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BRIEF REPORT

Spatial Updating Strategy Affects the Reference Frame in Path Integration

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Abstract This study investigated how spatial updating strategies affected the selection of reference frames in path integration. Participants walked an outbound path consisting of three successive waypoints in a featureless environment and then pointed to the first waypoint. We manipulated the alignment of participants' final heading at the end of the outbound path with their initial heading to examine the adopted reference frame. We assumed that the initial heading defined the principal reference direction in an allocentric reference frame. In Experiment 1, participants were instructed to use a configural updating strategy and to monitor the shape of the outbound path while they walked it. Pointing performance was best when the final heading was aligned with the initial heading, indicating the use of an allocentric reference frame. In Experiment 2, participants were instructed to use a continuous updating strategy and to keep track of the location of the first waypoint while walking the outbound path. Pointing performance was equivalent regardless of the alignment between the final and the initial headings, indicating the use of an egocentric reference frame. These results confirmed that people could employ different spatial updating strategies in path integration (Wiener, Berthoz, & Wolbers *Experimental Brain Research 208*(1) 61–71, 2011), and suggested that these strategies could affect the selection of the reference frame for path integration.

Keyword Spatial updating · Path integration · Reference frame · Virtual environment

Introduction

Path integration refers to the process by which navigators continuously integrate sensory cues in order to estimate their current location and orientation relative to a destination in the absence of position-informative information (Gallistel, 1990). The cognitive processes underlying path integration have received much experimental and theoretical interest because path integration may be a key component of forming a cognitive map (Tolman, 1948; Wang, 2016), which is typically considered the most advanced form of spatial knowledge. In this study, we manipulated the spatial updating strategy in path integration, and examined how it affected participants' selection of a reference frame.

The use of an egocentric reference frame in path integration refers to the process whereby the navigator represents and updates its location in an environment using a reference system centered on the body (Wang, 2016). One of the integral characteristics of an egocentric reference frame is that the principal reference direction (front) or axis (front–back) is constantly changing with respect to the environment during locomotion. The use of an allocentric reference frame refers to the process whereby the navigator represents and updates its position in the environment using a reference system external to the body and anchored in the environment (Klatzky, 1998). In such a reference system, the reference directions or axes are stable with respect to the local environment (although they may change from one region of the environment to another; see Meilinger et al., 2014). There is evidence of the use of both egocentric and allocentric reference frames in path integration and spatial updating (Gramann et al., 2005; Kelly et al., 2007; Mou et al., 2004).

Figure 1a illustrates the use of an egocentric reference system in which the principal reference axes are defined by facets of the body. The correct turning angle to home is the

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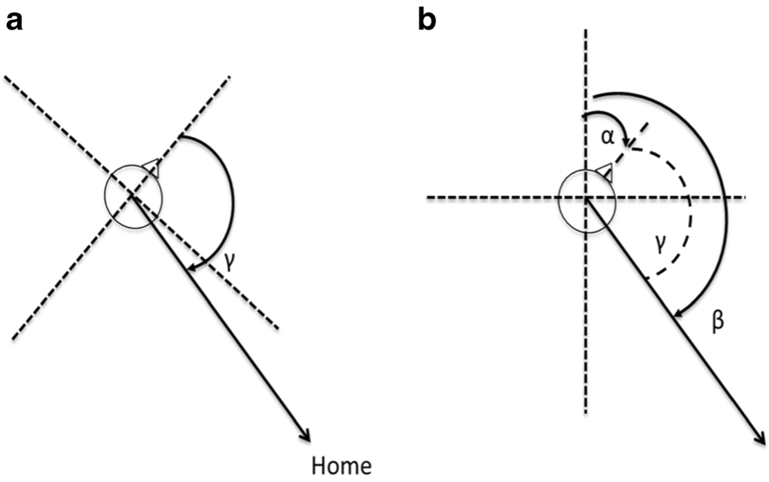

