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Homing by path integration when a locomotion trajectory crosses itself

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Abstract. Path integration is a process with which navigators derive their current position and orientation by integrating self-motion signals along a locomotion trajectory. It has been suggested that path integration becomes disproportionately erroneous when the trajectory crosses itself. However, there is a possibility that this previous finding was confounded by effects of the length of a traveled path and the amount of turns experienced along the path, two factors that are known to affect path integration performance. The present study was designed to investigate whether the crossover of a locomotion trajectory truly increases errors of path integration. In an experiment, blindfolded human navigators were guided along four paths that varied in their lengths and turns, and attempted to walk directly back to the beginning of the paths. Only one of the four paths contained a crossover. Results showed that errors yielded from the path containing the crossover were not always larger than those observed in other paths, and the errors were attributed solely to the effects of longer path lengths or greater degrees of turns. These results demonstrated that path crossover does not always cause significant disruption in path integration processes. Implications of the present findings for models of path integration are discussed.

Keywords: crossover, dead reckoning, encoding-error model, inertial navigation, pathway completion

1 Introduction

In order to navigate successfully, navigators need to remain oriented with respect to a surrounding environment. Spatial orientation is typically maintained by recognizing landmarks in known locations, but the navigators can also derive their current position and orientation by integrating signals that indicate the extent of self-motion along their locomotion trajectory. The signals include those generated inside the body (eg vestibular and proprioceptive signals) and those provided externally (eg optic and acoustic flow). This process, which is known as path integration (or dead reckoning), is a fundamental constituent of spatial navigation ability in many species including humans (Etienne & Jeffery, 2004; Gallistel, 1990; Loomis, Klatzky, Golledge, & Philbeck, 1999; Mittelstaedt & Mittelstaedt, 1982; Wehner & Srinivasan, 2003). For example, blindfolded human navigators can walk to a previously viewed target up to 20 m away without showing any systematic error (Rieser, Ashmead, Talor, & Youngquist, 1990; Thomson, 1983). Similarly, it has been well documented that spatial knowledge about the environment acquired from blind walking alone is comparable with spatial knowledge obtained through other modalities (eg Harrison & Turvey, 2010; Schwartz, 1999; Yamamoto & Shelton, 2005). These findings demonstrate that humans possess reasonably good ability at path integration.

In the literature path integration has often been studied by examining how well navigators can come back to their initial position after locomotion without the aid of external landmarks. To explain performance in this homing task, two classes of models have been proposed. One postulates that the navigators always maintain a homing path that directly takes them back to the origin of locomotion (Fujita, Loomis, Klatzky, & Golledge, 1990; Merkle, Rost, & Alt, 2006; Müller & Wehner, 1988; Séguinot, Cattet, & Benhamou, 1998).

According to this class of models, the homing path is computed on a moment-by-moment basis by continuously integrating changes in travel direction and distance as the navigators take each step. As a result, these models require little or no internal representation of a locomotion trajectory and posit that homing performance is independent of the shape of the trajectory. By contrast, the other class of models, which are referred to as configural models (Klatzky, Beall, Loomis, Golledge, & Philbeck, 1999), assumes that the navigators first encode direction and distance of their traveled path during navigation, and then derive the homing path from stored representations of the traveled path when needed (Fujita, Klatzky, Loomis, & Golledge, 1993; Klatzky et al., 1990; Loomis et al., 1993). Because the traveled path is explicitly encoded and utilized to determine the homing path, the configural models predict that geometric properties of the traveled path influence homing performance. Although there has been some evidence that humans use both of these path integration strategies (Wiener, Berthoz, & Wolbers, 2011; Wiener & Mallot, 2006), it has frequently been the case that human path integration is described as a process that follows the configural models (Klatzky et al., 1999; May & Klatzky, 2000; Péruch, May, & Wartenberg, 1997).

A primary reason why the configural models have been frequently applied to human path integration is that one particular configural model, the encoding-error model (Fujita et al., 1993), has been quite successful in accounting for performance in a simple homing task. This model posits that error in homing arises entirely from systematic bias in encoding a traveled path. In other words, it assumes that no additional error emerges from computation and execution of a homing path. Although this assumption might seem simplistic, by properly modeling the observed pattern of encoding bias, the encoding-error model explained more than 90% of the variance in homing performance when blindfolded participants were guided through two linear segments and walked unaided to the origin—specifically, it accounted for 93% of the variance in the distance walked in an attempt to go back to the origin and 92% of the variance in the turn made at the end of the guided path to face the origin (Fujita et al., 1993; Loomis et al., 1993). Subsequently, the model was further validated by applying it to data from other experiments in which participants performed homing tasks after traversing one- or two-segment paths under a variety of conditions (Klatzky et al., 1999; May & Klatzky, 2000; Péruch et al., 1997).

