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Remembered landmarks enhance the precision of path integration

John W. Philbeck* and Shannon O'Leary
George Washington University, USA

When navigating by path integration, knowledge of one's position becomes increasingly uncertain as one walks from a known location. This uncertainty decreases if one perceives a known landmark location nearby. We hypothesized that remembering landmarks might serve a similar purpose for path integration as directly perceiving them. If this is true, walking near a remembered landmark location should enhance response consistency in path integration tasks. To test this, we asked participants to view a target and then attempt to walk to it without vision. Some participants saw the target plus a landmark during the preview. Compared with no-landmark trials, response consistency nearly doubled when participants passed near the remembered landmark location. Similar results were obtained when participants could audibly perceive the landmark while walking. A control experiment ruled out perceptual context effects during the preview. We conclude that remembered landmarks can enhance path integration even though they are not directly perceived.

An important function of vision is to facilitate navigation from one location to another. Even if we are lost within a large environment such as an unfamiliar city, vision provides information about where we are relative to nearby objects. This on-going stream of information allows us to keep track of our current location in the local environment as we progress through it. A variety of animals are quite good at keeping track of their location while walking even when vision is not available (Etienne, Maurer, & Séguinot, 1996). Humans are no exception, and in fact the average human can sight a target up to 20 m away or more, and then walk to it quite accurately while blindfolded (Elliott, 1987; Loomis, Da Silva, Fujita, & Fukusima, 1992; Mittelstaedt & Mittelstaedt, 2001; Rieser, Ashmead, Talor, & Youngquist, 1990; Thomson, 1983). This task, known as visually-directed walking or simply blindfolded walking, has proven to be a powerful paradigm for studying visual space perception, self-motion sensing, and the neural underpinnings of locomotor control (Loomis, Da Silva, Philbeck, &

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Fukusima, 1996; Philbeck, Behrmann, Levy, Potolicchio, & Caputy, 2004; Worsley et al., 2001).

When direct perception of the surrounding environment is prevented, in principle one may maintain an approximation of his or her current position by monitoring internally generated self-motion signals, such as vestibular information, efference copy, and proprioception. This process is called "path integration[1]" (Etienne et al., 1996). One source of evidence of path integration in animals comes from studies in which animals navigate to well-learned locations by generating novel trajectories; path integration is implicated because only internally-generated signals are available to guide the animals' progress through the unexplored territory (e.g., Alyan & McNaughton, 1999; Whishaw, Hines, & Wallace, 2001). Although many of these studies involve movement into unexplored territory and/or trajectories involving whole-body rotations, these features are not required to elicit path integration. In humans, good performance in blindfolded walking tasks, which often involve simple linear trajectories, is evidence that humans perform path integration well along these paths (Loomis et al., 1996). Path integration is implicated because response precision and accuracy remain high even when self-motion information is restricted to idiothetic sources and participants are prevented from pre-programming their response before they begin walking (Philbeck, Loomis & Beall, 1997; Rieser et al., 1990).

Research on human path integration has tended to focus on characterizing path integration ability under various conditions and on determining the relative weighting of the sensory cues available for self-motion sensing (Loomis, Klatzky, Golledge, & Philbeck, 1999). However, navigation in the real world takes place in the context of a variety of non-sensory factors, such as goals, expectations, and stored representations of the local environment. The aim of this paper is to investigate the impact of one such factor, namely memory of nearby landmark locations, on path integration.

To illustrate the possible impact of remembered landmarks on path integration, Figure 1 shows a very simple path integration task, in which a navigator extinguishes the lights and then must cross the room in darkness to reach the bed. There is no reason to expect men and women to behave differently in such situations, but to be concrete, let us assume the navigator is a woman. The navigator is prevented from using vision to unambiguously determine her location relative to objects in the room; instead, she can only determine her position approximately, via path integration. The precision and accuracy of one's estimated position when path integrating will be limited by errors in sensory self-motion information. Thus, the farther our navigator walks from the last known location (in Figure 1, the left part of the room), the

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[1] Although path integration is defined such that it excludes methods of determining one's self-location on the basis of direct perception of landmarks (e.g., through vision), this exclusion does not entirely rule out the use of vision for path integration. In fact, visual information provides an important input to path integration by way of optic flow when identification of specific landmarks is carefully prevented (Redlick, Jenkin, & Harris, 2001).

more these errors will tend to accumulate, and the more uncertain her current position estimate will become (see Figure 1a). In keeping with this notion, within-subject variability in path integration tasks tends to increase more or less proportionally with walked distance (Rieser et al., 1990). Even without vision, brushing against an object at a known location can allow the navigator to unambiguously determine her position (e.g., “I am now beside the table”), and, in effect, any positional uncertainty that has accrued up to that point drops to zero (see Figure 1b). If our navigator continues on to the bed without touching anything else, her positional uncertainty will start to accumulate again. Just before she reaches the bed, she will have a more precise idea about where she is than she would if she had not encountered the table (as in Figure 1a).