Fig. 1 The *circle* and the *triangle* represent a navigator and the facing orientation. **a** Egocentric reference system, in which γ is the correct turning angle to face home. **b** Allocentric reference system, in which α is the navigator's allocentric heading, β the allocentric bearing of home, and γ the correct turning angle to face home and must be computed from α and β

egocentric bearing of home, or the angle between egocentric front and the vector from the body to home (γ). In an egocentric reference system, the navigator's heading is always parallel to the principal reference direction, and hence the return angle computation (or retrieval) is equivalent across different headings. Therefore, if performance in walking or pointing to home is comparable across all headings, we assume that navigators adopted an egocentric reference frame. Figure 1b illustrates the use of an allocentric reference system in which the principal reference axes are fixed in the environment. The correct turning angle to home is not explicitly represented, and must be computed from the allocentric bearing of home and the allocentric heading of the navigator ($\gamma = \beta - \alpha$). In an allocentric reference system, if the navigator's heading or the home location's bearing is parallel to the assumed reference direction (i.e., α or β is 0°), the computation (or retrieval) of the correct return angle is assumed to be facilitated (Klatzky, 1998; Mou et al., 2004). Therefore, if performance in walking or pointing to home is better for headings or return directions parallel to the assumed principal reference direction than for other headings or directions, we assume that navigators adopted an allocentric reference frame.

Regardless of which type of reference frame is used, a navigator needs to update the information necessary to return home during path integration. Researchers have identified two spatial updating strategies that humans employ during this process (Wiener et al., 2011). In *continuous updating*, navigators represent and update the vector from their body to the starting location or other salient destination. This vector is often referred to as the "homing vector". In *configural updating*, navigators represent and update the outbound path itself as they locomote, and compute the homing vector at the end of the outbound path. There is empirical evidence supporting continuous updating (Wiener et al., 2011; Wiener & Mallot, 2006) and configural updating (Berthoz et al., 1995; Fujita et al., 1993; Loomis et al., 1993).

Wiener et al. (2011) showed that configural updating generally produced better homing performance than did continuous updating (only response time was faster for continuous updating). Although Wiener et al. did not discuss the use of alternative spatial reference systems, an implicit assumption of their research is that configural updating uses an allocentric reference system and continuous updating uses an egocentric reference system. We hypothesized that the spatial updating strategy could influence the selection of the reference frame in path integration, because different strategies induce different amounts of updating workload under different reference frames. Continuous updating could be implemented in either an egocentric or an allocentric reference frame but is more compatible with the former. The homing vector can be updated directly using the outputs of the system that updates the navigator's heading during locomotion (Wang, 2016). Use of an allocentric reference frame would require the homing vector to be computed indirectly from the allocentric heading of the navigator and the allocentric bearing of the destination as the navigator translated and rotated. Configural updating could also be implemented in either reference frame but is more compatible with an allocentric reference frame, as the spatial structure of the outbound path can be constructed using a single reference system as the navigator locomotes. Configural updating with an egocentric reference frame would require continuous re-alignment of spatial relationships computed using continuously changing reference frames.

Participants in the current study walked to three successive waypoints in a featureless virtual environment and then pointed to the first waypoint. The environment was featureless to ensure that body-based cues but only limited visual cues were available for path integration (Chen et al., 2017; Zhao &

Warren, 2015). Use of virtual reality enabled participants to walk independently from waypoint to waypoint thereby fully engaging the path integration system (Chen et al., 2015). The same starting position was used on all trials to encourage participants to use the initial heading as the principal reference direction should an allocentric reference system be used (Shelton & McNamara, 2001); by having participants point to the first waypoint, we ensured that they could not monitor just one home location across trials. We required participants to point to the target, rather than to turn to face or walk to it, because their heading at the end of the final leg was a key manipulation, and we wanted to ensure that they adopted and held this heading to the end of each trial and consistently across trials.

Following Wiener et al. (2011), participants were instructed to use either a configural updating strategy (Experiment 1) or a continuous updating strategy (Experiment 2). Strategy was manipulated between participants (cf. Wiener et al.) to mitigate fatigue and motion sickness which can be produced by extensive locomotion in virtual environments (each experiment alone incorporated 30 trials). To determine which reference frame participants adopted, we manipulated the alignment between the final heading in the outbound path and the initial heading, which by assumption determined the principal reference direction in an allocentric reference system. We found that the alignment between the initial and final heading affected pointing performance when participants used configural updating—consistent with the use of an allocentric reference frame—but not when they used continuous updating—consistent with the use of an egocentric reference frame.

Experiment 1

Method

Participants Twelve students (7 women) from Vanderbilt University participated in this experiment in return for extra credit in psychology courses.

