Developing Global and Local Cognitive Maps through Path Integration

by

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Abstract

This study investigated whether people can develop a global representation of local environments by path integration. Participants learned objects' locations in two misaligned rectangular rooms in an immersive virtual environment. After learning, they adopted a local view in one room and judged directions of objects inside the same room; the views in two consecutive trials were from different rooms and locally or globally consistent (priming task). Participants were either teleported (Experiment 1) or they locomoted (Experiment 2) between the rooms during learning and then finished the priming task. In Experiment 3, participants learned directions of five buildings before locomoting within and between the two rooms. During testing, after the priming task, participants pointed to the buildings while adopting local views inside rooms (across-boundary pointing task). Participants' estimated global headings were calculated from their responses to the buildings. Experiments 4 and 5 replicated Experiments 3 and 2 respectively except that participants locomoted between the rooms through a hallway, which minimized piloting cues. Results showed only a local priming effect in Experiments 1, 2 and 5, only a global priming effect in Experiment 4, and both local and global priming effects in Experiment 3. Consistent with the global priming effect, participants' estimated global headings were also accurate in Experiments 3 and 4. These results suggest that people can develop a global cognitive map of two local environments by path integration; prior global representation may be important to integrating local spaces into a global map; both the global and local representations can be separately developed to multiscale cognitive maps, although this may require significant cognitive resources.

Preface

This thesis is an original work by Xuehui Lei. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name “Human spatial cognition”, No. Pro00052545.

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1. Introduction

People live in multiscale spaces (Han & Becker, 2014). For example, a living room is located in a house, a house is located in a neighbourhood, and a neighbourhood is located in a city. Whether and how people develop mental representations of locations in an immediate local space (e.g., a room) are well examined and understood (Easton & Sholl, 1995; Kelly & McNamara, 2010; Meilinger, Strickrodt, & Bülthoff, 2016; Mou & McNamara, 2002; Sargent, Dopkins, Philbeck, & Chichka, 2010; Shelton & McNamara, 2001; Waller & Hodgson, 2006; Wang & Spelke, 2000; Yamamoto & Philbeck, 2013; see McNamara, 2013 for a review). However, whether and how people integrate representations of immediate local spaces into a representation of a broader space (e.g., a city) are still not clear (Marchette, Vass, Ryan, & Epstein, 2014; Shine, Valdés-Herrera, Hegarty, & Wolbers, 2016; Wang & Brockmole, 2003). The current study addresses this question.

Spatial relationships between two locations can be learned through two different systems. The first one relies on perception (primarily vision). We refer to this system as the piloting system. Through the piloting system, people directly perceive the spatial relationships between two locations (Cheng & Spetch, 1998). The other system depends on self-movement cues. Self-movement cues include internal cues such as proprioceptive information and vestibular signals, and external cues such as optic flow (Etienne & Jeffery, 2004; Loomis, Klatzky, Golledge, & Philbeck, 1999; Yamamoto & Shelton, 2005). We refer to this system as the path integration system. Through the path integration system, people can calculate the Euclidian spatial relationships between two locations that might be traversed on a circuitous path (Mittelstaedt & Mittelstaedt, 1980; Müller & Wehner, 1988; Wang, 2016).

The roles of the piloting system and the path integration system in learning spatial relationships depend on the scale of spaces. In an immediate local environment (a vista space, Montello, 1993), people can directly view the distance and direction between any two locations at a single viewpoint. In a relatively large environment (an environmental space, Montello, 1993), people may need to view two locations from two different viewpoints. When people see a common reference location (e.g., a high building) at both viewpoints, they still can infer the spatial relationships between the two locations. However, when they cannot see any common reference location at both viewpoints, they have to use the path integration system to infer the spatial relationships between the two locations. Although spatial relationships between locations in a vista space may be learned primarily through the piloting system, a lot of theorists have hypothesized that spatial relationships between locations in an environmental space are learned primarily through the path integration system (Gallistel, 1990, p. 106; Gallistel & Matzel, 2013; Jacobs & Schenk, 2003; Loomis et al., 1999; McNaughton, Battaglia, Jensen, Moser, & Moser, 2006; Meilinger, 2008).

Nevertheless, the empirical findings seem inconsistent with the theoretical view that the path integration system is critical to a global spatial representation (Kelly, Avraamides, & Loomis, 2007; Marchette, Vass, Ryan, & Epstein, 2014; Wang & Brockmole, 2003; Spiers, Hayman, Jovalekic, Marozzi, & Jeffery, 2015). Participants in Wang and Brockmole (2003) walked a path starting at a laboratory room inside of the psychology building, traversing outside the psychology building, re-entering the building, and ending at the laboratory room. While walking the path, participants were asked to point to one other building on campus. The results showed that participants who were standing inside the psychology building could not point to the other building although they could once they walked outside the psychology building. This finding indicates that participants in the study might not have been able to develop accurate representations of a location inside a building based on the global environment outside. One may argue that the lack of the global spatial representations in this study may be due to the complicated path that participants walked. Participants did develop a global representation but the global representation was too noisy to be accessible because errors in the path integration system quickly accumulated along the complicated path (Etienne et al., 2004; Gallistel, 1990, p. 106; Kelly, McNamara, Bodenheimer, Carr, & Rieser, 2008; Loomis et al., 1993; Müller & Wehner, 1988; Zhao & Warren, 2015a, 2015b).

Studies using a quite simple path still suggest that people may not develop a global representation of two separate spaces through path integration (Kelly et al., 2007; Marchette et al., 2014). In Kelly et al. (2007), participants learned objects' locations in a virtual room, then adopted imagined headings and pointed to the objects in the room using memories. During testing, participants either stayed in the learning room or physically walked to an adjacent room along a straight path. The results showed that participants' performance decreased with the increase of the angular distance between participants' physical heading and the imagined heading when these two headings were in the same room. However, this sensorimotor alignment effect disappeared when these two headings were in different rooms. If we assume that a sensorimotor alignment effect occurs whenever the imagined heading and the actual heading are specified in the same reference system (or in the same cognitive map), then the null sensorimotor alignment effect when participants walked to an adjacent room suggests that participants did not encode these two rooms in the same global cognitive map.

In a recent study, Marchette et al. (2014) provided direct evidence that people may not develop a global representation of two separate spaces through path integration while travelling a simple path. Participants in the Marchette et al. study learned positions of objects in different rooms by visually travelling a simple path with one turn between rooms in a desktop virtual environment. During the test, participants did a priming task. They were asked to imagine adopting one view inside a room and then to judge the direction of one object in the same room. In two consecutive trials, the imagined views could be the same or different according to a local reference frame (e.g., the principal axis of the room) or according to a global reference frame outside rooms (e.g., the distal orientation cues indicating global directions). The results showed that a participant's response was facilitated if the view in the current trial was locally consistent with that in the preceding trial. This local priming effect was evident even when the two consecutive trials involved two different rooms. In contrast, there was no priming effect when the views in the two consecutive trials were globally consistent (i.e., both facing the same direction relative to the environment outside the rooms). Furthermore, the neural activity in the retrosplenial complex was more similar for the same local headings than for different local headings. Again, neural activity in the retrosplenial complex was not sensitive to global headings.

In a follow-up study, Marchette, Ryan, & Epstein (2017) reported that participants tended to confuse locations in two different rooms when the locations were locally consistent but not when the locations were globally consistent, indicating that participants might not have formed global representations of these rooms. As an interesting echo, Spiers et al. (2015) reported that place cells of rats could not disambiguate different compartments in an environment containing multiple visually identical compartments although rats locomoted between compartments, suggesting that the place cell map is local rather than global and the path integration system may not be able to differentiate between rooms.

The theory that the path integration system is critical to developing a global map of different local environments is undermined if people cannot encode spatial relationships between two locations in two rooms by travelling a simple path (Kelly et al., 2007; Marchette et al., 2014; Marchette et al., 2017). One alternative hypothesis is that although a cognitive map (of a within-boundary space) can be developed by the path integration system (Wang, 2016), the path integration system cannot operate across boundaries (Wang & Brockmole, 2003). We refer to this hypothesis as the local-map-only hypothesis.

On the other hand, the literature of human path integration indicates that people are able to accomplish a triangle completion task. In particular, after walking a path with a single turn people can compute the vector from the current location to the origin of the path (Klatzky, Loomis, Beall, Chance & Golledge, 1998; Loomis et al., 1993). People can also establish a single global reference frame to obtain configural knowledge of more than three traversed legs (Mou, McNamara, & Zhang, 2013; Yamamoto & Shelton, 2005). Furthermore, one recent study showed that the path integration system might not be sensitive to a boundary (Mou & Wang, 2015). Participants in this study learned objects' locations and then pointed to the objects after walking a circuitous path within or across a boundary. When the piloting cues were removed, pointing to objects within a boundary was comparable to pointing across a boundary. These findings imply that the path integration system can be used to develop a global representation of two local spaces across boundaries.

