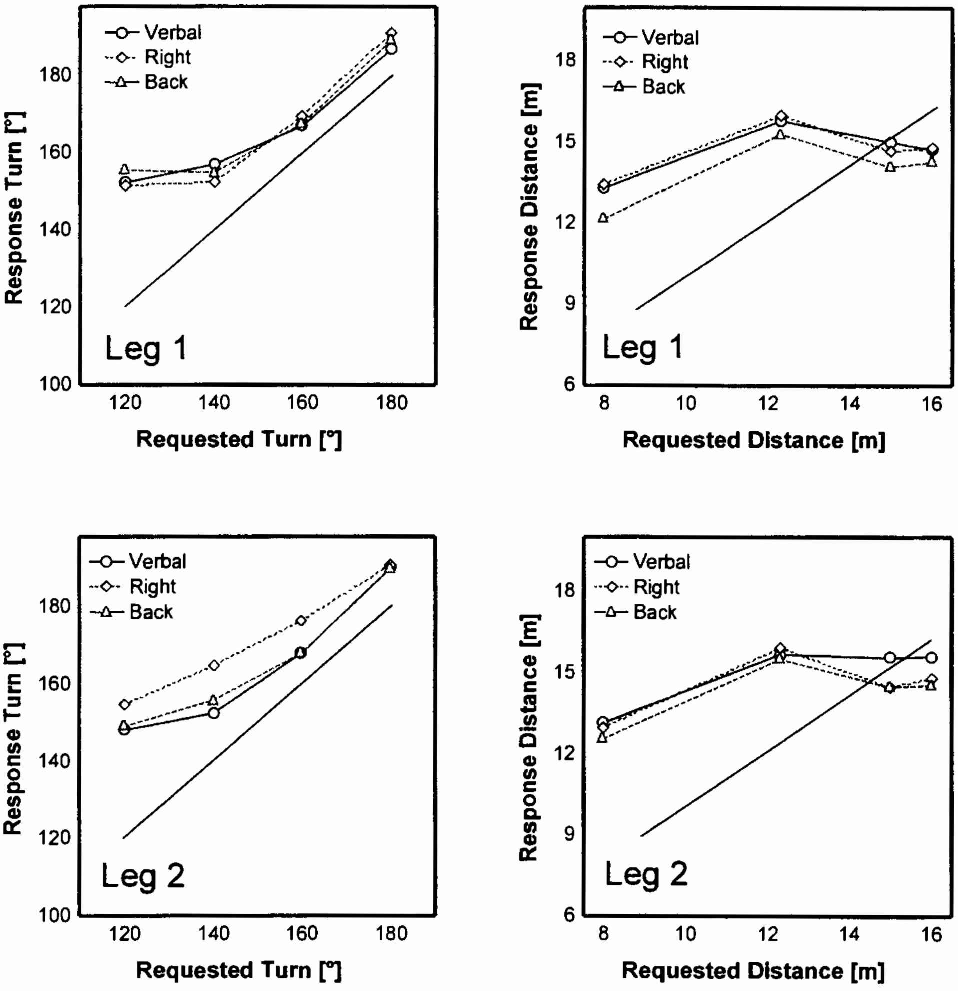

Figure 7. Observed turns (left panels) and distances (right panels) for distractor conditions, distractor placement, and pathways in Experiment 3. A requested turn of 180° and a requested distance of 16 m correspond to a 0° turn on the outbound path. Verbal = verbalizing; Right = moving rightward; Back = moving backward.

significant: turn angle by distractor condition, *F*(6, 90) = 1.00, *MSE* = 4.70; turn angle by distractor placement, *F*(3, 45) = 0.58, *MSE* = 5.31; and distractor placement by condition, *F*(2, 30) = 1.09, *MSE* = 7.07. The three-way interaction was not significant, *F*(6, 90) = 0.34, *MSE* = 5.89. Conditions whose confidence interval excluded the mean for the control were moving rightward on Leg 2 and moving backward on Leg 1 and Leg 2.

Ignoring irrelevant movements. Participants were able to ignore the rightward irrelevant movement on Leg 1. As in Experiment 1, the irrelevant backward movement on Leg 1 could be ignored when participants were making the turn, but the distance estimates were affected. As in Experiment 2, participants were unable to ignore the effects of the rightward irrelevant movement on Leg 2 with respect to both turn and distance. They could ignore the effect of the backward movement along Leg 2 on turn ($I > 100\%$, reflecting lower error in this condition than in the control condition) but not on distance.