The precision of one's estimate of self-location under these conditions is very likely affected by factors other than the random errors inherent in the sensory systems that signal self-motion. Imagine a case in which our navigator does not actually brush the table, but instead passes within a centimeter of it as she passes. If only sensory noise influences the precision of her path integration, her positional uncertainty will steadily accrue from the origin until she reaches the bed, because she has no direct feedback that she has passed the table. More realistically, however, as she passes the table without touching it, she has a strong impression that it is nearby; the basis for this impression comes from the path integration performed up to that point, which tells her that she is likely to be near the remembered location of the table. It is reasonable to expect that this subjective sense of being near the table should have a similar effect on the precision of our navigator’s self-location estimate as actually touching the table. If this is true, she should feel more certain of her location when path integration indicates that she is passing the table, even though there is no externally supplied sensory information that the table is nearby (see Figure 1c). This predicts that, in the laboratory, the consistency of responding across trials in a blindfolded walking task should vary according to whether or not participants are remembering specific objects in the laboratory and using them as they would visible landmarks; furthermore, these differences in response consistency should be observable even though the walking path and all other sensory inputs to path integration are unchanging.

One implication of this is that believing oneself to be near a known landmark may be beneficial for navigation by way of enhancing the precision of path integration. This possibility would not only have implications for real-world navigation, but also for conducting laboratory experiments and interpreting their results (because visible objects in the environment might potentially be remembered and function as landmarks). In addition, a cognitive factor of this kind would be important to incorporate in computational models of human path integration; it would bear on functional models of the brain structures thought to be engaged in path integration and on what kind of navigational deficits to expect after different kinds of brain injury (Aguirre & D'Esposito, 1999; Maguire et al., 1998; Philbeck et al., 2004; Wolpert & Ghahramani, 2000; Worsley et al., 2001).

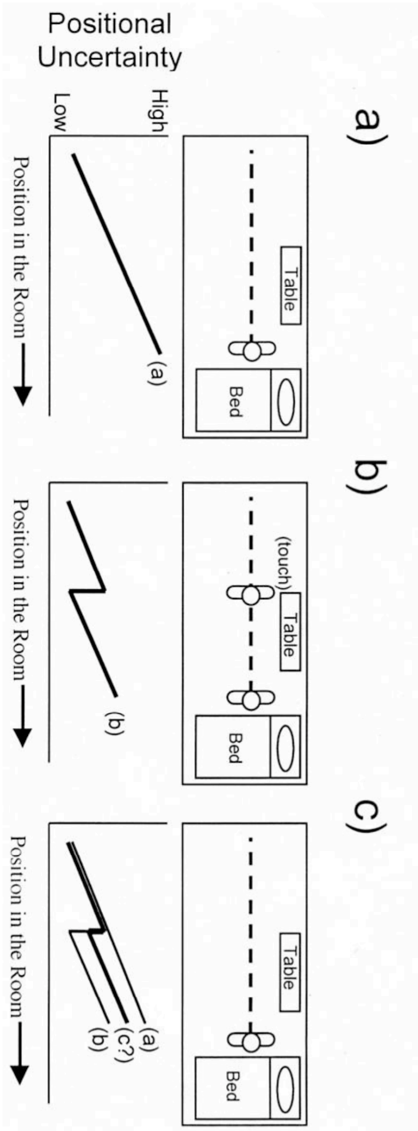

Figure 1. Illustrative example of a real-world path integration task, involving turning off the lights at the left side of each panel and then walking across the room to the bed on the right without vision. (a) The uncertainty of the self-location estimate progressively increases as the navigator progresses through the room due to noise in sensory self-motion signals. (b) When the navigator can see a table (black box) before the lights are extinguished and then touches it while passing by in the dark, positional uncertainty drops to zero because self-location can be unambiguously determined. Positional uncertainty then begins to increase again until the bed is reached. (c) When the navigator passes the remembered table location (gray box) without touching the table, the positional uncertainty is predicted to drop; the uncertainty at the end of the path (near the bed) is predicted to be less than in case (a), perhaps equal to or somewhat greater than in case (b).