There are also studies demonstrating that people develop a global representation of an environmental space (Ishikawa & Montello, 2006; Shine et al., 2016; Sholl, Kenny, & DellaPorta, 2006; Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014). People can develop survey knowledge in an environmental space, although there are large individual differences in the accuracy of the integrated configurational knowledge (Ishikawa & Montello, 2006; Weisberg et al., 2014). Participants in Weisberg et al. (2014) learned buildings arrayed along two separate routes and then learned a third route connecting the first two routes. They then pointed to buildings within the same route and between routes. Some participants could perform well in between-route pointing, suggesting that they had integrated separate routes into a global configuration. Sholl, Kenny and DellaPorta (2006; see also Burte & Hegarty, 2014) showed that with the increase of the angular distance between the participants' physical heading and the to-be-judged heading which was illustrated by a photo of campus buildings, participants performed worse at judging the heading. Before viewing the photos, participants who were located inside a laboratory room were asked to understand their physical heading by looking outside the room through the windows. This finding indicates that participants inside the room could understand the relationships between global headings illustrated by photos and their own current physical heading. In addition, in contrast to Spiers et al. (2015), Carpenter et al. (2015) reported that grid cells of rats formed a global representation of connected compartments that were visually identical.

However, the global representations in the human studies reported above might not have been developed through the path integration system exclusively. Participants in the route integration studies (Ishikawa & Montello, 2006; Weisberg et al., 2014) might be able to see some common reference points at different routes. As we discussed, the piloting system may be involved when people can see some common reference points from two different viewpoints. To examine people's global headings developed through path integration, we should have people estimate their global headings when they cannot see the global environment (e.g., inside a room), as in an across-boundary paradigm (Wang & Brockmole, 2003). Although participants in Sholl et al. (2006) were tested about their global headings when they were inside a room, they were asked to obtain their global headings by looking outside the window of the room. Hence, the piloting cues outside the windows might still have contributed to their global heading judgments.

Shine et al. (2016) has provided clearer evidence that people can develop a global representation of separate vista spaces. Similar to Marchette et al. (2014), participants in Shine et al. (2016) learned views inside rooms by locomoting between rooms. However, there are also important differences in the learning procedures between the studies conducted by Shine et al. (2016) and Marchette et al. (2014). First, participants in Shine et al. (2016) were explicitly required to understand the headings of the views inside rooms relative to the environment outside rooms. They were required to walk outside rooms if they incorrectly judged the global heading of a probed local view. Second, participants in Shine et al. (2016) physically turned their body when they turned in the virtual environment whereas participants in Marchette et al. (2014) used a keyboard to turn their viewpoints in the virtual environment. In the testing phase, participants in Shine et al. (2016) judged whether two consecutive views that were from different rooms were globally consistent or not. The behavioural results showed that participants were very accurate when judging global headings. In addition, the neural activity in the retrosplenial complex was reduced if the current view and the preceding view were globally consistent, indicating that the retrosplenial complex is also sensitive to global headings. These findings indicate that participants in Shine et al. (2016) developed a global representation of the rooms. However, one may argue that as participants were explicitly required and trained to learn their global headings inside rooms, it is not very surprising that they could judge their global heading during testing. Thus, a stronger investigation into whether people can develop a global representation of local spaces through the path integration system should probably exclude such explicit instructions and training.

As reviewed above, there is inconsistent evidence to support the prevailing theory that people develop a global representation of an environmental space through the path integration system (see Table 1 for a summary). The primary purpose of the current study was to further test this prevailing theory. In particular, we investigated whether participants could develop a global representation of two local spaces after walking a simple path between them, with minimum piloting cues, and without explicit instructions to learn global relationships. We used a simple path because the path integration system is supposed to be very noisy along a complicated path and the real global representation may not be measurable (Wang & Brockmole, 2003). By minimizing the piloting cues, we could test the pure function of the path integration system in developing a global spatial representation.

One potential variable that may explain the inconsistent evidence for a global spatial representation is the task (see Table 1). In most studies that did not find evidence of global representations, participants judged the spatial relationships of objects within the local space (except Wang & Brockmore, 2003). In particular, participants pointed to the targets within the same local space in which the imagined facing object was located (e.g., Kelly et al., 2007; Marchette et al. 2014). In contrast, in all studies that find evidence of global representations, participants judged the spatial relationships of objects between local spaces. For example, participants judged whether the views in two different rooms were globally consistent (e.g., Shine et al., 2016). Hence, a global spatial representation may be accessed when people judge spatial relationships of two objects in different local spaces but not when people judge spatial relationships of two objects within the same space. Therefore, to find the evidence of a global representation, in the current study we asked participants to point to buildings outside a room when they adopted a view inside a room. We referred to this task as an across-boundary pointing task.

Table 1 Inconsistent evidence about whether people can develop a global representation of an environmental space through path integration

	Path complexity (complex vs. simple)		Available global piloting cues (rich vs. minimum)		Tasks (within vs. across local spaces)		Global representation
	Complex	Simple	Minimum	Rich	Within	Across	
Wang & Brockmole, 2003	√		√			√	No
Kelly et al., 2007; Marchette et al., 2014; Marchette et al., 2017		√	√		√		No
Ishikawa & Montello, 2006; Sholl et al., 2006; Weisberg et al., 2014	√			√		√	Yes
Shine et al., 2016		√	√			√	Yes

In contrast to the local-map-only hypothesis, there are two versions of hypotheses claiming a global representation of local spaces learned through the path integration system. One stipulates that people can maintain separate representations of local spaces in addition to a global representation whereas the other one stipulates that people only maintain one global spatial representation. We refer to the former hypothesis as the multiscale-map hypothesis and the latter as the global-map-only hypothesis. As we are living in multiscale spaces, we may have spatial memories of different scale spaces (Han & Becker, 2014; McNamara, 1986; Meilinger, 2008; Poucet, 1993; Stevens & Coupe, 1978). However, there is no evidence that people can develop a global spatial representation through the path integration system and still maintain local spatial representations. Shine et al. (2016) indicated that participants developed a global representation of two rooms but did not test whether participants also developed separate spatial representations of each room. To differentiate the global-map-only hypothesis and the multiscale-map hypothesis, we used the priming task developed by Marchette et al. (2014). Participants adopted one view inside a room and then judged the direction of one object in the same room. In two consecutive trials, the imagined views could be the same or different according to a local reference frame (e.g., the principal axis of the room). The local priming effect, a faster judgment when the view of the current trial was locally the same as the view of the preceding trial, would indicate a local representation in favour of the multiscale-map hypothesis over the global-map-only hypothesis.

In addition to the local priming trials, we also used the global priming trials in Marchette et al. (2014). In the global priming trials, in two consecutive trials, the imagined views could be the same or different according to a global reference system (e.g., the distal orientation cues indicating global directions). Note that in the global priming trials, participants still judged the spatial relationships within the local space (i.e., the viewing object and the target object in the same space). By contrasting the findings in the across-boundary pointing task (while facing a local view inside a room, participants pointed to the buildings outside the room) and the global priming trials, we could test whether a global spatial representation is accessed only in an across-boundary pointing task or also in a within-boundary task, e.g., a global priming task.

Table 2 summarizes the five experiments in the current study. All experiments were conducted in an immersive virtual environment. Participants locomoted by physically turning their heads to change their viewpoints and using a joystick to translate forwards and backwards along their viewpoints.

Experiment 1 was conducted to assure that our testing trials in the priming paradigm could replicate the local priming effect reported by Marchette et al. (2014). Participants in an immersive virtual environment learned views of two rooms. Participants were teleported between the two rooms during learning to remove any global experience. During testing, participants conducted the priming task including both global and local priming trials.

Experiment 2 was conducted to see whether the path integration system would develop a global representation. This experiment was the same as in Experiment 1 except that participants locomoted between these two rooms along a simple path instead of being teleported.

Experiment 3 differentiated among the local-map-only, global-map-only, and multiscale-map hypotheses using an across-boundary pointing task as well as the local priming trials. Also, by comparing the results of the across-boundary pointing task and the global priming trials, this experiment tested whether the within-boundary task, such as the priming task, could access the global representation. Participants first learned directions of five buildings in the environment. Then, as in Experiment 2, they locomoted within and between rooms to learn views inside the two rooms. During testing, they conducted the priming task, followed by an across-boundary pointing task, in which participants imagined adopting views inside a room but were asked to point to the buildings outside of the room.