Discussion

Comparison of the CEs in the irrelevant movement conditions with the verbalization control replicated the patterns observed in Experiments 1 and 2: When the distractor was on Leg 1, turn estimates showed no increased error due to irrelevant movement, whereas distance errors were increased by backward but not rightward movement. These distance effects are like those found in Experiment 1, in which the path was less complex (a single leg) and turn errors were prevented. When the distractor was on Leg 2, error increased relative to the verbalization control after both types of movement, but not equally for turn and distance responses. Specifically, rightward movement on Leg 2 affected both turn and distance error relative to verbalization, whereas backward movement affected only distance. This was the pattern found in Experiment 2, in which distractors occurred only on Leg 2. Given the stimulus parameters described above, the difference in turn error

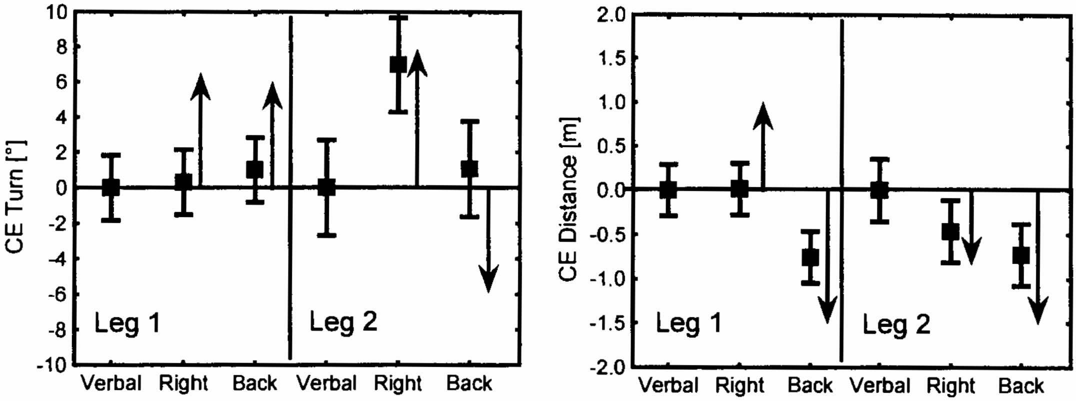

Figure 8. Effects of intermediate tasks in relation to the control condition (verbalization [verbal]) in Experiment 3. Error bars indicate 95% confidence intervals (see Loftus & Masson, 1994). The tips of the arrows show the expected errors, assuming that participants were unable to ignore the irrelevant movement. CE = constant error; Right = moving rightward; Back = moving backward.

following moving rightward and moving backward on Leg 2 is unlikely to reflect differential changes in bearing to the origin from the stopping point.

Fitting the Encoding-Error Model to Experiments 2–3

The data of Experiments 2 and 3 were next fit by the encoding-error model of Fujita et al. (1993), which assumes that the systematic error measured by CE can be attributed to processes that encode the values of leg lengths and turns in the stimulus. The model was fit under the following assumptions: (a) The turn between Leg 1 and Leg 2 is encoded by a linear function (which is the type of function that emerged when Fujita et al. [1993] estimated separate parameters for the encoded value corresponding to each value of turn in the experimental stimuli). (b) The leg length in the experimental stimuli also is encoded by a linear function, but because the value of leg length was constant here (always 8 m), the function is replaced by a constant. (c) The encoded values are used to compute the return distance and turn, without error in computation or execution of the computed value. Although the model computes the responses by means of trigonometry, Fujita et al. pointed out that it does not assume that something akin to trigonometry is performed by human processors.

Thus, for the purposes of the present data, the model fits three parameters: encoded length of each outbound leg and slope and intercept of a linear encoding function for the turn between the outbound legs. The data used to derive these parameters are the observed values of response distance and turn for each of four triangles. Note that with such a small ratio of observations to parameters, we used the model here to further develop an understanding of the data rather than to test its adequacy.

Table 2 presents the three parameters fit to the model by experiment and condition (as defined by distractor placement and type). Goodness of fit can be assessed by the correlation and slope relating predicted errors in turn and distance to observed errors, computed across stimuli and distractor conditions ($N = 12$ in Experiment 2 and $N = 24$ in Experiment 3). In Experiment 2, the correlation was greater than .99 for distance and .94 for turn, and the slope was 0.91 for both measures. In Experiment 3, the correlation was .95 for distance and .75 for turn, and the slope values were 0.85 and 0.72, respectively. Thus, fits were excellent in Experiment 2 and somewhat worse in Experiment 3, possibly reflecting the nonmonotonic trend in the distance responses. We discuss the implications of the model in the General Discussion section.

Experiment 4

In Experiments 1–3, participants physically moved within the spatial environment without vision. They therefore experienced proprioceptive feedback, including vestibular signals, but not optical flow patterns or sight of landmarks. The presence of vestibular information that is correlated

Table 2
Encoding-Error Model Parameters Derived for Each Experiment and Condition

Experiment and condition	Leg-length parameter (m)	Turn slope parameter	Turn intercept parameter (°)
Experiment 2			
Verbalizing	6.43	0.53	12.52
Leg 2, moving rightward	5.73	0.58	−6.32
Leg 2, moving backward	5.77	0.56	7.24
Experiment 3			
Leg 1, verbalizing	7.73	0.50	−0.04
Leg 1, moving rightward	7.61	0.53	0.10
Leg 1, moving backward	7.47	0.50	−0.03
Leg 2, verbalizing	8.02	0.58	0.02
Leg 2, moving rightward	7.48	0.39	0.04
Leg 2, moving backward	7.58	0.54	−0.05

Note. Actual leg lengths were 8 m; a turn slope of 1.00 and a turn intercept of 0° would constitute error-free encoding.

with locomotion may be critical to people's inability to ignore movement in a distractor interval. Experiment 4 was conducted to determine if failure to ignore the distractor would occur if pathways were explored in the absence of correlated locomotor proprioception. It replicated Experiment 1 within a virtual visual environment by examining how different intermediate tasks affected the accuracy of estimates of the distance along a one-legged path that was encoded by visual cues (along with proprioception from joystick control).