The approach in the following experiments was to assess the consistency of responses in a blindfolded walking task. Of most interest is the comparison between situations in which observers see a single walking target in a well-lit environment, versus situations in which they see a walking target plus a visually similar stimulus that might be used as a landmark. Our central hypothesis is that when path integration indicates that the observer should be in the vicinity of a remembered landmark, the observer's positional uncertainty will decrease, in a similar manner as it would for a landmark that was physically touched. This change is predicted to be manifested as lower within-subject variability in the final stopping location when there is a "landmark" present during the preview. At a minimum, an evaluation of this idea would involve two conditions, one in which a salient landmark is available during the preview and another in which there is no salient landmark. In the primary test of our main hypothesis, we tested one group of participants using a design in which landmark availability was manipulated within subjects, with a "no landmark" block coming first, followed by a "remembered landmark" block. We will refer to these participants as the "Remembered Landmark" group. This block order ensured that when participants took part in the "no landmark" condition, they had not yet been alerted to the possible utility of remembering a landmark while walking. Given this design, one concern is that the experience of participating in a second block of trials might itself increase response consistency. To assess this, we added a second group of participants ("No Landmark") who also participated in two blocks of trials, but for whom there was no manipulation of landmark availability across blocks; that is, in both blocks, no salient landmark was visible near the target during the preview. Finally, we wanted to verify that positional uncertainty would indeed decrease if participants had direct perceptual information that they were passing a landmark while walking blindly to a target. To test this idea, we included a third group ("Audible Landmark") who participated in nearly the same set of conditions as the Remembered Landmark group, with the exception that in the second block, participants in the Audible Landmark group were allowed to directly perceive the landmark's location via audition as they passed by it on the way to the target.

To summarize, we predicted that when a salient landmark near the target is visible during the preview, blindfolded walking trajectories that pass near the landmark will exhibit greater terminal point consistency than when there is no salient landmark during the preview. Our primary test of this idea involved the Remembered Landmark participants, for whom landmark availability was manipulated within subjects. Although we did not expect response consistency to be markedly affected by simple re-exposure to the task in the second block, we included the No Landmark group to evaluate this possibility. Finally, we included the Audible Landmark group to verify that response consistency would indeed improve when participants could directly perceive a landmark while navigating by path integration. Experiment 2 was conducted to verify that the presence of a landmark does not substantially alter the initial perceptual localization of the target under the viewing conditions of Experiment 1.

EXPERIMENT 1

METHOD

Participants. Thirty-six individuals participated in this experiment in exchange for course credit. Their ages ranged from 18 to 24 years (mean age: 19 years). Participants were randomly assigned to one of three groups (6 males and 6 females in each). All were naïve as to the purposes of the study.

Design and Apparatus. The experiment took place in a well-lit indoor classroom (3.8 m x 10 m). There were two blocks of trials, consisting of a Pre-Test block, in which all groups performed the same task under identical conditions, followed by an Experimental block, in which individuals were exposed to different stimuli and instructions according to their group (described below). In all trials, participants wore close-fitting hearing protectors over the ears to minimize auditory information that participants might potentially use to determine their position while walking. Trials in both blocks involved a preview phase, in which participants viewed one or more stimuli in the testing environment, and a response phase, in which participants closed their eyes and attempted to walk without vision to a specified target.

(a) Pre-Test trials: These trials served to establish a baseline level of performance under conditions in which no salient landmark was visible near the target during the preview. As we will see, the Experimental trials generally involved two orange stimulus cones (23 cm tall): a target and a landmark. To equate the viewing conditions as much as possible across blocks, we presented two cones during the preview phase of Pre-Test trials. The *target* cone could appear 2.0, 4.2 or 6.2 m from the participants' toes. The *second* cone in Pre-Test trials was always placed 10 cm from the participants' toes. A stimulus at this distance is not likely to reduce positional uncertainty markedly during blindfolded walking (because very little uncertainty will have accrued by the time participants pass this cone), so we considered Pre-Test trials to be "no landmark" trials. Each of the three target cone distances was presented 5 times and the presentation order was randomized (15 trials, total).

(b) Experimental trials: All groups saw a target cone at 6.2 m during the preview phase. On each of five consecutive trials, participants briefly viewed this target and then attempted to walk to it without vision. For individuals in the No Landmark group, this target cone was the only cone presented. For individuals in the Remembered Landmark group, the target cone at 6.2 m was presented along with a "landmark" cone at 4.2 m. Participants in this group were instructed to pay attention to the nearest cone as they walked by it (still without vision) on their way to the target cone. In the Audible Landmark group, there was again a target cone at 6.2 m and a landmark cone at 4.2 m; in addition, a small portable cassette tape player placed alongside the 4.2 m position played a recording of white noise bursts pulsed at 4 Hz. An experimenter initiated the noise bursts by activating the tape recorder when the participant was about 2 m from the 4.2 m location and stopped the recording after the participant terminated his or her walking response. The noise pulses were clearly audible through the hearing protectors, and therefore provided direct perceptual information about the landmark's location as the participant passed it.

Procedure. Before starting the experiment, participants were instructed that they would be asked to view a target cone and attempt to walk to its location with their eyes and ears covered. Participants were briefly familiarized with walking while wearing a blindfold and hearing protectors. While at the starting position, they were instructed to lower the blindfold and walk into the middle of the room and then stop. After doing so, they were guided back to the starting position without vision and without error feedback to begin the first Pre-Test trial.