Experiment 4 removed possible confounding effects from relatively rich piloting cues in Experiment 3 in which participants directly saw the spatial relations between the two rooms although they could not see spatial relations between views inside the two rooms. Participants locomoted between the two rooms through an L-shaped hallway so that they never saw the spatial relation between the two rooms directly.

Experiment 5 was the same as Experiment 4, except that participants did not learn the five buildings. The contrast between Experiments 4 and 5, like the contrast between Experiments 2 and 3, investigated whether prior global spatial learning (i.e., learning the five buildings) is important to the development of a global representation through path integration while travelling a simple path.

Table 2 The learning procedures, tasks and results in all experiments. Pointing task refers to the across-boundary pointing to buildings.

Exp	Learning phase	Testing phase	Priming effect		Estimated global heading
			Local	Global	
1	Teleported between two rooms	Priming task	√	×	N/A
2	Locomote between two rooms in the open field	Priming task	√	×	N/A
3	Learn five buildings and then locomote between two rooms in the open field	Priming task; Pointing task	√	√	Accurate
4	Learn five buildings and then locomote between two rooms in the hallway	Priming task; Pointing task	×	√	Accurate
5	Locomote between two rooms in the hallway	Priming task	√	×	N/A

2. Experiment 1

Experiment 1 was conducted to ensure that our priming task could replicate the local priming effects reported by Marchette et al. (2014). In Marchette et al. (2014), the local priming effect was observed in Experiment 1 but not in Experiment 2, indicating that the local priming effect might be sensitive to slight changes in the experimental materials, design and procedure. In the current experiment, we used an immersive virtual environment instead of the desktop virtual environment used in Marchette et al. (2014). In addition, there might be other changes that could eliminate the local priming effect. Therefore, it is important to make sure that we can replicate the local priming effect reported by Marchette et al. (2014). To maximize the likelihood of replicating the local priming effect, participants in the current experiment were teleported between two rooms and did not have any experience of spaces outside rooms, as any global experience might undermine the local priming effect.

2.1 Method

2.1.1 Participants

Forty university students with normal or corrected-to-normal vision were recruited. Their participation was counted as partial fulfillment of a requirement for an introductory psychology course. Four participants were removed for scoring less than 70% correct overall. Thirty-six participants (18 female) remained in data analysis.

2.1.2 Materials and design

The physical experimental room was a 4m × 4m square room. The virtual environment was displayed in stereo with an nVisor SX60 head-mounted display (HMD) (NVIS, Inc. Virginia). The participants' head motions were tracked by an InterSense IS-900 motion tracking system (InterSense, Inc., Massachusetts). Only orientation information about the head motion was used to update participants' viewpoints in the virtual environment. Thus, participants physically turned their bodies to change their orientation in the virtual environment. Participants used a joystick to move forward or backward along their head orientation in the virtual environment. The centre of the virtual environment overlapped with the centre of the physical room.

The virtual environment had a grass-textured ground without any distal orientation cues. In the virtual environment there were two rectangular rooms, with a 90° angular difference between them (Figure 1). Although participants locomoted within the rooms, they were teleported between the two rooms and were never allowed to locomote outside the rooms. As a result, they could not obtain any global information.

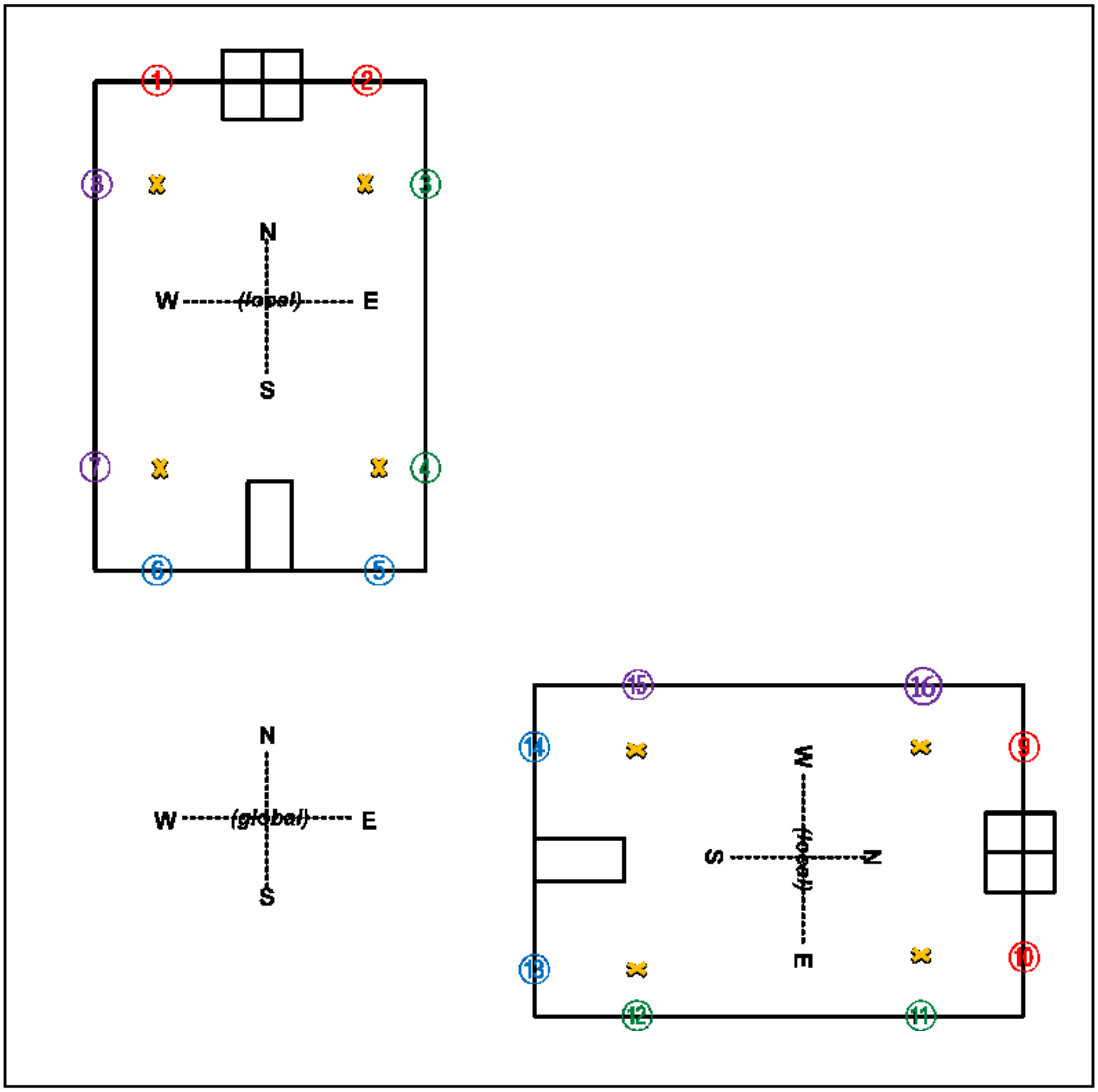

Figure 1. Schematic diagram of the room setup and object arrangements (bird's eye view). The numbers are objects (located in the alcoves) in the rooms. The yellow crosses are participants' standing positions when learning objects in the rooms. Each room also has a long carpet from the entrance to the back wall. Two rooms have different interior and exterior textures and colors. When participants stood on the yellow cross, only two objects in the same corner were visible.

These two rooms had identical geometry, with an aspect ratio of 0.6 (36m by 60m), but distinguishable interior and exterior textures and colours. A large window was set on the back wall of each room. Both rooms had a long carpet from the entrance to the back wall but with different colours and textures. Each room consisted of four yellow stages in the corners and eight alcoves containing eight nameable objects. Every alcove had a door so that participants could not see the object in the alcove unless they stood on the corresponding yellow stage to make the doors of the alcoves in this corner disappear. As a result, whenever participants viewed the same object, they had a fixed standing position and facing direction.

For each object (view), we could use local and global reference frames to code the location and heading of that view. The global principal direction (i.e., global north) in Figure 1 was arbitrarily defined. We assumed that the local principal direction (i.e., local north) in each room was from the door to the window. For example, if participants stood on the corresponding yellow stage and faced View 9, then global coding would be standing in the global northeast corner and facing global east (90°), while local coding would be standing in the local northwest corner and facing local north (0°).