Method

Participants. Fifteen participants (5 women and 10 men; mean age = 25.3 years *SD* = 5.6 years) participated in the experiment for a payment of DM 20 (US $12). All participants had normal or corrected-to-normal vision.

Materials and apparatus. The experiment took place in a dimmed room. Participants sat on a chair in front of a table to which a joystick was attached. Two loudspeakers were placed on either side of the participants for providing auditory instructions.

Experimental control, rendering, reading of input, and storage of trajectory data were accomplished by a standard PC (Pentium 166 MHZ with an ATI Mach64 graphics card). The joystick was an advanced GRAVIS self-centering analog joystick providing 8-bit resolution for left–right and forward–backward movement. The joystick was read out through the game port. Auditory instructions were generated by playing digital sound samples via a 16-bit sound card and displayed by two standard loudspeakers. Computer graphics were displayed on a Cybermaxx head-mounted display with a resolution of 320(h) × 200(v) pixels for each eye. The field of view was 56°(h) × 35°(v). The same images were displayed for both eyes; the head-tracking function of the head-mounted display was disabled.

Generation and rendering of virtual environments was accomplished with Virtek 3D-Ware, a DOS-based graphics engine, and were displayed at 32 frames/s. Virtual environments consisted of thin vertical lines (representing trees) in three different colors (red, green, and blue), randomly placed on an unbounded black plane (the virtual forest). Assuming an observer's eye height of 1.6 m, the trees appeared to be 2 m high. Mean distance between trees in the virtual forest was 1 m; maximal distance was 2 m. About 20 to 40 trees were visible at a time; participants encountered between 80 and 160 trees while moving along the outbound and homebound pathways. A new random forest was generated for every trial. This virtual setting provided a considerable amount of spatial information (i.e., dynamically changing linear displays with size and density gradients of trees) without allowing the use of landmark-based navigation strategies (i.e., similarity of trees and changing spatial perspectives did not allow participants to recognize individual trees or clusters of trees).

Maximal translation speed was 1.5 m/s; maximum rotation speed was 30°/s. Participants could control the speed of translational and rotational movements by the amount the joystick was extended forward, leftward, or rightward, with the center position leading to no movement at all. As in the physical walking experiments, participants were allowed to choose a movement speed comfortable for them but were asked to keep the velocity constant during and across trials. Most participants preferred to use maximum speed for translational and rotational movements.

Procedure. The participants' task was essentially the same as that used in Experiment 1. They had to home to a starting point (locomotor distance estimation) after having moved away from that point for different virtual distances (9, 12, 15, or 18 m). The outbound path was interrupted at a random point for a distractor interval of 6 s, during which participants performed one of four different intermediate tasks (continued verbalizing, counting backward by threes, moving rightward, or moving backward).

After the task and the virtual environment were explained to the participants, the head-mounted display was adapted to the individual participants' head size and visual acuity. Participants were informed that wearing the head-mounted display might cause nausea and that they were free to interrupt the experiment at any time if they experienced it. Participants were asked to stay seated and not to move their heads during trials. Participants' heads were not fixed, so some movement may have occurred, but this movement should not be correlated with the optical flow indicating locomotion. Before starting on the experimental trials, participants completed 16 practice trials to get used to the tasks and the device. To allow participants to learn about the spatial requirements of the locomotor task, they were provided with numerical feedback about their performance on each practice trial (number of pixels of over- or undershooting). No feedback was given during the experimental trials.

When the participants were ready to begin a trial, they pushed a button on the joystick. Subsequently, the virtual environment was displayed as seen from the starting point of the pathway. After an acoustical instruction (German key word: "los"), the participants used the joystick to move along the outbound path. To keep conditions comparable with those used in Experiment 1, participants were instructed to verbalize the nonsense phrase "aja-beja" during the entire outbound journey. Movement direction was confined to forward, and speed varied with the degree of extension of the joystick.

At a random point along the outbound journey, the forward movement stopped, and an auditory instruction (German key word: "stopp") informed participants about the beginning of the distractor interval. In the upper left corner of the screen, a key word was displayed to indicate the different distractor tasks: (a) verbalizing (key word: "weitersprechen")—participants had to stay in position and continue to verbalize the nonsense syllables, (b) counting backward by threes from a seed number (key word was the seed number, ranging between 40 and 99), (c) moving rightward (key word: "rechts")—participants had to move 2 m to the right by pushing a button on the joystick, and (d) moving backward (key word: "zurück")—participants had to move backward for 2 m by pushing a button on the joystick. Distractor movements stopped automatically after a virtual displacement of 2 m. The use of the button as an input device for the rightward and backward displacements was chosen to make the distractor movement distinguishable from the other joystick-induced movements along the pathway (cf. shuffling foot movements vs. normal walking in Experiments 1–3). Movement speed for rightward and backward movement during the distractor interval was held constant at 0.33 m/s and was chosen to hold the time requirements for distractor movements comparable with those used in earlier experiments. Participants were explicitly told that they should ignore any spatial changes resulting from movements during the distractor interval. After 6 s, the intermediate task was terminated by an acoustical instruction to continue moving forward (key word: "weiter"), and participants completed the remaining part of the outward bound pathway.