Given its simplicity, the success of the encoding-error model is impressive. However, it should be noted that currently the scope of the model is limited to simple paths that consist of two linear segments and a single intervening turn (Klatzky et al., 1999; May & Klatzky, 2000; Péruch et al., 1997). When Fujita et al. (1993) applied the model to paths that were composed of three linear segments and two turns, the model's performance declined rather quickly—it accounted for only 71% of the variance in the walked distance and 64% of the variance in the turn, even after adding one more parameter to the model. In particular, this breakdown of the model was attributed to conditions in which the third segment of a traveled path crossed the first segment (figure 1). Participants made particularly large homing errors after they were guided along this path (Klatzky et al., 1990; Loomis et al., 1993), but the model failed to predict these errors. According to Fujita et al. (1993, page 311), it was "in precisely these cases, which subjects find most difficult, that the encoding-error model itself breaks down."

Considering the great potential of the encoding-error model, it is important to extend the model to include complex paths that have more than two linear segments. Given the current understanding that the crossover in a traveled path is particularly problematic to the model (Fujita et al., 1993; Klatzky et al., 1990; Loomis et al., 1993), what follows logically would be an attempt to construct a new version of the model that assumes the role of path crossover in path integration. However, it should be pointed out that it is not yet clear to what extent

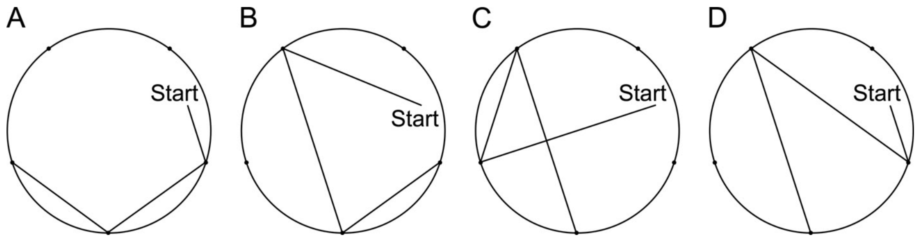

Figure 1. Three-segment paths used in previous studies (Klatzky et al., 1990; Loomis et al., 1993) in which the effect of path crossover was reported. All four paths were used by Klatzky et al. (1990). Only paths A and C were used by Loomis et al. (1993). In these experiments blindfolded participants were guided along these paths and asked to walk directly back to the starting point from the end of each path. Turns were made at the vertices of a pentagon (indicated by filled dots in the figure). This pentagon inscribed a circle whose diameter was 3 m or 10 m in the Klatzky et al. (1990) study and 6 m in the Loomis et al. (1993) study. The starting point was near the midpoint of one side of the pentagon.

the increased homing error observed in previous studies (Klatzky et al., 1990; Loomis et al., 1993) was attributable to the possible effect of path crossover. These previous studies were not designed to examine the effect of path crossover per se, and as a consequence the presence of path crossover was not controlled independently of other factors that are known to affect path integration performance: the length of a traveled path and the amount of turns experienced along the path (Böök & Gärling, 1980; Lederman, Klatzky, Collins, & Wardell, 1987; Wan, Wang, & Crowell, 2013; Worchel, 1951). Because path integration is carried out without the aid of external sources of locational information, more errors accumulate as navigators travel farther and make greater turns (Etienne, Maurer, Georgakopoulos, & Griffin, 1999). The particular path that contained a crossover was indeed the longest of the four three-segment paths that were used in the previous studies, and the total degrees of turns involved in the crossover path were almost as large as those contained in the path of the greatest turns (figure 1). Therefore, even if path crossover had some effects on path integration, they were confounded by the effects of the path length and turns in the previous studies.

Given that the role of path crossover in path integration, if confirmed, would significantly constrain the way in which the encoding-error model is extended, it is important to clarify whether path crossover truly causes any additional errors above and beyond what the path length and turns produce. Thus, the present study was designed to address this issue by examining the effect of path crossover on errors in a homing task while controlling lengths and turns of traveled paths. Findings from this study would provide important guidance for further development of theoretical models of human path integration.