The priming task occurred in a different physical room. In each trial, participants were asked to imagine facing one object while standing on the corresponding stage, and to judge whether another target object in this room was to their left or right. There were 74 trials. The first 11 trials were counted as practice and not included in the data analysis. The remaining 63 testing trials were in three blocks (21 trials each). In each block, the two consecutive trials were always between rooms. The first trial in each block was not used in the data analysis. Each remaining trial, from the second to the 21st in each block, could be assigned to one of the five conditions based on the relationships between it and its previous trial (Table 3). If only their global headings were the same, the condition was defined as a global heading (*HG*) condition; if only their local headings were the same, the condition was defined as a local heading (*HL*) condition; if only their global positions were the same, the condition was defined as a global position (*PG*) condition; if only their local positions were the same, the condition was defined as a local position (*PL*) condition; if both their positions and headings were different globally and locally, the condition was defined as a *None* condition, which was included as one baseline condition. The trial lists in each block were created to have equal trials for five conditions without repeating the facing-target object pairs (in particular four trials in each condition and in each block). We note that although we created the *PG* trials as in Marchette et al. (2014), the global positions in the two consecutive trials for the *PG* trials were in two different rooms (e.g., when facing View 1 in one room and facing View 14 in the other room). Consequently, we did not expect that there was a global position priming effect for the *PG* trials. Furthermore, no global position priming effect for the *PG* trials was reported in Marchette et al. (2014). Therefore, in the current study, the *PG* condition was treated as another a priori baseline condition in data analysis.

Table 3 Examples of views in two consecutive trials for different conditions of the priming task

Condition	Facing objects example
HG (global heading)	2→15
HL (local heading)	1→10
PG (global position)	1→14
PL (local position)	2→11
None	1→12

2.1.3 Procedure

The experiment had two phases: the learning phase and the testing phase. After reading the instruction and signing consent forms, blindfolded participants closed their eyes and were guided into the experimental room. They then sat on the swivel chair in the centre of the room, removed the blindfold and donned the HMD. They were required not to look at the physical experimental room. In the beginning, they could see nothing but grassy ground in the darkness in the virtual environment.

In the learning phase, participants were teleported to stand at the entrance of one room and face the window. They then learned the locations of eight objects in the room by locomoting inside the room. Participants always started learning from the left corner under the window and then locomoted to the next view clockwise. After five minutes of learning, all objects were removed and participants replaced the objects using their memory. One probed object was shown at the corner of the HMD. Participants needed to locomote to the corresponding stage to face the corresponding alcove and then press a button to put the object back. As a feedback, the probed object reappeared at the correct alcove. If participants made a mistake, they were informed about the correct alcove and were asked to locomote there to see the target. Participants replaced objects in two blocks. In each block, all objects were probed once and the order was randomized. Participants needed to repeat the learning and the replacing task until they could correctly replace all objects in the second block of the replacing task. After learning the objects' locations in one room, they were teleported to stand at the entrance and face the window of the other room to learn the other eight objects' locations. Room order was counterbalanced during learning. Finally, participants conducted a block of replacing all 16 objects once, randomly ordered, followed by the feedback. Participants pressed a button to be teleported to the other room if necessary. After replacing all objects, they were allowed to view the objects' locations again. After the learning phase, participants closed their eyes and the HMD was removed. Then they put on blindfolds and were led to another experimental room for the testing phase.

In the testing phase, participants used the left and right arrow keys on a keyboard to judge whether a target object would be located to their left or right if they were standing on the corresponding stage and facing the corresponding alcove of a facing object. For each trial, the names of the facing object and the target object were presented simultaneously in white letters on two lines at the centre of the black screen (for example, "Facing the mug" "lamp"). Participants were told to report left or right broadly, not just directly to the left or right (for example, when facing View 1, View 5 would be to the right). There was no feedback during testing. The trial ended as soon as the participant responded, and the inter-trial interval was 750 ms. Participants were required to respond as fast and accurately as possible.

2.1.4 Data analysis

Only the correct trials were used in data analysis of reaction times. Mean reaction times were calculated for each condition. We used the *None* condition and the *PG* condition as the a priori baseline conditions. If the reaction time in the *PL* or *HL* condition was shorter than the reaction time in the baseline conditions, the local priming effect was obtained. Since participants did not have any global experience, they should not have known the global heading relationship between two consecutive trials. Thus, we did not expect any shorter reaction time in the *HG* condition than in the baseline conditions.

2.2 Results

The overall accuracy was 93.19% (*SD* = 10.10%). The overall mean reaction time was 5.25s (*SD* = 3.13s). There was no difference in accuracy across conditions, $F(4,140) = .65$, $p = .63$, $\eta_p^2 = .02$. The reaction time of the five conditions is summarized in Table 4. To examine if there were priming effects for the *PL*, *HG* and *HL* conditions, paired sample *t* tests were conducted between these conditions and the a priori (*None+PG*) baseline condition. No comparison was significant ($ts(35) \leq 1.60$, $ps \geq .12$, Cohen's $ds \leq .38$).

Table 4 The reaction time (M ± SE, in seconds) of five conditions for all views and initial views in Experiment 1

	None	PG	PL	HG	HL
All views	5.07 ± 0.38	5.31 ± 0.30	5.41 ± 0.35	5.38 ± 0.32	4.87 ± 0.30
Initial views	5.90 ± 0.83	5.76 ± 0.34	5.32 ± 0.44	5.64 ± 0.46	4.22 ± 0.39

Since there were no priming effects when we analyzed trials for all views, we only analyzed trials with facing objects for initial views (views 1, 2, 9 and 10). Initial views are the first views that participants saw when they entered the room. We were interested in the initial views because the initial views could be used to establish the reference frame (Shelton & McNamara, 2001). For trials with initial views, the overall accuracy was 96.96% (*SD* = 9.77%), and the overall mean reaction time was 5.37s (*SD* = 3.15s). There was no significant difference in accuracy across conditions, $F(4,140) = 2.28$, $p = .07$, $\eta_p^2 = .06$. The reaction time of the five conditions in trials with initial views is summarized in Table 4. The paired sample *t* test contrasting the *HL* condition with the (*None+PG*) baseline condition showed a significantly shorter reaction time in the *HL* condition ($t(35) = 4.58$, $p < .001$, Cohen's $d = 1.08$), indicating a local heading priming effect. The paired sample *t* tests contrasting the *PL* and *HG* conditions with the (*None+PG*) baseline condition did not show significant differences (ts$(35) \leq 1.46$, ps $\geq .15$, Cohen's ds $\leq .35$), indicating neither a local position priming effect nor a global heading priming effect. In the current experiment, participants were only exposed in local environments without global information. However, we still did not get a significant local position priming effect. Therefore, we decided to include *PL* as another baseline condition and we used (*None* + *PG* + *PL*) as a new baseline condition to test the priming effects in the current experiment and the following experiments (see Figure 2). The reaction time in the *HL* condition was still significantly shorter than in the (*None* + *PG* + *PL*) baseline condition ($t(35) = 4.71$, $p < .001$, Cohen's $d = 1.11$), indicating a local heading priming effect. The difference between the *HG* condition and the (*None* + *PG* + *PL*) baseline condition was still not significant ($t(35) = .14$, $p = .89$, Cohen's $d = .03$), indicating no global heading priming effect.

The above results indicate a local heading priming effect when we analyzed the trials with the initial views. Therefore, we replicated the local heading priming effect reported in the study of Marchette et al. (2014). In the current experiment, participants only learned in local environments without global cues. Therefore, there should be no global heading priming effect, which is what the result showed.

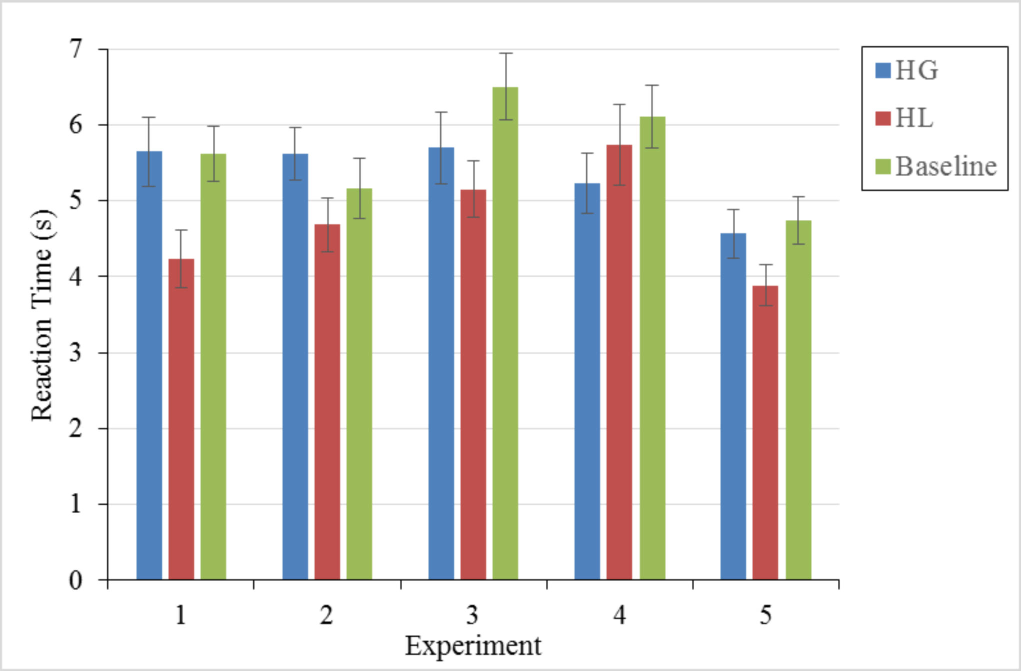

Figure 2. Reaction time of the priming task for trials with initial views in three conditions (*HG*, *HL*, and baseline (*None*+*PG*+*PL*)) in the five experiments.