At the endpoint, an auditory instruction (key word: "halt") indicated the end of the outbound path. At that point, participants had to accomplish a full turn (180° to the right) using the joystick; the rotation automatically stopped after 180° (similar to Experiment 1, in which participants were rotated 180° before the response). They then made the distance estimation by using the joystick to simulate moving forward the same distance as they believed they had translated along the outbound path, ignoring any irrelevant movements. Participants were free to stop at any point along the homebound trajectory by centering the joystick. They indicated the end of the trial by pushing a button on top of the joystick; the computer calculated and recorded their locomotor distance estimate on the basis of the resulting spatial position in the virtual environment. After a short pause, a new virtual forest was generated, and participants could start with the next trial. Three blocks of 20 trials were separated by a short break during which participants were allowed to take off the head-mounted display. One experimental session lasted about 100 min.

Design. The experiment constituted a complete within-subject design with four requested-distance conditions (9, 12, 15, or 18 m) crossed with four distractor conditions (verbalizing, counting backward, moving rightward, or moving backward). Each of the three 20-trial experimental blocks consisted of 16 trials (4 distances × 4 distractors) plus 4 dummy trials, selected as in Experiment 1, in random order. The dependent variable was the CE of the distance estimates.

Results

Constant error. Figure 9 shows distance responses; deviation from the diagonal constitutes CE. The slopes of the functions were 0.61, 0.57, 0.64, and 0.72 in the verbalizing, counting-backward, moving-backward, and moving-rightward conditions, respectively; all slopes differed significantly from 1.00. The overall CE was negligible ($M = -0.2$ m), but distances were overestimated for shorter paths and underestimated for longer paths. An ANOVA revealed significant main effects of distance, $F(3, 42) = 21.25$, $MSE = 16.83$, and distractor condition, $F(3, 42) = 3.09$, $MSE = 38.39$. The interaction was not significant, $F(9, 126) = 1.19$, $MSE = 6.30$. The means and confidence intervals in relation to the verbalization control are shown in Figure 10. Only the moving-backward condition had a confidence interval around the mean that did not include the verbalization mean.

Ignoring irrelevant movements. As shown in Figure 10, the irrelevant backward movement could not be ignored, as the significant deviation from the control defined by the verbalization condition shows. The ignorability index was only 16% (cf. 77% for the comparable condition in Experiment 1 involving movement of the whole body). The rightward movement, which was predicted not to induce error, did not differ significantly from the control, so that the numerator of the index would effectively be zero (the index itself was undefined for this condition).

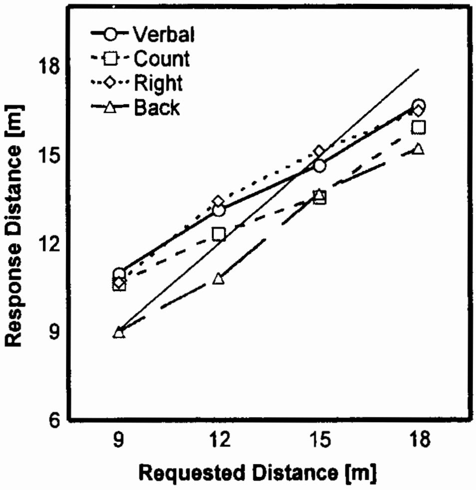

Figure 9. Observed distances for distractor conditions and requested distances in Experiment 4. Verbal = verbalizing; Count = counting backward; Right = moving rightward; Back = moving backward.

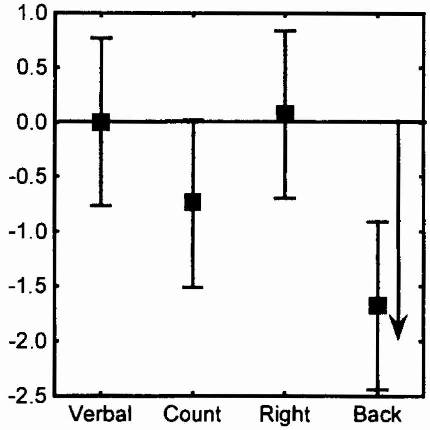

Figure 10. Effects of intermediate tasks in relation to the control condition (verbalization [verbal]) in Experiment 4. Error bars indicate 95% confidence intervals (see Loftus & Masson, 1994). The tip of the arrow shows the expected error, assuming that participants were unable to ignore the irrelevant movement. CE = constant error; Count = counting backward; Right = moving rightward; Back = moving backward.

Discussion

This experiment, using virtual locomotion, produced results similar to those in Experiment 1. In both studies, participants were unable to ignore backward movement during a one-legged path, whereas counting backward and moving rightward did not interfere. This finding suggests that the results of irrelevant movement do not rely on correlated vestibular signals.