Materials and Design The experiment was conducted in the Learning in Immersive Virtual Environments Laboratory (LIVE lab) at Vanderbilt University. The virtual environment was presented through Oculus Rift DK2 (from Oculus VR, Irvine, CA, USA) head-mounted display (HMD), which presented stereoscopic images at 960 × 1080 pixel resolution per eye, refreshed at 60 Hz. The HMD field of view was approximately 100° diagonally. Graphics were rendered by a 2.4-GHz Intel Xeon(R) processor with a NVIDIA Quadro FX 3800 graphics card using Vizard software (WorldViz, Santa Barbara, CA, USA). The built-in Oculus Rift head tracker was used for head orientation tracking, and a motion tracking system (Bonita; Vicon Motion Systems, Oxford, UK) tracked head position. Graphics displayed in the HMD were updated based on sensed head position and orientation.

There were 15 possible locations of waypoints (Fig. 2a). The environment had no walls, floors or ceilings, and was colored with light blue (Fig. 2b). Instructions in text would appear in the left or right side of the screen for 2 s to inform participants of the direction of the next waypoint on the outbound path.

Three experimental conditions manipulated the facing direction at the end of the outbound path (final heading) and the correct pointing direction (Fig. 3): random, in which the participant's final heading and the correct pointing direction were not parallel to the assumed fixed reference direction; reference direction aligned (RDA), in which participants' final heading was parallel to the assumed fixed reference direction, but the correct pointing direction was not; target direction aligned (TDA), in which participants' final heading was not parallel to the assumed fixed reference direction, but the pointing direction was parallel. Because the environment was featureless, we assumed that the initial heading, or the red arrow shown on the ground (see Procedure), would be used as the fixed reference direction, if participants adopted an allocentric reference frame. Therefore, performance across different experimental conditions should be equivalent under the egocentric reference frame, whereas performance in the RDA condition should be better than in the random condition under the allocentric reference frame. Performance in the TDA condition could also be better than in the random condition (but see Rump & McNamara, 2013). The distance from the final waypoint to the target location was not manipulated because the models did not make unambiguous predictions about effects of spatial reference systems on this variable.

Each participant completed five blocks of six trials each, and each block had two trials from each of the three experimental conditions (ten trials in each condition in total), presented in random order. Because the task was to remember the location of the first waypoint, we defined the outbound path as the path from the first to the third waypoints (two segments). Properties of the outbound paths were matched across experimental conditions[1] (Table 1). It is reasonable, however, to consider the segment from the starting point to the first waypoint as part of the outbound path (three segments), and we do not know how participants conceptualized the paths. Hence, we also include in Table 1 statistics on the paths from the fixed starting point to the third waypoint. These three-segment paths did not differ significantly in length or turning angle across conditions (Fs < 1).

The dependent variables were pointing error and response time. Pointing error was defined as the absolute value of the

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[1] The direction of turns (e.g., left–right–left or right–right–right) was not matched across conditions.

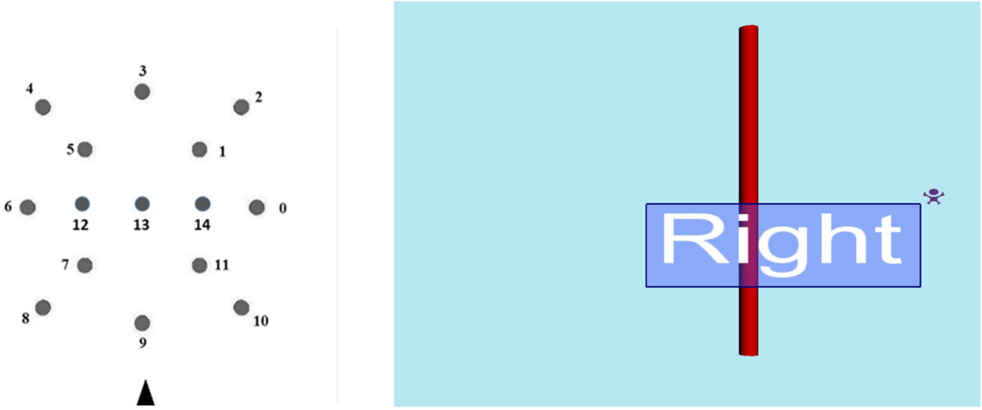

Fig. 2 The layout of posts and participants' actual view in Experiments 1 and 2. **a** Layout of posts. Participants only saw one post at a time. The *triangle* corresponds to the fixed starting position in every trial. **b** Participants' actual view and the instruction indicating the direction of the post

angular difference between the correct direction of the first waypoint and the participant's actual pointing direction. Response time was the elapsed time between the time at which the participant reached the third waypoint and the time at which the pointing response was detected (i.e., the joystick was deflected beyond the threshold).