3. Experiment 2

Experiment 2 investigated whether people could have a global representation of two separated local spaces by walking a simple path between the local spaces. Unlike in Experiment 1 where participants were teleported between the rooms, participants in Experiment 2 locomoted between the two local rooms in the learning phase. In addition, distal orientation cues were presented. The same priming task was used to determine whether there existed a global heading priming effect in addition to the local heading priming effect.

3.1 Method

3.1.1 Participants

Thirty-six university students (18 females) with normal or corrected-to-normal vision were recruited. Their participation was counted as partial fulfillment of a requirement for an introductory psychology course.

3.1.2 Materials and design

The two local rooms and the object arrangements remained the same as in Experiment 1, but there existed distal orientation cues outside the two rooms (Figure 3). Unlike in Experiment 1, participants in the current experiment locomoted between the two rooms.

3.1.3 Procedure

As in Experiment 1, Experiment 2 included a learning phase and a testing phase. In the beginning of the learning phase, participants were at the centre of the virtual environment, with only distal orientation cues available. Then the two local rooms appeared. Inside the rooms, participants could see the distal orientation cues through the windows. The learning procedure and the testing procedure were the same as in Experiment 1, except that participants locomoted from the center of the virtual environment to the first room and also locomoted between rooms rather than being teleported in the learning phase.

3.1.4 Data Analysis

As in Experiment 1, we used (*None* + *PG* + *PL*) as the baseline condition to test global and local heading priming effects. Still, trials with initial views were used in data analysis.

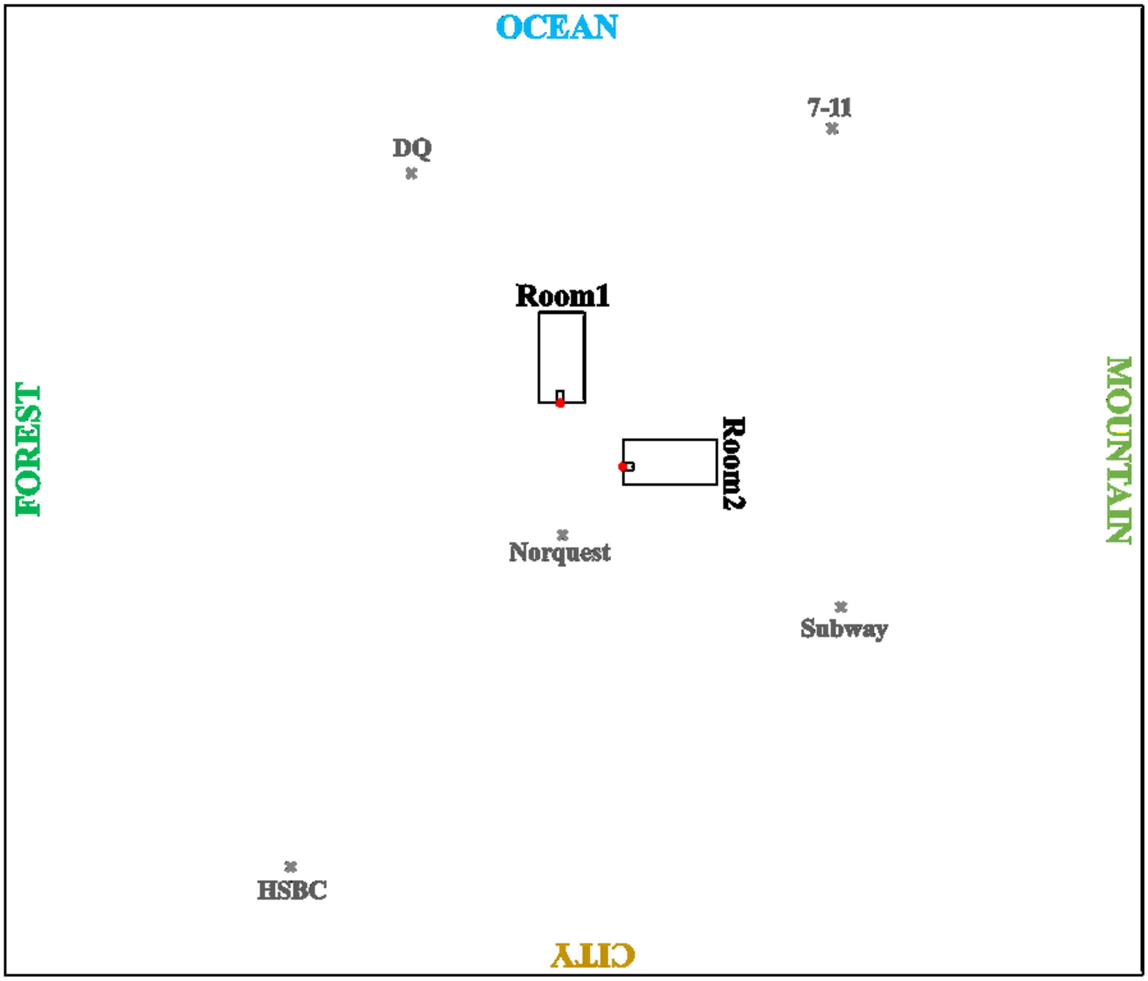

Figure 3. Schematic diagram of the experimental setup (bird's eye view) in Experiments 2 and 3. For both experiments, the ground was covered with grass. Four distal (in an infinite distance) orientation cues (ocean, mountains, city scene, and forest) were always presented. For Experiment 3 only, before viewing the two rooms, participants learned five buildings (DQ, 7-11, Subway, Norquest College, HSBC). The red dots are the five buildings' learning positions, which are at the doorways of the two rooms. The two rooms and the five buildings were never simultaneously presented. When learning the five buildings, participants only saw the doorways of the two rooms, whereas when participants started to learn objects in the two rooms, the five buildings disappeared.

3.2 Results

For trials with initial views, the overall accuracy was 94.61% (*SD* = 16.25%), and the overall mean reaction time was 5.21s (*SD* = 2.79s). There was no difference in accuracy across conditions, $F(4,140) = .99$, $p = .42$, $\eta_p^2 = .03$. Before combining *PL* with *None* and *PG* into a baseline condition, we tested whether a local position priming effect existed. As revealed by a paired sample *t* test, there was no significant difference between the *PL* condition and the (*None* + *PG*) baseline condition, $t(35) = .81$, $p = .42$, Cohen's $d = .19$. Then we combined (*None* + *PG* + *PL*) to be the new baseline condition for further data analysis.

Paired sample *t* tests contrasting *HG* and *HL* conditions with the (*None* + *PG* + *PL*) baseline condition were conducted to test the priming effects (see Figure 2). The responses in the *HL* condition were marginally faster than in the baseline condition ($t(35) = 1.93$, $p = .06$, Cohen's $d = .45$), demonstrating some evidence of a local heading priming effect. However, the difference between the *HG* condition and the (*None* + *PG* + *PL*) baseline condition was not significant ($t(35) = 1.36$, $p = .18$, Cohen's $d = .32$), indicating no global heading priming effect.

The results in Experiment 2 show that there is no evidence for a global representation after travelling a simple path between two local environments, indicating that people may not be able to develop a global representation of an environmental space through the path integration system while walking a simple path. However, it is also possible that the priming task cannot reveal the global representation because in the priming task, the imagined heading and the to-be-judged target are within the same local space. As discussed in the Introduction, an across-boundary pointing might be necessary to reveal a global representation.

4. Experiment 3

In Experiment 3, except for the priming task, participants also did an across-boundary pointing task to directly examine their global headings as well as their global positions when they adopted local views inside the rooms. Different from Experiment 2, participants in Experiment 3 learned five buildings before the two rooms were presented (see Figure 3). In the testing phase, participants adopted views inside rooms and then pointed to the five buildings. A best-fit method was used to calculate participants' global headings and positions from their pointing directions of the buildings.