An additional pair of experiments attempted to replicate Experiments 2 and 3, again using the virtual visual environment. However, extremely high constant and variable errors, as well as high between-subject variability, precluded interpretation of the data. Apparently, participants had great difficulty constructing an intact representation of these more complex paths from the virtual environment. This interpretation is at least in agreement with earlier experiments showing severe distortions of spatial representations when navigators have to encode changes of heading (turns) on the basis of optical flow alone (Klatzky et al., 1998; Péruch et al., 1997).

General Discussion

These four studies were intended to test the proposal that perceptually signaled movements are automatically incorporated into a configural representation of spatial position and that instructions to ignore some movements lead to a compensatory process that attempts to amend the representation but is subject to error. The present results support this proposal through a number of findings. Moreover, the present approach allowed us to model the nature of the errors introduced by the compensatory process and to investigate specifically the effects of imagined rotation on the underlying representation. The following sections of this article focus on the nature of compensation and its effects.

Implication of Control Conditions

Two control conditions were used in these experiments. One was a verbalization condition that did not introduce irrelevant movement. The second used a counting-backward distractor that should have increased cognitive load but should not have been specifically related to compensating for changes in spatial position. Counting backward produced errors that were equivalent to or only modestly greater than the verbalization control, whereas irrelevant movement—real or virtual—produced more substantial error. This finding indicates that movement had effects greater than could be attributed to cognitive load per se.

The overall pattern of CE observed in the verbalization condition should reflect basic sources of error introduced by path integration in this task, without the need to ignore irrelevant movement. This condition tended to show a general pattern of (a) overestimation of turn responses, less so the greater the turn magnitude, and (b) a transition from overestimating distance (or in Experiment 1, accurately estimating the lowest value) to increasingly underestimating it. Similar patterns of systematic errors have been found in earlier work on path integration without vision (e.g., Klatzky et al., 1999; Loomis et al., 1993). The effects of irrelevant movement, which are calculated relative to this basic pattern in the control condition, can then be taken as indications of the added processing induced by the demands to ignore movement distractors. We next deal with the added effects of those distractors.

Effects of Movement Distractors

Table 1 summarizes the results of the distractor effects on CE across experiments by giving the values of the ignorability index, *I*. Boldface values indicate conditions in which the index was not significantly different from 100% (generally in these cases, $I > 80\%$). In such cases, participants were essentially able to ignore the distractor. Table 1 reveals consistent outcomes across experiments. Rightward movement relative to Leg 1 was apparently easy to ignore (or compensate for), producing neither additional turn nor distance error relative to the control. Further distance error was induced, however, by rightward movement on Leg 2 and by backward movement on either leg. The magnitude of these distance errors was not systematically affected by either distractor placement (Leg 1 vs. Leg 2) or type of irrelevant movement on Leg 2 (rightward vs. backward). Whereas distance error was found in several conditions, turn error was induced only by a rightward movement on Leg 2; the effects of other distractor movements on response turns could apparently be ignored. The virtual visual environment produced the same pattern of error due to a distractor on Leg 1 as the whole-body locomotor environment.

Differences between the effects of rightward and backward movement on Leg 2 support the assumption that responses are based on a configural representation of the path and not just a homing vector indicating the desired response components. The rationale for this argument was given in the introduction and is not repeated here. Although the ignorability index indicates when effects of distraction could or could not be compensated for without error, a more complete understanding of these effects can be obtained by fitting the model to the data. The model then indicates how the representation underlying responses is altered by compensatory processes that respond to the request to ignore distractor movement.

Encoding-Error Model Fits

When the encoding-error model was fit to the data of Experiments 2 and 3, the derived parameters generally indicated that the leg lengths and turns tended to be encoded as less than their physical values. This is consistent with previous fits of the model (Klatzky et al., 1999; Loomis et al., 1993). With only one exception, the leg length was estimated to be encoded as less than its actual value of 8 m. The turn encoding function had a slope value no higher than 0.58 in any condition.

Most important for the present purposes are differences in the encoding functions when there was irrelevant movement, as compared with the verbalization control. Whereas the parameters fit to the control condition indicate systematic errors in encoding the outbound pathway that result from basic processes in path integration, the parameters fit to the conditions with a movement distractor indicate how the attempt to compensate for the distraction led to further distortion in the underlying representation.

First, consider the distractor conditions in which the observed responses showed greater distance error than the control but equivalent turn error (i.e., moving backward on Leg 1 or 2). These distractor conditions tended to differ from the control only by having a smaller distance parameter, that is, by rescaling (adjusting distances). In general, rescaling would produce error in response distance but not turn, whereas modifying the shape representation (adjusting turns) would introduce turn as well as distance error. Thus, the model's indication that there was underencoding of distance values, but not turn values, together with the observed pattern of errors, suggests that the change in the representation due to compensating for irrelevant backward movement took the form of scaling the triangle representation downward, rather than altering its shape.