(a) Pre-Test trials: Participants began each trial with their toes aligned with a starting location indicated by a piece of tape on the floor. Participants binocularly viewed the two stimulus cones in the classroom. After approximately five seconds, participants lowered the blindfold and attempted to walk to the remembered location of the target cone using their own self-determined pace. An experimenter removed both cones from the walking path before participants began to walk. When the participants stopped walking, the walked distance was measured with a tape measure and the experimenter guided them back to the starting location, still without vision and without error feedback.

(b) Experimental trials: At the end of the Pre-Test trials, participants were instructed about the changes that would be made in the next set of trials. No mention was made that the target cone's location would be unchanging in the upcoming trials. The No Landmark group was instructed that there would be only one cone during the preview, and to walk to that cone. The Remembered Landmark group was instructed to walk to the far cone of the pair that would be visible during the preview; the instructions specified that paying attention to the nearer cone while walking might help them reach the target cone more accurately. The Audible Landmark group similarly was instructed to walk to the far cone of the pair visible during the preview, and that a tape player beside the near cone would play a sound to help them keep track of their location as they walked by it. Participants in all groups viewed the room and the cone(s) for approximately five seconds, then lowered the blindfold and attempted to walk to the target cone without vision. An experimenter recorded the walked distance and guided the participant back to the starting location without error feedback.

Data analysis. We performed separate analyses on the constant (systematic) error and the random (unsystematic) error. Constant error was calculated as the signed difference between the target distance and the participant's walked distance on each trial. This measure reflects systematic tendencies to over- or undershoot the target location. Although remembering a landmark might systematically bias one's estimated location while walking and therefore introduce constant errors, our primary interest was in the effect of remembered landmarks on the precision of self-location estimates. We assessed this by examining the random error, which we calculated as the within-subject standard deviation in stopping locations across the 5 measurements per condition.

RESULTS AND DISCUSSION

We will consider the Pre-Test and Experimental data separately. The data are shown in Figure 2.

(a) Pre-Test trials: To establish that the three groups were well-matched before participating in the Experimental block, we analyzed the Pre-Test data in two analyses of variance (ANOVA), one for constant error and one for random error, with "group" included as a between-group variable and "distance" included as a within-group variable. There were no significant effects in terms of constant error in the Pre-Test block (group: $F[2, 33] = .865$; distance: $F[2, 66] = 1.491$; group x distance: $F[4, 66] = 1.449$; all p's > .05). Averaging across distances and group, there was a slight tendency to overshoot the target (by about 1.6%). In terms of random error, there was neither a main effect of group ($F[2, 33] = 2.09$, $p > .05$) nor a group x distance interaction ($F[4, 66] = 0.918$, $p > .05$). This confirms that the groups were well matched before participating in the Experimental block. Within-subject random error increased reliably with increasing target distance ($F[2, 66] = 27.28$, $p < .0001$), and averaged about 10.2, 9.4, and 8.6% of the target distance for the 2.0, 4.2, and 6.2 m targets, respectively. Tables 1 and 2 show the mean constant and random errors, respectively, for the Pre-Test trials in Experiment 1.

(b) Experimental trials: To evaluate whether or not response consistency indeed increased when a salient landmark was visible near the target during the preview, we performed one-tailed, paired-sample t-tests on the Remembered Landmark group's data to compare their Pre-Test and Experimental trial performance. We analyzed the data from trials involving the 6.2 m target, which was the only target distance common to both blocks of trials. This analysis showed a reliable drop in random error in Experimental trials relative to Pre-Test trials ($p = .008$), confirming our primary prediction. A two-tailed t-test showed that this group did not perform significantly differently across blocks in terms of constant error ($p = .27$). Similar analyses for the Audible Landmark group yielded comparable results (random error: $p = .02$; constant error: $p = .50$). Consistent with our predictions, then, the presence of a landmark, whether audible or remembered, during blindfolded walking was associated with significant changes in response consistency relative to conditions in which there was no such landmark.

One issue that must be confronted is the possibility that simply being re-exposed to the task in the Experimental trials might systematically influence responses. This is particularly a concern because in the Experimental trials, participants walked to the same target five times in succession, whereas in Pre-Test trials they generally walked to a different target distance on each trial. Analysis of the No Landmark group data permitted an assessment of this issue; this group performed under virtually identical stimulus conditions in the two blocks (the only difference being the presence of a stimulus cone 10 cm from the participants' toes in Pre-Test trials, a discrepancy that is very unlikely to exert an influence). We performed two-tailed, paired-sample t-tests on the No Landmark group's data to compare their Pre-Test and Experimental trial performance. There were no significant differences in terms of either constant error ($p = .23$) or random error ($p = .95$). Thus, simple re-exposure to the task in the second block does not appear to play a strong role.