Procedure

Participants walked to three waypoints in succession and then pointed to the first waypoint using a joystick. Participants were instructed to "mentally draw" and remember the trajectory of the path that they had walked before pointing. Procedural details were as follows:

Participants carried a joystick (Logitech Freedom 2.4 Wireless Joystick) and started every trial at the location and orientation depicted by the triangle in Fig. 2a. This position was indicated by a red arrow displayed on the virtual plane at the height of 0 m, and participants needed to look down to find it. The red arrow disappeared when participants pulled the trigger on the joystick to start the outbound path. The direction of the arrow also served as the initial heading indicator, which was the only visible cue participants could use for orienting. After pulling the trigger, a red post appeared in the virtual world (although not necessarily within the view of the participant) and a single word (left or right) was displayed in the HMD (Fig. 2b) indicating the shortest turning direction to face the red post. Participants were instructed to turn as indicated, and then to walk straight to the red post. The red post disappeared upon the participants' arrival. The same procedure was used for two blue posts presented in succession. The only visual cues to self-motion were the changes in size and position of the post in the field of view as participants walked toward it. When participants reached the second blue post, they were instructed by text presented in the HMD to use the joystick to point to the red post. Participants were not allowed to move or to change their facing orientation before pointing. When the joystick was deflected vertically or horizontally by more than 1 cm, a response would be recorded. Participants then searched for and positioned themselves over the red arrow to start the next trial. Participants completed four practice trials before starting the experiment. Practice trials were the same as the experimental trials except that the home and waypoint posts were randomly selected.

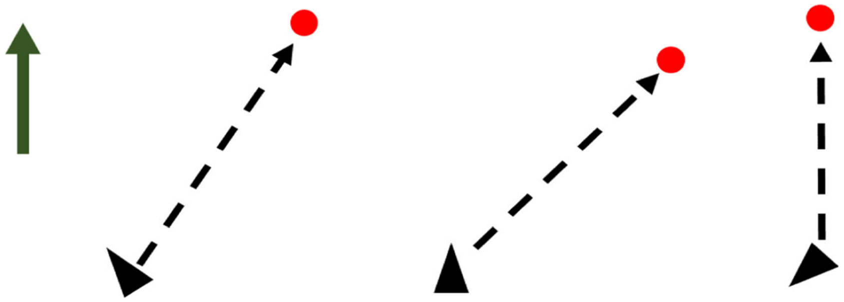

Fig. 3 Illustrations of the three experimental conditions. The *dark green arrow* represents the initial heading and the *red circle* represents the home location. The *triangle* represents the final heading, and the *dotted black arrow* represents the correct pointing direction. From left to right are random, reference direction aligned (RDA), and target direction aligned (TDA) conditions

Table 1 Properties of paths in the three experimental conditions

	RDA	Random	TDA
Outbound path length	3.07 (0.76); 5.51 (1.78)	3.07 (0.67); 6.02(1.21)	3.10 (1.16); 6.36 (1.50)
Outbound turning angle	251.1 (73.3); 265.4 (74.7)	244.9 (52.8); 260.6 (50.4)	241.5 (38.8); 265.4 (39.59)
Correct Distance to Target	1.73 (0.31)	1.69 (0.32)	1.76 (0.46)
Correct pointing angle	115.1 (37.5)	117.1 (29.3)	117.0 (31.6)
Example path	8 -> 7 -> 5	5 -> 1 -> 3	1 -> 8 -> 11

Means (standard deviations) of path properties. Distances in meters; angles in degrees. Outbound path length can be considered the sum of the lengths of the two segments of the path (the values before the semicolon), or the sum of the lengths of the three segments of the path (the values after the semicolon). Outbound turning angle can be considered the sum of the required turning angles to walk from the first to the second waypoints and from the second to the third waypoints (measured along shortest arc; values before the semicolon), or the required turning angles to walk from the starting point to the first waypoint, from the first to the second waypoints, and from the second to the third waypoints (measured along shortest arc; values after the semicolon). Correct distance to target is the straight-line distance from the third waypoint to the first waypoint. Correct pointing angle is the egocentric bearing of the first waypoint from the third waypoint (measured along shortest arc). Numbers in example paths correspond to posts in Fig. 2

Results and Discussion

Pointing error and response time were analyzed in ANOVAs with a single factor corresponding to the three experimental conditions (Fig. 4).[2]

For pointing error, the effect of condition was significant, $F(2, 22) = 4.23$, $MSE = 25.56$, $p = .03$, $\eta^2 = .28$. Pairwise comparisons showed that pointing error was significantly lower in the RDA condition than in the random condition ($t(11) = 2.24$, $p = .047$) and the TDA condition ($t(11) = 2.49$, $p = .03$). The random and TDA conditions did not differ significantly, $t(11) = 1.12$, $p = .28$.