2 Method

The experiment reported below was conducted in accordance with the Declaration of Helsinki (World Medical Association, 2008) and was approved by the Institutional Review Board of Cleveland State University.

2.1 *Participants*

Thirty-two participants (sixteen men and sixteen women, mean age = 25.6 years) were recruited from the Cleveland State University community. They received either monetary compensation or partial credit in psychology courses.

2.2 *Design*

The experiment took place in a 5.7 × 7.8 m laboratory. Room walls were covered with ceiling-to-floor curtains, and the floor had no discernible patterns. There were no objects in the room that could have functioned as landmarks.

Paths participants walked in the experiment began at a fixed starting point that was approximately in the center of the room. The paths had three segments (figure 2). The first and second segments were 2 m long each and separated by a right-angle turn. These two segments were parallel to two sides of the room. Between the second and third segments, participants made either a smaller (105°) turn or a larger (165°) turn. There were two lengths of the third segment (1 m or 3.9 m), which created two total lengths of the paths (shorter: 5 m; longer: 7.9 m). Thus, by factorially combining the angles of the second turn and the total lengths of the paths, the following four types of paths were constructed: smaller–shorter (105° and 5 m), smaller–longer (105° and 7.9 m), larger–shorter (165° and 5 m), and larger–longer (165° and 7.9 m). As depicted in figure 2, the first and third segments of the larger–longer path crossed each other. The angles of the second turn and the lengths of the third segment were selected so that (a) the straight-line distance between the end of any of the four paths and the starting point was always 2 m and (b) paths of the same length required a turn of the same magnitude when participants attempted to face the starting point at the end of the paths.

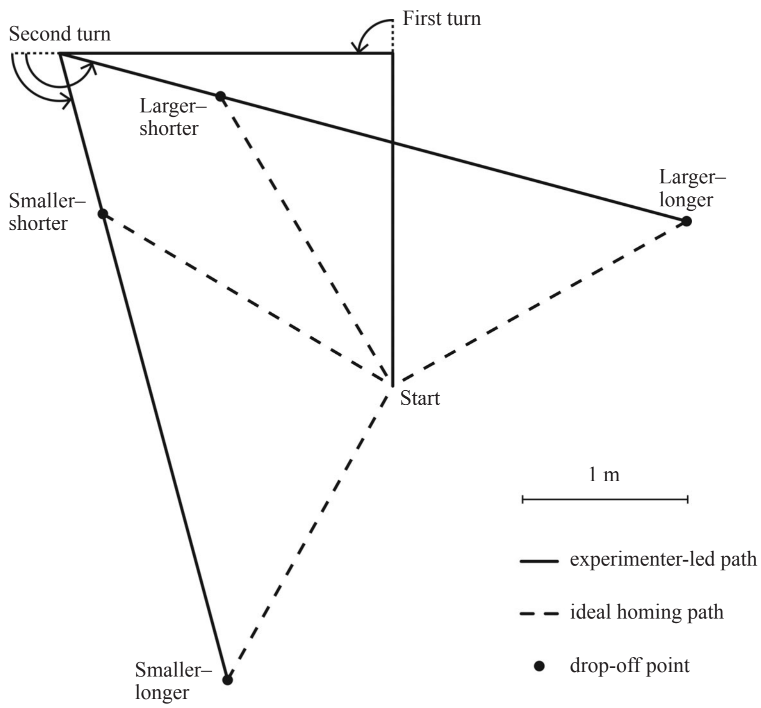

Figure 2. Configuration of paths that participants walked in the present experiment. Blindfolded participants were guided along segments indicated by solid lines and released at one of the drop-off points. They then attempted to walk straight back to the starting point (the ideal paths leading to the starting point are specified by dashed lines). By factorially combining two angles of the second turn (105° and 165°) and two lengths of paths (5 m and 7.9 m), the following path types were constructed: smaller–shorter (105° and 5 m), smaller–longer (105° and 7.9 m), larger–shorter (165° and 5 m), and larger–longer (165° and 7.9 m). Note that there were also paths in which participants made clockwise turns while being guided (ie at first and second turns). Those paths were bilaterally symmetrical to paths depicted in this figure around the first segment.

In addition to the main types of paths described above, four other paths were constructed by using 120° and 150° turns between the second and third segments (the lengths of the three segments as well as the configuration of the first and second segments remained the same). These additional paths were used only to increase the variability of the paths in the experiment. Thus, data from these additional paths were not included in the analysis.