The results about the across-boundary pointing accuracy and the priming effects in the current experiment could test the three hypotheses: local-map-only, global-map-only, and multiscale-map hypothesis (see Table 5). The local-map-only hypothesis predicted that there was a local priming effect and participants were not able to conduct the across-boundary pointing task. The global-map-only hypothesis predicted that participants were accurate in estimating their global heading in the across-boundary pointing task whereas there was no local priming effect. The multiscale-map hypothesis predicted that participants were accurate in estimating their global heading in the across-boundary pointing task and there was a local priming effect.

Comparing the results about the global heading priming effect and the across-boundary pointing task, we could also test whether the priming task as a within-boundary pointing task is sensitive to a global representation. If participants could have a global heading as revealed by the across-boundary pointing task but there was no global heading priming effect, then we would conclude that the priming task as a within-boundary pointing task is not sensitive to a global representation.

Table 5 Predictions of the results in Experiment 3 based on the three hypotheses regarding the existence of local and global maps.

Hypothesis	Local priming effect	Global priming effect	Accurate estimation in across-boundary pointing
Local-map-only	Yes	No	No
Global-map-only	No	Uncertain	Yes
Multiscale-map	Yes	Uncertain	Yes

4.1 Method

4.1.1 Participants

Forty-nine university students with normal or corrected-to-normal vision were recruited. Their participation was counted as partial fulfillment of a requirement for an introductory psychology course. One participant was removed for scoring less than 70% correct overall. Forty-eight participants (24 female) remained in the data analysis.

4.1.2 Materials and design

The two local rooms and the distal orientation cues remained the same as in Experiment 2. Before participants saw the two rooms, they learned locations of five extra buildings (Figure 3) in the environment. The two rooms and the five buildings were never presented simultaneously. When participants learned the five buildings, only the doorways (doorframes) of the two rooms were present and participants stood at each doorway. Two learning positions (two doorways) were used to assure that participants could encode the locations of the buildings accurately. When participants started to learn objects, the five buildings disappeared and the two rooms appeared.

The priming task was the same as in Experiments 1 and 2. After the priming task, participants also did an across-boundary pointing task using a joystick. Participants were asked to adopt a view inside one room and then to point to the direction of a building outside the room. The name of the local view was present in white letters on the black screen (for example, "Imagine you are facing the vase"). After participants pressed a button on the joystick, the name of the pointing building appeared (e.g., "point to 7-11"). Participants moved the joystick to point to the exact direction of the building.

To control the experiment time within two hours for each participant, we only used the views in two diagonal corners in each room in the across-boundary pointing task. The corners in different rooms were locally consistent for each participant. In particular, half of the participants conducted trials including views 1, 8, 4, 5 and views 9, 16, 12, 13; while the other half conducted trials including views 2, 3, 6, 7 and views 10, 11, 14, 15. For each view, participants pointed to all five buildings. Therefore, there were 40 trials in the across-boundary pointing task. The order of the trials was randomized for each participant.

4.1.3 Procedure

In the beginning of the learning phase, participants stood at the centre of the virtual environment with only distal orientation cues. Then both doorways of the rooms were present. Participants were asked to move towards one of the doorways. When participants stood in the middle of the doorway, the five buildings appeared. Participants learned the locations of these buildings while standing at the doorway for one minute. After learning, all five buildings disappeared and participants pointed to the original direction of each building using memory. Each building was probed by presenting it at the corner of the HMD. After the participants responded, the probed building was presented at the correct location as a feedback. There were two blocks of such pointing-feedback trials in the replacing-building task. In each block, the order of the probed buildings was randomized. If the participant was not accurate in the replacing-building task, the same learning procedure was repeated until the experimenter allowed the participant to pass. Otherwise, participants moved to the second doorway and had the same learning procedure there. Most of the participants learned buildings only once at each doorway. Then, a green pole was presented at the centre of the environment. Participants returned to the centre and closed their eyes for a three-minute rest. After the rest, the five buildings disappeared and the two complete local rooms, including the doorway, appeared. Participants locomoted between two rooms to learn the objects as in Experiment 2.

During the testing phase, participants performed the priming task first. Then they conducted the across-boundary pointing task. Participants were asked to respond as accurately as possible and take time to think.

4.1.4 Data Analysis

For the priming task, as in Experiments 1 and 2, we used (*None* + *PG* + *PL*) as the baseline condition to test global and local heading priming effects. Mean reaction times were calculated for correct trials with initial views in each condition (see Figure 2).

For the across-boundary pointing task, at each testing view we calculated participants' global heading and global position estimations using the least square of the errors in their response directions to the five buildings. A global heading is measured by an angular difference from the global north in Figure 1 and clockwise is positive (e.g. N is 0°, E is 90°, S is 180°, W is 270° or -90°); a global position is measured by a coordinate of x, y in the global coordinate system in Figure 1 (E is x positive and N is y positive). For any possible global heading and any possible global position, we calculated the direction from the given global position to the target building in terms of the given global heading (correct direction). The response direction was measured by the joystick travelling direction in terms of the joystick front at that testing view. Therefore, for any given global heading and any given global position, by subtracting the correct direction from the response direction, we obtained one response error for each building. Participants' global heading estimations and global position estimations of the given testing view were determined as the global heading and the global position that produced the least square of the response errors across the five buildings.

As a result, we obtained allocentric heading estimations for each testing view for each participant. Then, the circular mean of the heading across participants was calculated for each testing view (Batschelet, 1981). For position, we obtained coordinate estimations for each testing view for each participant. Since there were two kinds of view lists, to simplify data analysis, we converted heading and position estimations of the participants who had testing views 2, 3, 7, 6 and views 10, 11, 15, 14 to the corresponding estimations at testing views 1, 8, 4, 5 and views 9, 16, 12, 13 respectively (see Table 6). As views 2, 3, 7, 6 were the mirror reflections of views 1, 8, 4, 5 respectively along the direction of global 0° (i.e., global north), we flipped the heading of views 2, 3, 7, 6 to those of views 1, 8, 4, 5 along the global 0° (i.e., converting H to -H). Similarly, as views 10, 11, 15, 14 were the mirror reflections of views 9, 16, 12, 13 respectively along the direction of global 90° (i.e., global east), we flipped the headings of views 10, 11, 15, 14 to those of views 9, 16, 12, 13 respectively along the direction of global 90° (i.e., converting H to 180-H). Therefore, we only used testing views 1, 8, 4, 5 and views 9, 16, 12, 13 to represent four global headings (0°, 90°, 180°, and 270°) in each room.

Table 6 Conversion of position and heading estimates between the two view lists in the across-boundary pointing task

Before conversion			After conversion		
View	Position	Heading	View	Position	Heading
2	(x, y)	H	1	(-x, y)	-H
3			8		
7			4		
6			5		
10	(x, y)	H	9	(x, -y)	180-H
11			16		
15			12		
14			13		

4.2 Results

4.2.1 Priming task

For trials with initial views, the overall accuracy was 94.12% (*SD* = 15.87%), and the overall mean reaction time was 6.11s (*SD* = 3.89s). There was no difference in accuracy across conditions, $F(4,188) = 1.00$, $p = .41$, $\eta_p^2 = .02$. Paired sample *t* tests contrasting *HG* and *HL* conditions with the baseline condition were conducted to test the priming effects (see Figure 2). Participants responded significantly faster in both the *HG* and *HL* conditions than in the baseline condition ($t(47) = 2.13$, $p = .04$, Cohen's $d = .44$; $t(47) = 3.19$, $p = .003$, Cohen's $d = .65$ respectively), demonstrating both global and local heading priming effects.

4.2.2 Across-boundary pointing task

Figure 4 showed estimated standing positions and estimated global headings when participants imagined facing objects inside the rooms. From this figure we can see that the means of participants' estimated global headings were close to the correct headings, while their estimated positions reveal that they could distinguish different rooms but not positions within the same room. These observations were confirmed by the statistical analyses below.