Next, consider the single condition that manifested both turn and distance error in the data (i.e., moving rightward on Leg 2). The observed turn errors correspond to those predicted if participants were completely unable to ignore the change of bearing to the origin induced by the irrelevant movement. What the model parameters are describing, then, is how a person who misencoded the underlying two-legged path (i.e., the path defined by ignoring the distractor) would represent himself or herself as ending up at the same bearing from the origin as a person who walked the actually presented path, including the distractor. According to the parameters fit to the model, the rightward movement, like backward movement, caused leg lengths to be encoded as shorter than in the verbal control condition, and the effect on the leg-length parameter was about the same magnitude as that resulting from backward movement. In both experiments, the parameters further indicated that rightward movement on Leg 2 led to encoding the outbound turn as less than in the verbalization control, changing the encoded shape of the triangle.[2]

To summarize, backward movement on Leg 1 or Leg 2 leads to scaling the representation of the triangle downward relative to the verbalization control. This leads to increased distance error without a concomitant change in turn error. Rightward movement on Leg 2 leads to a representation that both rescales and reshapes a two-legged pathway, and hence induces turn as well as distance error.

Rotational Demands of Distractor Movements

Why should rightward movement on Leg 2 distort the shape of the pathway and so devastate turn performance? Note first that the design and the procedure rule out several potential confounding variables. Because the distractor was to be ignored, the values of requested response turn and distance were the same for rightward and backward distractors, and the distance between the true origin and the actual stopping point was equated by the stimuli. Because participants moved during the distractor period without rotating the body, neither backward nor rightward movement changed the participants' heading in space relative to the control.

However, as described in the introduction, the irrelevant movement did change the navigator's bearing, or direction, from critical points on the path. The bearing from the physical stopping point to the origin was changed by either a backward or a rightward distractor on Leg 2, but to roughly comparable and modest extents, so any differences in this variable are unlikely to produce the observed differences in the magnitude of error after rightward versus backward movement on Leg 2. But the bearing from the turning point (end of Leg 1) to the response point (end of Leg 2) was influenced only by a rightward distractor on Leg 2. As described in the introduction (see Figure 2), the rightward distractor changed the functional value of the outbound turn (even though the displacement of the stopping point was achieved by linear translation rather than direct rotation).

As discussed above, other circumstances in which errors increase markedly with to-be-ignored spatial position have been found to involve an imagined rotation. In tasks like that of Rieser (1989), the participant is to ignore his or her actual position and take an imagined one. In that case, rotational differences between the actual and the to-be-imagined position appear to be particularly difficult to process. Klatzky (1999) found that in the task of completing a triangle by touch on a tabletop, imagining a rotation of the triangle substantially increased angular (but not distance) error, whereas imagining a linear displacement of the triangle only modestly increased distance (and not angular) error. These contrasting effects parallel the present effects of rightward versus backward movement on Leg 2.

Considered in the context of such findings, the substantial turn error introduced by rightward movement on Leg 2, compared with the error introduced by backward movement, suggests that the two types of distractors introduce differential demands for mental rotation, in order to compensate. Consideration of the trigonometric changes induced by the distractor supports the need for rotational processes to compensate for to-be-ignored rightward movement. Table 3 formulates the trigonometric consequences of the movement in terms of a Cartesian coordinate system in which Leg 1 is aligned with the y-axis. Assume that the navigator goes along Leg 1 in the y direction for a distance D1, makes a turn that produces an angle between legs equal to α, then proceeds along a Leg 2 of length D2 to arrive at an endpoint (x,y). A movement of distance T during the distractor causes the navigator to assume new coordinates (x',y'), which differ from (x,y), as shown in Table 3.

The first row of Table 3 indicates the (x,y) coordinates in the control condition, in which there was no irrelevant movement. The remaining rows in the upper portion indicate the new coordinates that would result from irrelevant movement in each condition, and the lower portion indicates the computation that would be required to compensate for the undesired change in coordinate values and return them to the control value. For example, the second row of Table 3 indicates that moving backward by amount T along Leg 1 causes the the y-coordinate to decrease by a value of T, relative to the control condition, whereas the x-coordinate remains unchanged. The first row of the bottom portion of Table 3 indicates that to respond correctly in this condition, the participant must transform the altered y-coordinate back to its value in the control condition, which is done by adding T.

Table 3 allows us to explicitly compare the effects of backward versus rightward movement on Leg 2. Note first that in the control condition (top row), computing the (x,y) coordinates requires decomposing the turn between Legs 1 and 2 into sine and cosine components. Backward irrelevant movement on Leg 2 reduces its length by T, and the reduced value is then input to the same decomposition process (row 4 of Table 3). Rightward movement on Leg 2 (row 5 of Table 3), in contrast, introduces an additional angular term into both the x- and y-coordinates. These additional terms reflect the fact that the rightward movement has changed the bearing from the end of Leg 1 to the end of Leg 2.

---

[2] This encoding of turn as less than that in the control was achieved by somewhat different mechanisms in Experiments 2 and 3, according to the parameters. In Experiment 2, it resulted from the low intercept in the moving-rightward condition relative to the verbalizing condition. In Experiment 3, the underencoding of turn values in the moving-rightward condition was due to the small slope relative to the verbalization control.