Table 1. Mean Constant Errors (and Standard Errors) in Pre-Test Block of Experiment 1 [a]

	Group [b]		
	No Landmark	Remembered Landmark	Audible Landmark
Stimulus	M (SE)	M (SE)	M (SE)
2.0	.02 (.10)	-.01 (.04)	.17 (.08)
4.2	-.19 (.15)	.12 (.10)	.02 (.16)
6.2	-.08 (.25)	.41 (.24)	.13 (.28)

[a] All values expressed in meters.

[b] Group names denote manipulations that were introduced in the Experimental trials following the Pre-Test block. There were no group manipulations in the Pre-Test trials shown here.

Table 2. Mean Standard Deviations (and Standard Errors) in Pre-Test Block of Experiment 1 [a]

	Group [b]		
	No Landmark	Remembered Landmark	Audible Landmark
Stimulus	M (SE)	M (SE)	M (SE)
2.0	.19 (.04)	.22 (.02)	.21 (.02)
4.2	.36 (.06)	.42 (.07)	.40 (.07)
6.2	.47 (.07)	.66 (.06)	.47 (.06)

[a] Standard deviations were calculated within subjects across five measurements per condition. Standard errors were calculated between subjects in each group ($n = 12$). All measurements are in meters.

[b] Group names denote manipulations that were introduced in the Experimental trials following the Pre-Test block. There were no group manipulations in the Pre-Test trials shown here.

The preceding analyses involved only within-group comparisons. Our design also allows for between-groups comparisons. Of primary concern in this regard is the difference between the No Landmark group and each of the two landmark groups. If, as we hypothesize, landmarks can increase the precision of path integration, whether directly perceived or remembered, the random error for the two landmark groups should be *less* than that of the No Landmark group. To compare between groups, we created difference scores for each participant by subtracting errors in the Pre-Test block from errors in the Experimental block (6.2 m target only). Using difference scores allowed us to capture the change in each individual's responses in Experimental trials relative to his or her own responses in the Pre-Test trials. We then compared the *random error* difference scores between the No Landmark vs. Remembered Landmark groups and the No Landmark vs. Audible Landmark groups, using one-tailed t-tests to take into account the directional nature of the predictions. Both tests revealed statistically significant differences ($p = .019$ and .041, respectively), again confirming our predictions. Similar tests involving the *constant error* difference scores showed no significant differences (No Landmark vs. Remembered Landmark: $p = .348$; No Landmark vs. Audible Landmark: $p = .476$). Although we had no specific predictions concerning how the Audible and Remembered Landmark groups would perform relative to each other, we compared the difference scores of these groups using two-tailed t-tests. These analyses showed there to be no significant between-group differences (constant error: $p = .80$; random error: $p = .68$). This between-group similarity of responding across blocks is apparent in Figure 2.

Consistent with our predictions, then, passing a salient landmark (a cone identical to the target), specified either by direct perception or by memory, is associated with increased consistency of nonvisual walking trajectories directed to a remembered target location. The No Landmark group did not see the "landmark" cone near the target location in either the Pre-Test or the Experimental trials, and their response consistency did not change (with standard deviations averaging .47 and .48 m in Pre-Test and Experimental blocks, respectively). The response consistency of the two landmark groups, by contrast, nearly doubled when they saw the "landmark" cone near the walking target during the visual preview; the average standard deviations for the two groups dropped from .56 m in the Pre-Test block to .32 m in the Experimental block. When a landmark is near the walking path on the way to a final destination, direct perception of the landmark (e.g., by audition or vision) should help an individual determine his or her current location with more certainty, and presumably this would be reflected in the consistency of walking trajectories across trials. Our data from the Audible Landmark group suggests that this is true. When the current estimate of self-location based on path integration indicates that a remembered landmark should be close by, this remembered landmark apparently can function in a very similar way as a directly-perceivable landmark, acting to specify an individual's current position estimate more precisely.