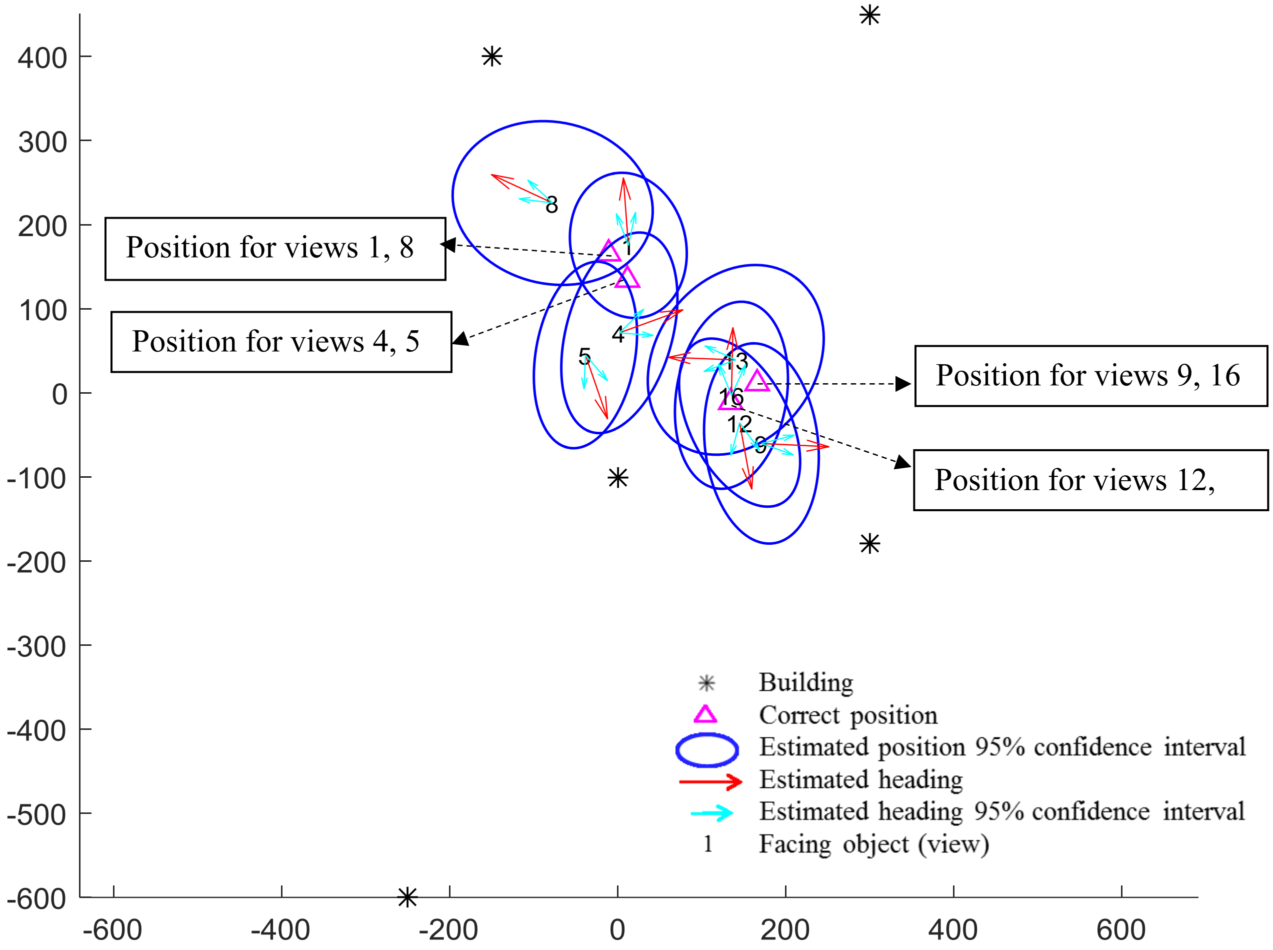

Figure 4. Estimated standing positions and headings when facing objects in the rooms in Experiment 3. The blue ovals represent 95% confidence intervals of the participants' estimated positions when they imagined facing objects in the rooms. The locations of the object numbers represent the centre of the ovals. The magenta triangles represent the correct standing positions. The black asterisks represent the five buildings' locations. The red arrows are the participants'

estimated headings for each object. The cyan arrows are the 95% confidence intervals of participants' estimated heading.

4.2.2.1 Heading estimations

The correct and estimated global headings for each facing object are plotted in Figure 5. From the results we can see that except for View 8 (correct heading 270°), the 95% confidence interval of the circular mean of each heading estimation included the corresponding correct heading. Furthermore, all circular means of heading estimations were close to the corresponding correct headings, indicating that participants had accurate global heading estimations for each view inside the rooms.

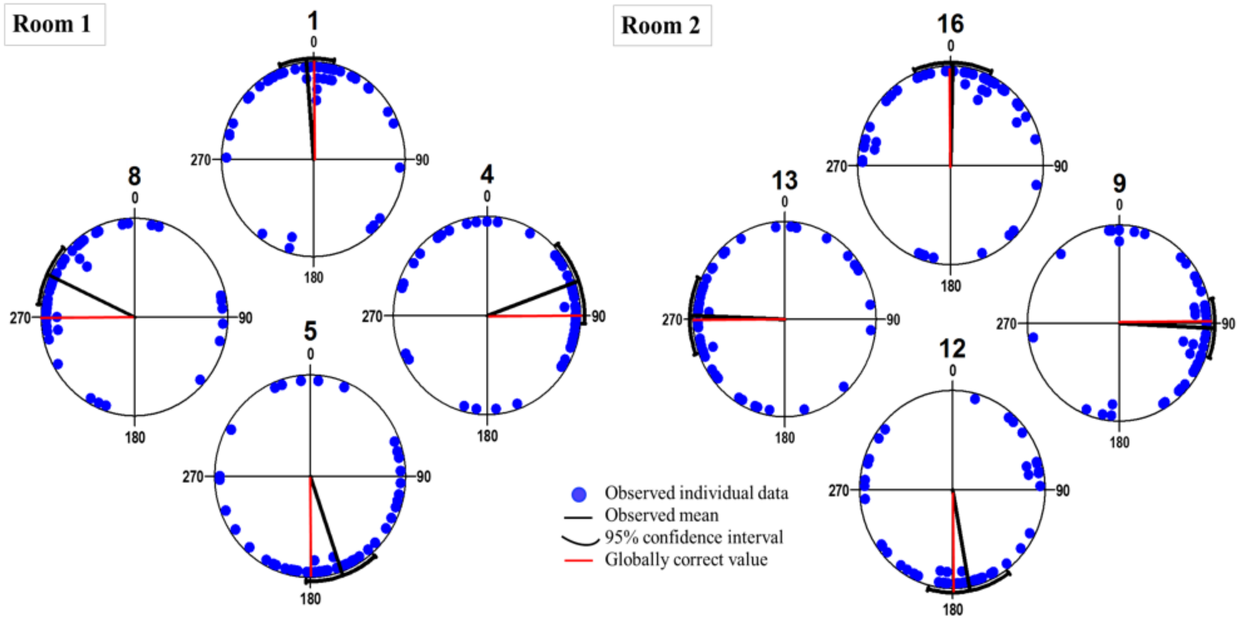

Figure 5. Correct global headings and estimated global headings for each facing object in each room based on the response pointing of buildings in Experiment 3.

Hotelling's paired tests contrasting the global headings of any two testing views were conducted to test whether participants could distinguish global headings at different testing views (the critical *p* value was reset to be .0018 due to multiple comparisons) (Table 7). The results showed that except for the marginal differentiation between View 4 (correct heading 90º) and View 16 (correct heading 0º) (*F*(1, 46) = 7.38, *p* = .0020), participants could distinguish any two different global headings (*F*s ≥ 8.48, *ps* ≤ .0007) but did not treat any two views with the same global heading as different headings (*F*s ≤ 2.84, *ps* ≥ .0690). These results indicate that participants represented global headings accurately.

Table 7 *P* values from Hotelling's paired tests used to examine global headings' differentiation (critical *p*= .0018 or .05/28) in Experiment 3. A *p* value smaller than the critical *p* indicates differentiation.

View / *p*	1	4	5	8	9	12	13	16
1	-----	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.2900
4		-----	0.0000	0.0000	0.0690	0.0000	0.0000	0.0020
5			-----	0.0000	0.0001	0.7140	0.0000	0.0000
8				-----	0.0000	0.0000	0.1980	0.0010
9					-----	0.0000	0.0000	0.0000
12						-----	0.0000	0.0000
13							-----	0.0007
16								-----

⬭ Indicates pairs of global headings that participants could not distinguish.

4.2.2.2 Position estimations

Figure 4 shows participants' estimated positions. Although the 95% confidence interval of the mean of each estimated position covered the corresponding correct standing position, it also covered the other standing position within the room, indicating that participants' global position representation was coarser.

Further analysis using Hotelling's T-squared test examined whether participants could distinguish standing positions when facing different objects (the critical *p* value was reset to be .0018 due to multiple comparisons) (Table 8). The results showed that participants could distinguish positions in different rooms (except for standing positions for View 4 vs. View 12 and View 4 vs. View 13) (*F*s ≥ 8.09, *p*s ≤ .0010), but could not distinguish positions within the same room (*F*s ≤ 4.92, *p*s ≥ .0116).