Each participant walked all types of paths. The four main types of paths (smaller–shorter, smaller–longer, larger–shorter, and larger–longer) were walked three times apiece. The four additional paths were walked once apiece. These 16 trials were randomly presented with the constraint that one of the additional paths was always used in the first trial (so that it served as a practice trial as well). Half the participants (eight men and eight women) always turned clockwise at the first and second turns, and the other half always turned counterclockwise.

As described below, half the participants (eight men and eight women) viewed the laboratory from the starting position immediately before performing the first trial. This procedure was intended to ensure that participants began the experiment with the equal state of spatial orientation. However, this preview also provided the participants with prior information about the possible extent of to-be-walked paths, which could have affected subsequent path integration performance (Philbeck, Klatzky, Behrmann, Loomis, & Goodridge, 2001; Yamamoto, 2012). To confirm that the preview manipulation did not introduce any significant bias in the data, the other half of the participants performed the experiment without viewing the laboratory at all. The availability of the viewing opportunity was fully crossed with participants' gender and turning direction. For example, out of the eight male participants who had the viewing opportunity, four participants always turned clockwise at the first and second turns.

2.3 *Procedure*

Participants were run individually in the experiment. Before entering the laboratory, participants were given instructions about the general procedure of the experiment (but no information about the configuration of the paths), and asked to wear a blindfold and hearing protectors (noise reduction rating = 21 dB). The hearing protectors were used to reduce the influence of auditory spatial cues that could have served as external landmarks. Then participants were guided to the starting point of the paths by following a circuitous route. Participants were not taken directly to the starting point so that they would be disoriented with respect to larger spatial structures (eg spatial relation between the laboratory and nearby rooms); this prevented participants from using these environmental reference frames to keep track of their location during the experiment. When positioned at the starting point, half the participants (eight men and eight women) lifted the blindfold to view the laboratory. At this point the room was empty except for a piece of tape on the floor that indicated the starting point. After this initial viewing, these participants remained blindfolded until the end of the experiment. The other half was not given this viewing opportunity. To carry out a trial, an experimenter held the participants' arm and guided them along one of the paths. To make the first and second turns, participants stopped at the end of a linear segment, pivoted to face the direction of subsequent walking, and proceeded to the next segment under the experimenter's guidance. At the end of the third segment (ie at one of the drop-off points in figure 2), participants were released and instructed to go directly back to the starting point—that is, by making a single turn and walking one straight path. The stopping point at which participants ceased to walk in an attempt to step exactly on the starting point was recorded. Subsequently, participants were guided to the starting point via a circuitous path so that they would not receive any feedback on their performance in the just-completed trial.

Prior to each trial, participants were given a five-digit number, which they attempted to recall immediately after executing their homing response. A new number was randomly generated for each trial. This number was typically retained through rehearsal, and thus this concurrent task was intended to interfere with subvocal pace counting while walking. Because the accuracy of recalling this number was generally good (M = 85% and SD = 14%) and recall errors were distributed across the four path types, participants' performance in the main homing task was not analyzed as a function of accuracy in this number recall task.

2.4 *Data analysis*

To evaluate participants' performance, the following three measures were derived from the stopping point: (a) the straight-line distance between the stopping point and the starting point (ie how far away participants were from the starting point when they stopped; this will be referred to as stopping distance hereafter); (b) the magnitude and direction of the turn made by participants at the drop-off point (ie the direction to which participants walked in an attempt to go back to the starting point); and (c) the straight-line distance between the drop-off point and the stopping point (ie the distance walked by participants). The latter two were computed under the assumptions that participants made a smaller of two possible turns (clockwise or counterclockwise) to face a given direction and showed only negligible veering while walking back to the starting point (observations during the experiment confirmed the validity of these assumptions). To assess participants' tendency in overestimating or underestimating the direction and distance to be walked, the walked direction and distance were compared against the direction and distance between the drop-off point and the starting point (ie the ideal direction and distance to be walked) and converted into *signed walked direction error* and *signed walked distance error*. These errors were defined as positive when the amount of turning and walking exceeded the ideal values required to accurately reach the starting point. To determine participants' accuracy in returning to the starting point, the absolute values of signed walked direction error (*absolute walked direction error*), signed walked distance error (*absolute walked distance error*), and stopping distance (*stopping distance error*) were also analyzed. Finally, to measure variability of participants' responses, standard deviations of walked direction (*variable walked direction error*), walked distance (*variable walked distance error*), and stopping distance (*variable stopping distance error*) were calculated from three trials in which the same path was presented.