For response time, the main effect of condition was not significant, $F(2, 22) = .217$, $MSE = .082$, $p = .806$, $\eta^2 = .019$. None of the pairwise comparisons was significant, $ts(11) < .56$, $ps > .58$.

The pattern of results for pointing error indicated that, when participants were instructed to use a configural updating strategy, they relied on a single reference direction defined by the participant's initial heading for path integration.

Experiment 2

Experiment 2 was identical to Experiment 1 except that participants were instructed to update their current position and direction continuously with respect to the red post. Our conjecture was that the use of this continuous updating strategy would lead participants to use an egocentric reference frame, and hence, eliminate the reference direction effect observed in Experiment 1.

Method

Participants Twelve students (6 women) from Vanderbilt University participated in this experiment in return for extra credit in psychology courses.

Materials, Design and Procedure Everything was identical to Experiment 1 except that participants were instructed to update their location and direction continuously with respect to the red post as they walked the outbound path.

Results and Discussion

Data were analyzed as in Experiment 1 (Fig. 5).

For pointing error, the main effect of condition was not significant, $F(2, 22) = 1.22$, $MSE = 38.56$, $p = .32$, $\eta^2 = .10$. None of the pairwise comparisons was significant, $ts(11) < 1.46$, $ps > .17$. The JZS Bayes factor for the condition effect (Rouder et al. 2009; prior odds = 1) was 2.34 (the corresponding Bayes factor in Experiment 1 was .41). In addition, the interaction between Experiments 1 and 2 in pointing error produced $F(2, 44) = 3.17$, $MSE = 32.07$, $p = .051$, $\eta^2 = .13$. Collectively, these results suggest that the patterns of results in these two experiments were different.

For response time, the main effect of condition was not significant, $F(2, 22) = .81$, $MSE = .07$, $p = .46$, $\eta^2 = .06$. None of the pairwise comparisons was significant, $ts(11) < 1.93$, $ps > .08$.

In contrast to Experiment 1, there was no evidence of a reference direction effect in pointing performance in Experiment 2. These results indicate that participants relied on an egocentric reference frame. The only procedural difference between Experiments 1 and 2 was in the instructions, so the combined results from Experiments 1 and 2 indicate that spatial updating strategy can affect the selection of the reference frame for path integration.

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[2] Preliminary analyses in both experiments revealed that there were no main or interaction effects involving gender.

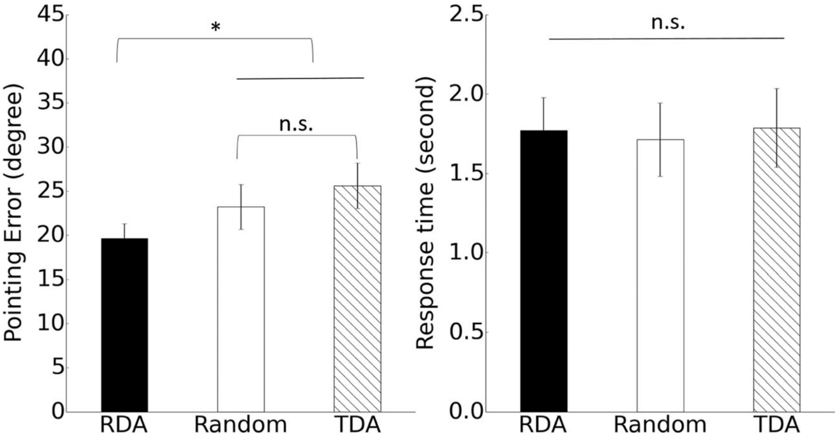

Fig. 4 Pointing error (*left*) and response time (*right*) for reference direction aligned (*RDA*), *Random*, and target direction aligned (*TDA*) conditions in Experiment 1. *Error bars* ±1 SEM estimated from data within conditions

There were no differences between the two experiments in overall pointing error ($t(22) = 1.83$, $p = .08$) or response time ($t(22) = 0.11$, $p = .91$). This pattern of results is in line with Wiener et al.'s (2011) study, which showed that the configural condition and the continuous condition differed significantly in direction error only in the long outbound path (15.3 m) but not in the short outbound path (8.3 m). The average outbound path length in our experiments was 3.9 meters.