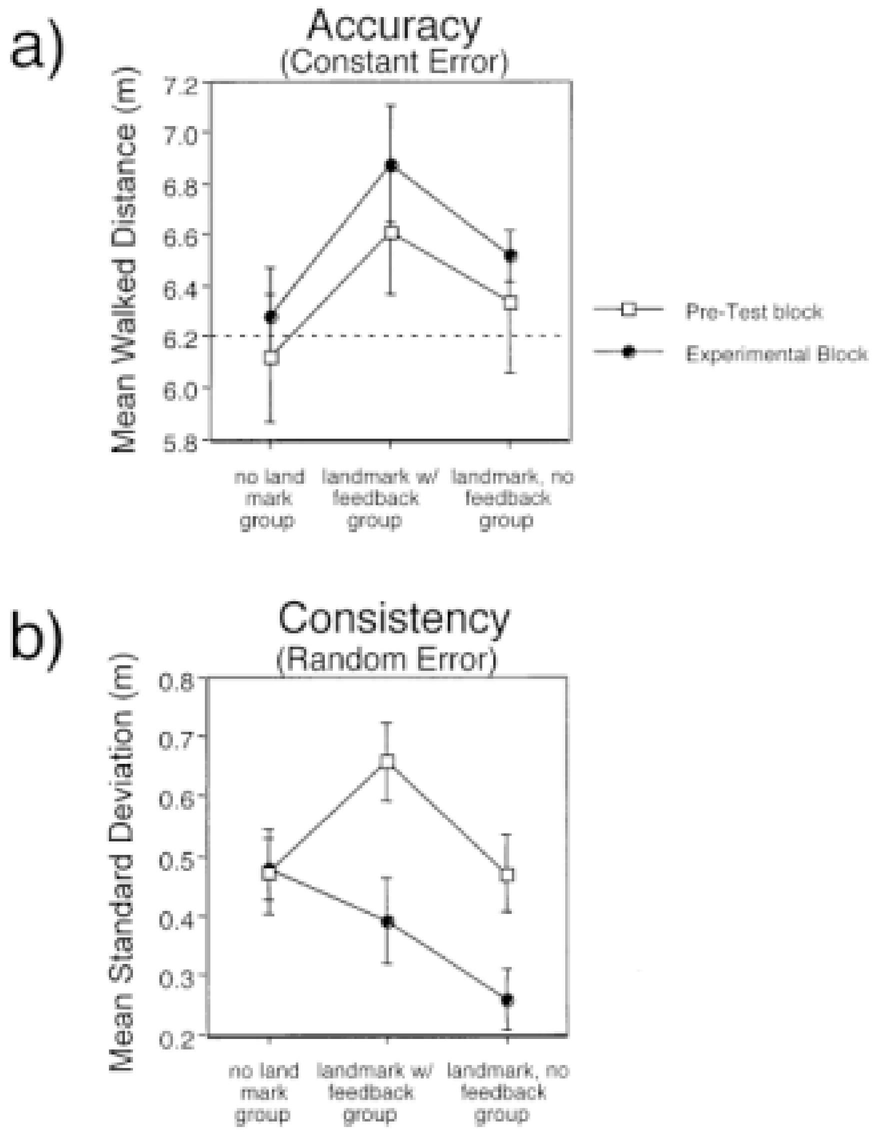

Figure 2. Results of Experiment 1 for each of three groups (6.2 m target only). Data for Pre-Test and Experimental blocks are show. Errors denote +/- one standard error of the mean. (a) Accuracy, as assessed by mean constant errors. Dashed horizontal line shows the physical stimulus distance. (b) Consistency, as assessed by the mean within-subject standard deviations across 5 repetitions per condition.

One condition of a study in our laboratory (Philbeck, 2000) is similar to the methods used here. In the previous work, participants saw two stimuli for five seconds, and after vision was obscured, one of these stimuli was specified as the walking target. Participants then attempted to walk to the specified target without vision. That study found no influence of seeing a target in the context of a visually similar stimulus placed nearer or farther than the target. One salient difference between that study and Experiment 1, here, is that Experiment 1 involved far fewer trials than the earlier work. It may be that as time wears on in an experiment, participants pay less and less attention to the landmark stimuli, and this tends to attenuate the benefits of calling to mind the landmark. More research is required to resolve this issue.

EXPERIMENT 2

In Experiment 1, the stimuli were placed in somewhat different configurations in the Pre-Test versus Experimental blocks; additionally, in the Experimental block, the No Landmark group saw only a single stimulus cone whereas the other groups saw two stimulus cones. This means that the observed differences between groups and between blocks could have been due to differences in the initially encoded stimulus locations prior to initiating the walking responses, rather than to landmark-related differences in path integration during the walk. The perceived location of a stimulus can indeed be influenced by the presence of other objects nearby (Foley, 1985; Gogel, 1965; Gogel & Tietz, 1977; Wist & Summons, 1976; see also Chamizo, 2003). These context effects remain poorly understood in multi-cue environments, but in some cases they can be quite powerful (Feria, Braunstein, & Andersen, 2003; Meng & Sedgwick, 2002; Sinai, Ooi, & He, 1998). This being the case, it is crucial to verify that a landmark stimulus placed within 2 m of the target cone does not influence the perceived location of the target cone when no path integration is required. This was the focus of Experiment 2.

METHOD

Participants. Twelve individuals (6 male, 6 female) took part in the experiment in exchange for course credit. Their ages ranged from 18 to 24 years (mean age: 20 years). All were naïve concerning the purposes of the experiment and none had participated in Experiment 1.