The means of these errors were computed for each participant and for each path type, and subjected to analyses of variance (ANOVAs) with preview (whether or not viewing the laboratory at the beginning) as a between-participant factor and turn angle (of the second turn: 105° or 165°) and path length (5 m or 7.9 m) as within-participant factors. Because walked direction errors were defined by directional data, their means and standard deviations were initially derived by both linear statistics and circular statistics (Fisher, 1993). However, no meaningful difference was present between the two sets of means and standard deviations, and therefore linear means and standard deviations were used in the following analyses. Means and standard deviations of other errors were calculated by linear statistics. Data were also analyzed without outliers, which were identified, separately for each error type and for each condition, as data points that were more than two standard deviations away from the mean. However, removal of the outliers did not alter the outcome of data analysis. Thus, all data points were included in the results reported below.

The design of the current experiment allowed us to statistically separate the effects of path crossover from those of turn angle and path length. If patterns of homing error were accounted for by turn angle or path length alone, then only main effects of these variables would be significant in the ANOVAs. On the other hand, the crossover effects would manifest themselves in the form of interaction between turn angle and path length—that is, the larger–longer path (the only path that contained a crossover) would yield worse performance than any other paths, and this performance decrement would not be explained by additive effects of turn angle and path length.

2.5 *Power analysis*

In previous studies in which the effect of path crossover was found (Klatzky et al., 1990; Loomis et al., 1993) the size of the effect (including cases in which the effect did not reach statistical significance) varied from 0.20 to 0.64 (expressed as η_p^2 values, which were derived from F ratios and degrees of freedom reported in the previous studies). Thus, in the present study we aimed to detect a crossover effect in the magnitude of $\eta_p^2 = 0.20$, with $\alpha = 0.05$ and $1-\beta = 0.95$. According to a priori power analysis, this required the sample size of 16, given the design of the current experiment. We tested thirty-two participants in this experiment so that it was sufficiently powerful to detect the crossover effect (if present) in each group of participants (ie with or without preview of the laboratory).

3 Results

As explained above, data were analyzed by ANOVAs in which preview was a between-participant factor and turn angle and path length were within-participant factors. However, preview showed no meaningful effects—all main effects and interactions involving preview were nonsignificant; and, importantly, the three-way interaction (preview × turn angle × path length) was minimal in any of the analyses ($F\text{s}_{1,30} < 1.41$, $p\text{s} > 0.24$, $\eta_G^2\text{s} < 0.02$) (for the definition of η_G^2 and the relation between η_G^2 and η_p^2, see Bakeman, 2005). This indicates that preview did not alter the way in which turn angle and path length interacted; that is, preview neither enhanced nor diminished crossover effects. Thus, detailed results are reported below in terms of only turn angle and path length.

Figure 3 displays scatterplots of stopping points separately for four path types. The distributions of stopping points suggest that homing errors yielded from the larger–longer path (the only path that contained a crossover) were not uniquely different from those observed in other three paths, and analyses reported below confirmed this observation. Among the eight types of error analyzed in the present experiment, signed walked direction error, variable walked direction error, and variable stopping distance error did not yield any significant effects ($F\text{s}_{1,30} < 2.99$, $p\text{s} > 0.09$, $\eta_G^2\text{s} < 0.03$). Thus, the following sections are focused on the other five kinds of error that showed significant results. Means of nonsignificant errors are summarized in table 1.

3.1 *Signed walked distance error*

Means and standard deviations of the four path types were as follows: $M = 0.28$ cm, SD = 57.08 cm (smaller–shorter); $M = 44.90$ cm, SD = 76.68 cm (smaller–longer); $M = 3.50$ cm, SD = 56.96 cm (larger–shorter); and $M = 36.51$ cm, SD = 62.97 cm (larger–longer). Participants tended to walk farther than they needed when they attempted to go back to the starting point after following longer paths. On the other hand, they did not exhibit any clear overestimation or underestimation tendency when they walked shorter paths. Importantly, signed walked distance errors yielded from the two longer paths resembled each other, suggesting that path crossover did not cause any increase of this type of error. These observations were supported statistically by the main effect of path length ($F_{1,30} = 11.77$, $p < 0.01$, $\eta_G^2 = 0.09$) and the lack of interaction between turn angle and path length ($F_{1,30} = 0.70$, $p = 0.41$, $\eta_G^2 < 0.01$). Turn angle did not have a main effect either ($F_{1,30} = 0.07$, $p = 0.80$, $\eta_G^2 < 0.01$).