Table 3
Computational Complexity of Distractor Conditions

Distractor	x-coordinate	y-coordinate
Control	D2 × sin (α)	D1 − D2 × cos (α)
Backward on Leg 1	D2 × sin (α)	D1 − D2 × cos (α) − *T*
Rightward on Leg 1	D2 × sin (α) + *T*	D1 − D2 × cos (α)
Backward on Leg 2	(D2 − *T*) × sin (α)	D1 − (D2 − *T*) × cos (α)
Rightward on Leg 2	D2 × sin (α) − *T* × cos (α)	D1 − D2 × cos (α) − *T* × sin (α)
	Compensatory x-coordinate computation	Compensatory y-coordinate computation
Backward on Leg 1	None	Add *T*
Rightward on Leg 1	Subtract *T*	None
Backward on Leg 2	Add *T* before decompose	Add *T* before decompose
Rightward on Leg 2	Remove additional decomposition	Remove additional decomposition

Note. The top portion shows coordinates at the end of the outbound path. The bottom portion shows the computations needed to compensate for distractor movement, relative to the control condition. D2 = length of Leg 2; α = inner angle between Leg 1 and Leg 2; D1 = length of Leg 1 (oriented along the y-axis); *T* = distance moved during the distractor task.

Although we have formulated the additional load of rightward movement on Leg 2 with respect to (x,y) decomposition, similar arguments pertain if one considers a polar representation and processes that might compute it. Consider, as shown in Figure 2, the configuration formed by (a) the leg between the origin and the first turning point and (b) the leg from that turning point to the point of response. From the leg lengths and the angle formed by them, the polar coordinates—which constitute distance and bearing from the original starting point—can be computed to complete the triangle. A backward movement on Leg 2 changes the computation only by subtracting the distractor distance from the second leg length. However, a rightward movement on Leg 2 rotates the navigator relative to the turning point (changes bearing), thus changing the inner angle and the second leg length. If the computation of the physical position resulting from the distractor is obligatory, it will be more difficult to compensate for the rightward movement and concomitant change in bearing than for the backward movement. Most important, the rightward movement will require a rotational adjustment.

Conclusion and Extensions

To summarize, the present results clearly indicate that updating position during locomotion is automatic, even without vestibular input. If positional changes are to be ignored, they require compensatory computational processes that adjust a configural representation, producing error that increases with the complexity of those processes. In particular, orthogonal movements along the first outbound leg are easily compensated for, but movements that introduce an implicit rotation are particularly difficult to computationally overcome. Inability to fully compensate for distractor movements leads to what can be characterized, at least to a large extent, as errors in encoding. Backward movement along a leg of the pathway tends to produce representational distortions in the form of downward rescaling, which makes sense in that the movement reduces the objective extent of the walked trajectory. Movements that lead to implied rotations go beyond rescaling to produce distortions of shape.

Further research would be useful to expand understanding of how compensatory processing changes the underlying representation. In the present studies, only backward movement along a leg of the path was induced, and the result was to rescale the representation downward. Forward movement might, in turn, enlarge the configural representation. Similarly, leftward movement from the second leg might lead to error in representing the turn as larger than its actual value, rather than smaller. These prospects remain to be explored.

These studies raise further questions about constraints on automatic movement encoding and situations in which it may not apply. One such case is when perceptual signaling of movement is inadequate, for example, when slow drift does not produce vestibular stimulation. One might expect changes resulting from drift to be ignored, although Experiment 4 indicates that the absence of vestibular signals is not sufficient by itself to guarantee that movement encoding will not automatically occur. Another interesting case in which movement might not be encoded relates to locomotion that occurs when attention is focused elsewhere. It is a common experience, for example, to be led by someone through a novel environment while conversing, only to discover at the end of the journey that one has little or no idea where one is. It is also possible that instructions that explicitly discouraged configural encoding would allow people to ignore displacements more effectively; for example, instructions to keep track of a homing vector might not have led to differential error due to rightward and backward movements on the second segment of the present configurations. When specific instructions not to use configural encoding were not given, however, the present results indicate that ignoring movement required cognitively demanding, error-prone, compensatory processing. The effects of this processing can be described within the encoding-error model, through the assumption that cognitive compensation results in systematic distortions in the representation of the configuration formed by movement.

References

Beritoff, J. S. (1965). *Neural mechanisms of higher vertebrate behavior.* Boston: Little, Brown.

Cutting, J. E. (1996). Wayfinding from multiple sources of local information in retinal flow. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 1299–1313.

Cutting, J. E., Vishton, P. M., Flückiger, M., Baumberger, B., & Gerndt, J. D. (1997). Heading and path information from retinal flow in naturalistic environments. *Perception & Psychophysics, 59,* 426–441.

Easton, R. D., & Sholl, M. J. (1995). Object–array structure, frames of reference, and retrieval of spatial knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 483–500.

Farrell, M. J., & Robertson, I. H. (1998). Mental rotation and the automatic updating of body-centered spatial relationships. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24,* 227–233.

Farrell, M. J., & Thomson, J. A. (1998). Automatic updating during locomotion without vision. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 51A,* 637–654.

Fujita, N., Klatzky, R. L., Loomis, J. M., & Golledge, R. G. (1993). The encoding-error model of pathway completion without vision. *Geographical Analysis, 25,* 295–314.

Fujita, N., Loomis, J. M., Klatzky, R. L., & Golledge, R. G. (1990). A minimal model for dead-reckoning navigation: Updating the homing vector. *Geographical Analysis, 22,* 326–335.