Discussion

The current study investigated how spatial updating strategy affected the selection of the spatial reference frame in path integration. We conjectured that navigators would prefer an allocentric reference frame when they needed to construct and remember the trajectory of the outbound path (i.e., configural updating strategy), but would prefer an egocentric reference frame when they needed to update their location and direction to home continuously (i.e., continuous updating strategy). As expected, we observed a reference direction effect when a configural updating strategy was encouraged (Experiment 1), indicating that an allocentric reference frame was used. In contrast, equivalent pointing performance across the experimental conditions was observed when a continuous updating strategy was encouraged (Experiment 2), indicating that an egocentric reference frame was used.

Our findings corroborate Wiener et al.'s (2011) conclusion that two cognitive mechanisms exist in human path integration. Wiener et al. (2011) showed that spatial updating strategies impacted homing error, response time, direction error, distance error, and head orientation. We extended their findings by demonstrating that these strategies also impact the selection of the reference frame for path integration. There are several methodological differences between Wiener et al.'s (2011) study and ours, and one of the most important ones is the response method: participants in our experiments were required to maintain their final heading while pointing to the target location, whereas participants in Wiener et al.'s experiment turned and walked back to the target. As explained previously, because the key manipulation in our study was the alignment between the final heading and the initial heading (the assumed reference direction in an allocentric

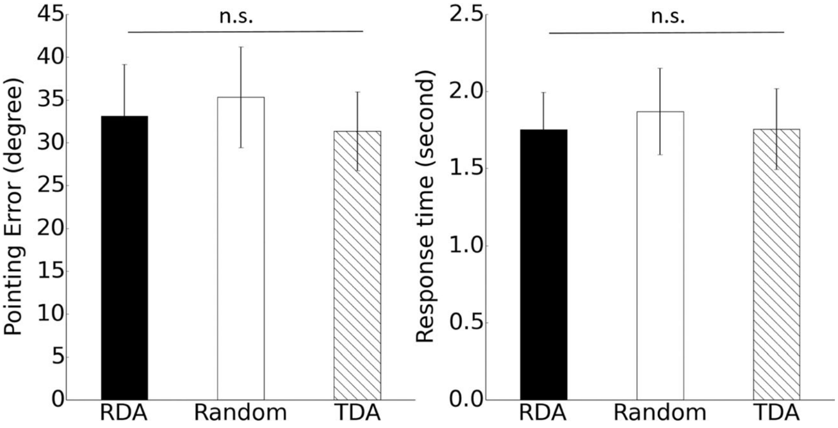

Fig. 5 Pointing error (*left*) and response time (*right*) for reference direction aligned (*RDA*), *Random*, and target direction aligned (*TDA*) conditions in Experiment 2. *Error bars* ±1 SEM estimated from data within conditions

reference frame), we wanted participants to maintain the final heading throughout the response. We predict that turning to face the target, with or without walking to it, would produce similar findings as long as participants consistently held the final heading before turning and turned ballistically. Another important difference between the two studies is the manipulation of path length. Wiener et al. (2011) found that differences between the two updating strategies were more pronounced for longer paths. Our models do not predict effects of path length on selection of a reference frame, although we suspect that, as paths become sufficiently long or complex, the cognitive workload of the configural strategy would become excessive and navigators would switch to a continuous strategy (Wiener & Mallot, 2006), and presumably use an egocentric reference frame.

Another question worth exploring further is how people choose between these spatial updating strategies. In Klatzky et al.'s (1998) study, heading error was low and unaffected by the disparity between the initial and the final headings (turning angle) when participants physically turned (walk and real-turn conditions), which suggests that, in the absence of instructions, participants used a continuous updating strategy in a triangle completion task if they had body-based cues to rotation. Wiener and his colleagues (2006, 2011) suggested that people will use the continuous updating strategy when the outbound path becomes sufficiently complex, because the demand on working memory increases under configural updating with increasing path complexity, but not so under continuous updating. Taking these results together, it is natural to ask under what circumstances people use a configural updating strategy without instructions to do so, as well as about the characteristics of the navigators who generally prefer configural over continuous updating. These are key questions for future research.

To conclude, the present study showed that, when people performed a path integration task in a virtual environment that provided full body-based cues but only limited visual cues to self-motion, spatial updating strategy influenced the selection of the reference frame: Navigators who were instructed to update the path trajectory relied on an allocentric reference frame, whereas navigators who were instructed to update the homing vector relied on an egocentric reference frame.

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