3.2 *Absolute walked distance error*

Means and standard deviations of the four path types were as follows: $M = 52.32$ cm, SD = 30.79 cm (smaller–shorter); $M = 75.24$ cm, SD = 54.99 cm (smaller–longer); $M = 54.38$ cm, SD = 36.33 cm (larger–shorter); and $M = 70.96$ cm, SD = 43.37 cm (larger–longer). Participants made greater errors after walking longer paths, as statistically shown by the main effect of path length ($F_{1,30} = 7.98$, $p < 0.01$, $\eta_G^2 = 0.05$). However, the interaction between turn angle and path length as well as the main effect of turn angle were not significant, ($F_{1,30} = 0.16$, $p = 0.69$, $\eta_G^2 < 0.01$) and ($F_{1,30} = 0.03$, $p = 0.86$, $\eta_G^2 < 0.01$), respectively, indicating that the pattern of absolute walked distance errors can be explained by path length alone.

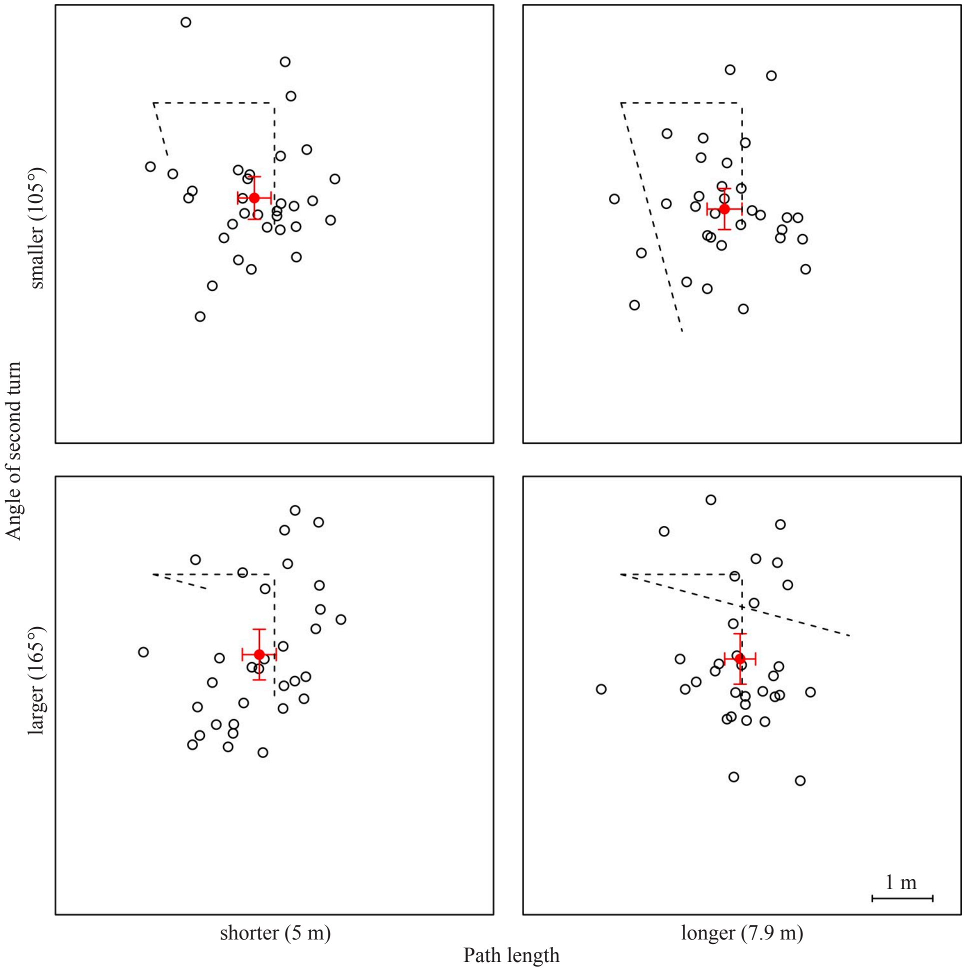

Figure 3. Distribution of stopping points. These are the points at which participants stopped when they attempted to walk from the end of a path to the starting point (the path is shown by dashed lines; the starting point is at the center of each panel). Each open dot shows the mean stopping point for one participant, collapsed over three attempts in each path type. The filled dots represent the overall mean stopping points for each of the four path types, collapsed over thirty-two participants. To compute these means, data from paths in which participants turned clockwise at first and second turns were bilaterally flipped around the first segment of the paths. Error bars indicate 95% confidence intervals along two orthogonal dimensions.