Gallistel, C. R. (1990). *The organization of learning.* Cambridge, MA: MIT Press.

Guth, R., & LaDuke, R. (1994). The veering tendency of blind pedestrians: An analysis of the problem and literature review. *Journal of Visual Impairment and Blindness, 88,* 391–400.

Juurmaa, J., & Suonio, K. (1975). The role of audition and motion in the spatial orientation of the blind and sighted. *Scandinavian Journal of Psychology, 16,* 209–216.

Keppel, G. (1973). *Design and analysis: A researcher's handbook.* Englewood Cliffs, NJ: Prentice Hall.

Klatzky, R. L. (1999). Path completion after haptic exploration without vision: Implications for haptic spatial representations. *Perception & Psychophysics, 61,* 220–235.

Klatzky, R. L., Beall, A. C., Loomis, J. M., Golledge, R. G., & Philbeck, J. W. (1999). Human navigation ability: Tests of the encoding-error model of path integration. *Journal of Spatial Cognition and Computation, 1,* 31–65.

Klatzky, R. L., Loomis, J. M., Beall, A. C., Chance, S. S., & Golledge, R. G. (1998). Spatial updating of self-position and orientation during real, imagined, and virtual locomotion. *Psychological Science, 9,* 293–298.

Klatzky, R. L., Loomis, J. M., Golledge, R. G., Cicinelli, J. G., Doherty, S., & Pellegrino, J. W. (1990). Acquisition of route and survey knowledge in the absence of vision. *Journal of Motor Behavior, 22,* 19–43.

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin and Review, 1,* 476–490.

Loomis, J. M., Da Silva, J. A., Fujita, N., & Fukusima, S. S. (1992). Visual space perception and visually directed action. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 906–921.

Loomis, J. M., Klatzky, R. L., Golledge, R. G., Cicinelli, J. G., Pellegrino, J. W., & Fry, P. A. (1993). Nonvisual navigation by blind and sighted: Assessment of path integration ability. *Journal of Experimental Psychology: General, 122,* 73–91.

Loomis, J. M., Klatzky, R. L., Golledge, R. G., & Philbeck, J. W. (1999). Human navigation by path integration. In R. G. Golledge (Ed.), *Wayfinding behavior: Cognitive mapping and other spatial processes* (pp. 125–151). Baltimore: Johns Hopkins University Press.

Loomis, J. M., Klatzky, R. L., Philbeck, J. W., & Golledge, R. G. (1998). Assessing auditory distance perception using perceptually directed action. *Perception & Psychophysics, 60,* 966–980.

Maurer, R., & Séguinot, V. (1995). What is modeling for? A critical review of the models of path integration. *Journal of Theoretical Biology, 175,* 457–475.

May, M. (1996). Cognitive and embodied modes of spatial imagery. *Psychologische Beiträge, 38,* 418–434.

May, M. (in press). *Kognition im umraum* [Cognition in spatial surroundings]. Wiesbaden, Germany: Deutscher Universitaetsverlag.

Mittelstaedt, H., & Mittelstaedt, M.-L. (1982). Homing by path integration. In F. Papi & H. G. Wallraff (Eds.), *Avian navigation* (pp. 290–297). Berlin, Germany: Springer.

Passini, R., Proulx, G., & Rainville, C. (1990). The spatio–cognitive abilities of the visually impaired population. *Environment and Behavior, 22,* 91–118.

Péruch, P., May, M., & Wartenberg, F. (1997). Homing in virtual environments: Effects of field of view and path layout. *Perception, 26,* 301–311.

Philbeck, J. W., & Loomis, J. M. (1997). Comparison of two indicators of perceived egocentric distance under full-cue and reduced-cue conditions. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 72–85.

Potegal, M. (1987). The vestibular navigation hypothesis: A progress report. In P. Ellen & C. Thinus-Blanc (Eds.), *Cognitive processes and spatial orientation in animal and man* (Vol. 2, pp. 28–34). Dordrecht, the Netherlands: Martinus Nijhoff.

Presson, C. C., & Montello, D. R. (1994). Updating after rotational and translational body movements: Coordinate structure of perspective space. *Perception, 23,* 1447–1455.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15,* 1157–1165.

Rieser, J. J., Frymire, M., & Berry, D. (1997). Geometrical constraints in imagery and action when walking without vision. *Abstracts of the Psychonomic Society, 2,* 38.

Rieser, J. J., Guth, D. A., & Hill, E. W. (1986). Sensitivity to perceive structure while walking without vision. *Perception, 15,* 173–188.

Sholl, M. J., & Nolin, T. L. (1997). Orientation specificity in representations of space. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23,* 1494–1507.

Wartenberg, F., May, M., & Péruch, P. (1998). Spatial orientation in virtual environments: Background considerations and experiments. In C. Freksa, C. Habel, & K. F. Wender (Eds.), *Spatial cognition: An interdisciplinary approach to representing and processing spatial knowledge* (pp. 469–489). Berlin, Germany: Springer.

Worchel, P. (1951). Space perception and orientation in the blind. *Psychological Monographs, 65*(15, Whole No. 332).

Received August 26, 1998
Revision received May 24, 1999
Accepted May 26, 1999 ■