Design and Apparatus. The experiment took place in the same laboratory as Experiment 1 and the same stimulus cones were used. A well-lit adjoining hallway (14.5 m x 1.5 m) was also used. This hallway ran parallel to the main laboratory with a wall separating the two. A 6.0 m long passageway connected the laboratory with the adjoining hallway.

On each trial, a stimulus cone could appear either by itself (4.5, 6.0, or 7.5 m from the observer's toes) or in the presence of a second stimulus cone. When two cones were presented together, they could appear at 4.5 and 6.0 m, or 6.0 and 7.5 m from the observer's toes. Within each pair, either of the two cones could be designated as the "target" with equal probability. There were four repetitions per condition (28 trials, total) and the order of trials was completely randomized.

Procedure. At the start of each trial, the participant binocularly viewed the stimulus cone(s) under normal indoor illumination for approximately five seconds. In two-cone trials, the experimenter verbally specified one of these cones as the "target" during this time. After five seconds, the participant walked to an observation location in the adjoining hallway, identified by a piece of tape on the floor. This observation location provided participants with a view down the (largely empty) hallway, while obscuring the locations of the stimulus cone(s) in the main laboratory. An experimenter stood approximately 7 m away and began moving a comparison cone toward the participant. The participant's task was to signal the experimenter to stop moving the cone when its egocentric distance matched the egocentric distance to the target cone in the main laboratory. When satisfied with the match, the participant walked back to the observation location in the main laboratory to begin the next trial while an experimenter recorded the adjusted location of the cone. No error feedback was given.

RESULTS AND DISCUSSION

As in Experiment 1, we analyzed the data in terms of both constant error and random error. Table 3 lists the mean constant error and Table 4 lists the mean random error (as measured by the within-subject standard deviations) from Experiment 2. Two-tailed, paired-sample t-tests (alpha = .05) were performed on the measures of both constant and random error. These analyses showed that there was no consistent pattern of differences in the *constant error* of matching responses depending on whether the target cone was seen by itself or in the presence of a nearby landmark cone. Specifically, there were two conditions in which a target could appear in the context of a farther landmark (target at 4.5 m + landmark at 6.0 m; target at 6.0 m + landmark at 7.5 m); when responses to the 4.5 m target seen by itself were compared with those to the same target as part of a 4.5 m – 6.0 m configuration, there was no significant difference in constant error (p = .78). However, the analogous comparison for slightly farther stimulus distances (6.0 m target alone versus same target as part of a 6.0 m – 7.5 m configuration) yielded a marginally significant difference (p = .05). By contrast, there were two conditions in which a target could appear in the context of a nearer landmark (target at 6.0 m + landmark at 4.5 m; target at 7.5 m + landmark at 6.0 m). When responses to the 6.0 m target seen by itself were compared with those to the same target seen as part of a 4.5 – 6.0 m configuration, there were no significant differences in constant error (p = .48). The analogous comparison for slightly farther stimulus distances (7.5 m target alone versus same target as part of 6.0 m – 7.5 m configuration) yielded a significant difference (p = .013). Thus, there is no consistent pattern in *constant error* depending on whether a target is seen by itself or in the context of a nearer or a farther landmark. In any event, an examination of the means in Table 3 shows that even for the comparisons that were significantly different, the difference between the underlying means is quite small (reaching a maximum of only 0.22 m). Importantly, when the analogous set of comparisons was performed on the *random error* data, there were no significant differences (p = .28 or greater for all comparisons). Taken together, then, there are at best only small and inconsistent context effects in a distance matching task involving the testing environment used in Experiment 1. The laboratory and viewing conditions were the same in both experiments, and although the separation between landmarks and targets in Experiment 2 was slightly less than in Experiment 1, if anything, this should magnify context effects (Gogel, 1979; Wist & Summons, 1976). These results indicate that the effects seen in Experiment 1 are unlikely to be due to differences in the initial localization of the target cone. We therefore conclude that the Experiment 1 effects occurred during the walking response itself.

Table 3. Mean Constant Errors (and Standard Errors) in Experiment 2 [a]

	Viewing Context of Target		
	With no landmark	With a farther landmark [b]	With a nearer landmark [c]
Target Distance	M (SE)	M (SE)	M (SE)
4.5	.25 (.05)	.22 (.10)	n/a n/a
6.0	.00 (.08)	.22 (.12)	.06 (.11)
7.5	.07 (.09)	n/a n/a	-.06 (.08)

[a] Means denote the mean signed error between the physical target distance and the distance participants created to match the target distance. All measurements are in meters.

[b] Stimulus combinations represented in this column include: target at 4.5 m + landmark at 6.0 m and target at 6.0 m + landmark at 7.5 m. "n/a" indicates that the target at 7.5 m was never paired with a farther landmark.