Table 1. Means of errors that did not show significant effects.

Path type	Error type		
	SDirec/°	VDirec/°	VStop/cm
Smaller–shorter	7.33 (±14.03)	28.15 (±9.03)	55.52 (±11.24)
Smaller–longer	2.81 (±8.56)	27.11 (±10.69)	55.69 (±11.07)
Larger–shorter	21.94 (±17.56)	31.06 (±9.27)	64.51 (±12.80)
Larger–longer	3.55 (±13.66)	28.07 (±6.91)	68.46 (±15.64)

Notes: Mean errors were first computed per participant and per path type, and then collapsed over participants to derive overall means reported in this table. Error types are abbreviated as follows: SDirec = signed walked direction error; VDirec = variable walked direction error; and VStop = variable stopping distance error. Values in parentheses give 95% confidence intervals.

3.3 *Variable walked distance error*

Means and standard deviations of the four path types were as follows: $M = 41.76$ cm, SD = 25.64 cm (smaller–shorter); $M = 54.36$ cm, SD = 31.96 cm (smaller–longer); $M = 50.03$ cm, SD = 39.90 cm (larger–shorter); and $M = 60.58$ cm, SD = 42.73 cm (larger–longer). Although the larger–longer path (the path containing a crossover) did yield the largest error, there was also a tendency that walked distances were more variable after walking longer paths in general. As consistent with this observation, the main effect of path length was significant ($F_{1,30} = 4.14$, $p = 0.05$, $\eta^2_G = 0.03$); but the interaction between turn angle and path length was not significant ($F_{1,30} = 0.03$, $p = 0.87$, $\eta^2_G < 0.01$), showing that the relatively large error observed in the larger–longer path was not due to path crossover. The main effect of turn angle was not significant either ($F_{1,30} = 1.84$, $p = 0.19$, $\eta^2_G = 0.01$).

3.4 *Absolute walked direction error*

Means and standard deviations of the four path types were as follows: $M = 35.66°$, SD = 28.87° (smaller–shorter); $M = 28.85°$, SD = 22.53° (smaller–longer); $M = 46.36°$, SD = 30.81° (larger–shorter); and $M = 34.37°$, SD = 22.31° (larger–longer). Participants tended to make greater errors after walking shorter paths. In addition, albeit small, there was a tendency that paths containing the larger second turn yielded increased absolute walked direction errors. In line with these observations, the main effect of path length was significant ($F_{1,30} = 6.01$, $p = 0.02$, $\eta^2_G = 0.03$), and the main effect of turn angle was marginally significant ($F_{1,30} = 3.68$, $p = 0.06$, $\eta^2_G = 0.02$). However, the interaction between turn angle and path length was not significant ($F_{1,30} = 0.81$, $p = 0.38$, $\eta^2_G < 0.01$), indicating the absence of crossover effects.

3.5 *Stopping distance error*

Means and standard deviations of the four path types were as follows: $M = 129.09$ cm, SD = 78.48 cm (smaller–shorter); $M = 136.89$ cm, SD = 65.29 cm (smaller–longer); $M = 160.80$ cm, SD = 82.18 cm (larger–shorter); and $M = 155.05$ cm, SD = 78.96 cm (larger–longer). Participants tended to be farther away from the starting point when they experienced the larger second turn, as statistically shown by the main effect of turn angle ($F_{1,30} = 6.50$, $p = 0.02$, $\eta^2_G = 0.03$). On the other hand, stopping distance error was not modulated by path length ($F_{1,30} = 0.01$, $p = 0.92$, $\eta^2_G < 0.01$). The interaction between turn angle and path length was not significant either ($F_{1,30} = 0.62$, $p = 0.44$, $\eta^2_G < 0.01$), showing that path crossover exerted little effect on stopping distance error.

4 Discussion

When homing errors showed any significant effects, there was a general tendency that the larger–longer path (the only path that contained a crossover) did not yield the greatest errors among the four path types. The interaction between turn angle and path length was virtually nonexistent in any of the error types ($F\text{s}_{1,30} < 1.02$, $p\text{s} > 0.32$, $\eta^2_G\text{s} < 0.01$) (including those reported in table 1), indicating that the homing errors were attributed to the sole or additive effects of turn angle and path length. Thus, in the present experiment it was clear that path crossover had little or no effect on participants' homing performance.

Among the eight kinds of error analyzed in the present study, signed walked distance error, absolute walked distance error, variable walked distance error, absolute walked direction error, and stopping distance error revealed observable effects of turn angle and path length. Specific patterns shown by each of these errors were consistent with those observed in previous studies. For example, just like participants in the present study, participants in the Lederman et al. (1987) study increasingly overestimated the distance between the drop-off point and the starting point as they walked longer paths (ie the pattern shown by signed walked distance error). Similarly, Wan et al. (2013) showed that absolute walked distance error enlarged as traveled paths lengthened, and that stopping points were farther away from the starting point when the paths contained larger turns. As for variable walked distance error, although it has often been the case that variable errors were not formally analyzed in previous studies, a general trend is that variable walked distance error becomes larger as the length of a stimulus path increases (eg Wan et al., 2013). Overall, the present results and corresponding previous findings converge to indicate that greater path lengths and turns make path integration more erroneous (Böök & Gärling, 1980; Lederman et al., 1987; Wan et al., 2013; Worchel, 1951).

Results shown by absolute walked direction error might appear a little more complex, but they are also largely consistent with previous findings. One straightforward aspect of the results is that participants' response direction was less accurate when there was a greater turn in a stimulus path—a finding that has been reported in the literature (eg Wan et al., 2013). The other aspect of the present results is that the shorter paths (smaller–shorter and larger–shorter) yielded larger absolute walked direction errors than the longer paths (smaller–longer and larger–longer). It is not readily clear why this had to be the case, but one relevant factor may be that in the shorter paths participants executed a response turn shortly after making the second turn (see figure 2). As a result, it is possible that participants experienced greater interference between the two turns in the shorter paths. If present, such interference would lead to more erroneous response turns. Indeed, Faineteau, Gentaz, and Viviani (2003, 2005) showed that in a manipulatory space (ie a space that can be explored by hand and arm movements alone; Lederman et al., 1987) path integration tends to be performed less accurately when inflection points in a traveled path are more clustered together. The present results suggest that the same would apply to path integration in an ambulatory space (ie a space that entails whole-body locomotion for its exploration), although more thorough investigation has to be conducted before making any conclusions.

It is important to note that, when previous studies found the possible detrimental effect of path crossover on path integration, participants' homing performance was characterized by using a subset of errors that were measured in the present study—namely, signed walked direction error, signed walked distance error, absolute walked direction error, and absolute walked distance error (Klatzky et al., 1990; Loomis et al., 1993). Thus, different conclusions drawn from the present study and the previous studies were not due to difference in measures used. In fact, although interpreted differently, results from the present study and those from the previous studies were largely consistent in that they both showed worsened homing errors after participants walked longer paths containing larger turns. Considering the results from other studies that indicate the roles of path length and turn angle in path integration (Böök & Gärling, 1980; Lederman et al., 1987; Wan et al., 2013; Worchel, 1951), it is possible that increased homing errors yielded from crossover paths in the previous studies were chiefly explained by additive effects of the long path lengths and large turns, both of which were concomitant to path crossover (see figure 1).

Although the focus of the present study was on the encoding-error model, it is worth mentioning that findings from this study are also consistent with models that do not involve mental representations of a locomotion trajectory in path integration processes. As discussed in the introduction, these models postulate that a homing path is computed by continuously integrating changes in travel direction and distance. Because integration errors would accumulate as more changes are integrated, these models also predict that homing errors increase as navigators traverse greater direction and distance (Etienne et al., 1999). Furthermore, according to these models, geometric properties of the locomotion trajectory do not play any roles in path integration. Therefore, path crossover should be irrelevant to homing performance in the first place. The lack of crossover effects in the present study accords with this prediction as well.

Results from the present study have important implications for possible extension of the encoding-error model. The present study demonstrated that path crossover does not always impair path integration performance, and thus new versions of the model should not incorporate the effect of path crossover, at least as something that is omnipresent. Rather, given the suggested importance of path length and turn angle, the new versions of the model should more clearly reflect the fact that path integration errors enlarge as navigators walk farther and make greater turns. For example, in the current version, information about path length and turn angle is used only to derive their effects on signed walked direction error and signed walked distance error (Fujita et al., 1993). The roles of path length and turn angle in the model may need to be expanded by including their contributions to other types of error—for example, the effect of path length on absolute walked distance error, which was found to be significant in the present study (for a relevant discussion, see Wan et al., 2013). Such an effort would advance our understanding of human path integration.

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