[c] Stimulus combinations represented in this column include: target at 6.0 m + landmark at 4.5 m and target at 7.5 m + landmark at 6.0 m. "n/a" indicates that the target at 4.5 m was never paired with a nearer landmark.

Table 4. Mean Standard Deviations (and Standard Errors) of Responses in Experiment 2 [a]

	Viewing Context of Target		
	With no landmark	With a farther landmark [b]	With a nearer landmark [c]
Target Distance	M (SE)	M (SE)	M (SE)
4.5	.28 (.05)	.37 (.07)	n/a n/a
6.0	.35 (.06)	.34 (.04)	.34 (.05)
7.5	.27 (.05)	n/a n/a	.24 (.03)

[a] Standard deviations were calculated within subjects across five measurements per condition. Standard errors were calculated between subjects in each group (n = 12). All measurements are in meters.

[b] Stimulus combinations represented in this column include: target at 4.5 m + landmark at 6.0 m and target at 6.0 m + landmark at 7.5 m. “n/a” indicates that the target at 7.5 m was never paired with a farther landmark.

[c] Stimulus combinations represented in this column include: target at 6.0 m + landmark at 4.5 m and target at 7.5 m + landmark at 6.0 m. “n/a” indicates that the target at 4.5 m was never paired with a nearer landmark.

GENERAL DISCUSSION

In Experiment 1, there was a dramatic increase in response consistency when participants saw a salient landmark stimulus near the walking path during the preview compared with conditions in which there was no landmark. The results of Experiment 2 suggest that this result was not due to differences in the perceived location of the walking target caused by the presence of the landmark during the preview. This result is consistent with other examples of increased response consistency in more complex path integration tasks when participants walk in the context of nearby remembered landmarks (Philbeck, Klatzky, Behrmann, Loomis, & Goodridge, 2001; Rieser, 1999), but the current work is the first to show this effect in a simple single-segment walking trajectory. Our interpretation of these increases in response consistency is the following. When participants believe that they are close to the landmark (a determination based on path integration), they become more certain of their self-location. At a more mechanistic level, this reduction in positional uncertainty might be thought of as discarding a portion of the accrued random error in estimated self-location that is inherent in the path integration process. This flushing of random error near remembered landmarks is presumably responsible for the overall increase in response consistency in reaching the final target.

Interestingly, even when there was no landmark cone near the target, the entire workspace was visible during the preview. Therefore, in principle, participants in the "no landmark" conditions could have imagined themselves passing any remembered object in the workspace and increased their response consistency by the same process as the Remembered Landmark group presumably did. To some extent, then, the flushing of random error in estimated self-location appears to be under the participants' control. If this is so, why do participants not simply maintain the most precise self-location estimate possible throughout the walking path, rather than wait until there is a particularly salient landmark to do so? Part of the answer no doubt lies in the fact that certain locations or objects in the environment are more likely than others to be selected as reference points (Sadalla, Burroughs, & Staplin, 1980). This being the case, cues that draw attention to particular parts of the environment (in our experiment, the presence of a cone that was visually similar to the target cone) may enhance the likelihood that those locations will be selected as a landmark for the purposes of navigation. In addition, maintaining a maximally precise location estimate on-line may very well be more effortful or otherwise consume more cognitive resources than updating one's location relative to a single location on the way to a final destination. More research is required to determine the boundary conditions for the beneficial effects of remembered landmarks on path integration.

Dividing the trajectory into subunits may effectively reduce the time scale over which path integration must be performed, even if there are no direct sensory cues to signal unambiguously the transition between subunits. In this view, remembered or imagined landmarks could reduce demands on memory by serving as spatial placeholders; once a landmark has been passed, path integration need only be performed relative to that landmark. Interestingly, the highly expert navigators in the Republic of Micronesia apparently make use of just such a strategy to help them keep track of their position while sailing large distances without instruments (Gladwin, 1990). They update their progress relative to a series of islands, some of which do not exist but which are imagined to be just out of sight below the horizon. Thus, the islands are not directly perceptible and cannot be used for landmark-based navigation.

Finally, throughout this paper, we have referred to walking near a remembered landmark location as a situation in which direct perception of the landmark is not possible. Participants do have direct perceptual access to on-going sensory self-motion information and presumably update the position of the remembered landmark based on this perception. In this sense, the remembered landmark enjoys a certain psychological reality that, in many ways, is akin to perceiving the landmark through touch or vision (Rieser, 1989). The remembered and updated landmark location may even be coincident with its corresponding physical location to the extent that path integration provides an accurate estimate of self-location. The fact remains, however, that under these conditions, only internally generated self-motion information can be used for estimating self-location, and because this information is subject to cumulative random error, self-location cannot be determined unambiguously. We therefore consider this paradigm to rely upon path integration and not piloting (landmark-based navigation).

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