Table 8 *P* values from Hotelling's T-squared tests used to examine global positions' differentiation (critical *p*= .0018 or .05/28) in Experiment 3. A *p* value smaller than the critical *p* indicates differentiation.

View / *p*	1	4	5	8	9	12	13	16
1	-----	0.1242	0.0116	0.1724	0.0000	0.0006	0.0010	0.0004
4		-----	0.4732	0.0164	0.0001	0.0020	0.0064	0.0007
5			-----	0.0183	0.0000	0.0000	0.0007	0.0001
8				-----	0.0000	0.0000	0.0000	0.0000
9					-----	0.7872	0.1999	0.3884
12						-----	0.3845	0.8292
13							-----	0.7888
16								-----

⬚ Indicates pairs of standing positions that participants could distinguish.

4.2.2.3 Correlation between heading error and position error

The absolute heading error was calculated by the angular difference between the estimated heading and the correct heading (Table 9). The range of the absolute heading error was [0º, 180º]. There was no significant difference among the absolute heading errors across different views, $F(7, 329) = 1.11$, $p = .36$, $\eta_p^2 = .02$.

Table 9 Absolute heading error (M ± SE, in degrees) when facing different views in Experiment 3.

View	1	4	5	8	9	12	13	16
Heading error (°)	42.21 ± 6.72	55.69 ± 7.67	54.52 ± 7.29	50.33 ± 7.48	43.71 ± 5.85	56.02 ± 6.89	52.85 ± 7.28	57.00 ± 6.95

Taking environmental scale into consideration, the position error was calculated by the following formula: position error = |distance from the correct position to the buildings – distance from the estimated position to the buildings| / distance from the correct position to the buildings. So the position error was essentially the percentage error of the correct distance to the buildings (Table 10).

Table 10 Position error (M ± SE, in percentage) when facing different views in Experiment 3.

View	1	4	5	8	9	12	13	16
Position error (%)	47.42 ± 2.83	60.14 ± 4.65	56.79 ± 4.50	60.13 ± 8.79	56.00 ± 7.37	57.58 ± 5.70	69.30 ± 9.93	57.10 ± 5.55

There was a significant positive correlation between the absolute heading error and the position error, $r(48) = .48$, $p < .001$ (Figure 6). With a smaller error in global heading representation, participants represented positions more accurately.

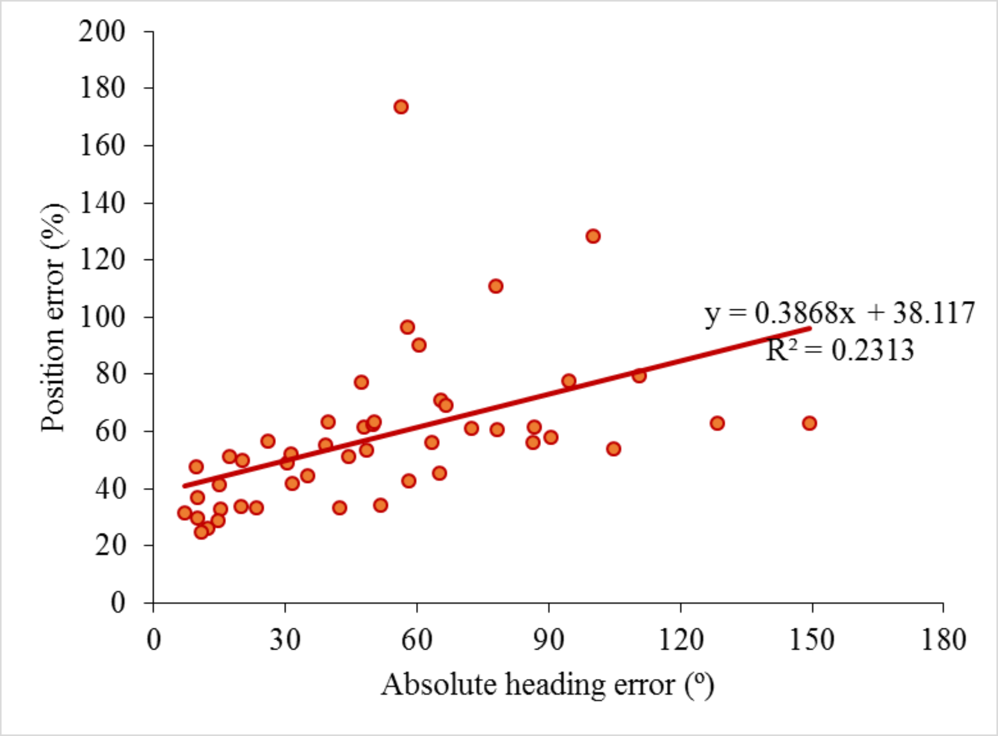

Figure 6. The position error as a function of the absolute heading error in Experiment 3. The absolute heading error was calculated by the angular difference between the estimated heading and the correct heading. The position error was calculated by the following: position error = |distance from the correct position to the buildings – distance from the estimated position to the buildings| / distance from the correct position to the buildings.

The results in Experiment 3 show that there are both local and global heading priming effects, and people can have an accurate estimation of their global headings at local views inside the rooms. These results support the multiscale-map hypothesis. In addition, the global heading priming effect indicates that the within-boundary priming task can still reveal the existence of a global representation. Therefore, people can develop a global representation using the path integration system. They may switch between local and global maps to orient efficiently in the priming task.

However, the current experiment might not use an environment with minimum piloting cues. When participants learned five buildings' directions at both doorways, the doorways were presented simultaneously. Participants could also see the two rooms when they were locomoting between the rooms. Testing participants inside a room, we ensured that participants never directly saw the spatial relation between any two local views across rooms and the spatial relation between any two local views across rooms was developed through path integration. However, viewing the spatial relation between the doorways and between the rooms might facilitate the path integration system. Experiment 4 was conducted to address this issue.

5. Experiment 4

The purpose of Experiment 4 was to study the function of the path integration system to develop a global representation with minimum piloting cues about the global environment. There were four changes to minimize the piloting cues in the learning phase. First, only one of the doorways was shown as the first location to learn the five buildings. The second learning location was indicated by a pole that participants would never visit or notice after learning the buildings (see Figure 7 for the second learning location). Participants still had two learning positions to ensure that they perceived the locations of the buildings accurately. Second, participants locomoted between the two rooms through an L-shaped hallway with a roof and opaque walls, so that they could not see the global environment. Third, opaque fog was placed in the hallway so that participants could not see both rooms simultaneously in the hallway, even at the turning corner of the hallway. Fourth, the windows in the two rooms were opaque so that participants could not see distal orientation cues outside. In the testing phase, participants still conducted the priming task, followed by the across-boundary pointing task.

5.1 Method

5.1.1 Participants

Forty-eight university students (24 females) with normal or corrected-to-normal vision were recruited. Their participation was counted as partial fulfillment of a requirement for an introductory psychology course.

5.1.2 Materials and design

The two local rooms remained the same as in previous experiments except that the windows of the two rooms were opaque so that participants could not see the distal orientation cues outside. There was a hallway with a roof and opaque walls connecting the two rooms (see Figure 7). As a result, when participants locomoted between the two rooms to learn objects, they could not see the global environment. The hallway has two legs, 118m long each, and a 90º turning corner. Opaque fog was placed 70 meters in front of the participants when they were locomoting in the hallway so that they could not see the two rooms simultaneously at the turning corner. The distal orientation cues and the five buildings remained the same. The priming task and the across-boundary pointing task also remained the same as in Experiment 3.

5.1.3 Procedure

In the beginning of the learning phase, participants were at the centre of the virtual environment with only distal orientation cues shown (see Figure 7). Then one doorway of the room was presented, and participants were asked to move to the doorway, where they learned five buildings' directions as in Experiment 3. When participants pointed to each building using their memory, participants' response directions were recorded to ensure that they had learned the five buildings' directions accurately. After that, the doorway remained in place and a red pole was shown in the environment (see Figure 7 for the exact location). Participants moved towards the red pole and then learned the five buildings' directions and finished the replacing-building task there again. The location of the red pole was a place that would not be visited or noticeable when participants learned objects in the two rooms afterwards, so that there would be no direct relationship between this learning location and the two rooms. Half of the participants learned from the doorway of one room and the other half learned from the doorway of the other room. After learning, participants moved back to the doorway and closed their eyes to have a three-minute rest.

After the rest, the two complete local rooms and the hallway were presented. The participant who was still standing at the doorway could not see the global environment. Participants locomoted between the two rooms through the hallway to learn the objects inside the two rooms. In addition, participants could not see the two rooms simultaneously at the turning corner of the hallway because of the opaque fog in front of the participants.

During the testing phase, participants performed the priming task and the across-boundary pointing task the same as in Experiment 3.

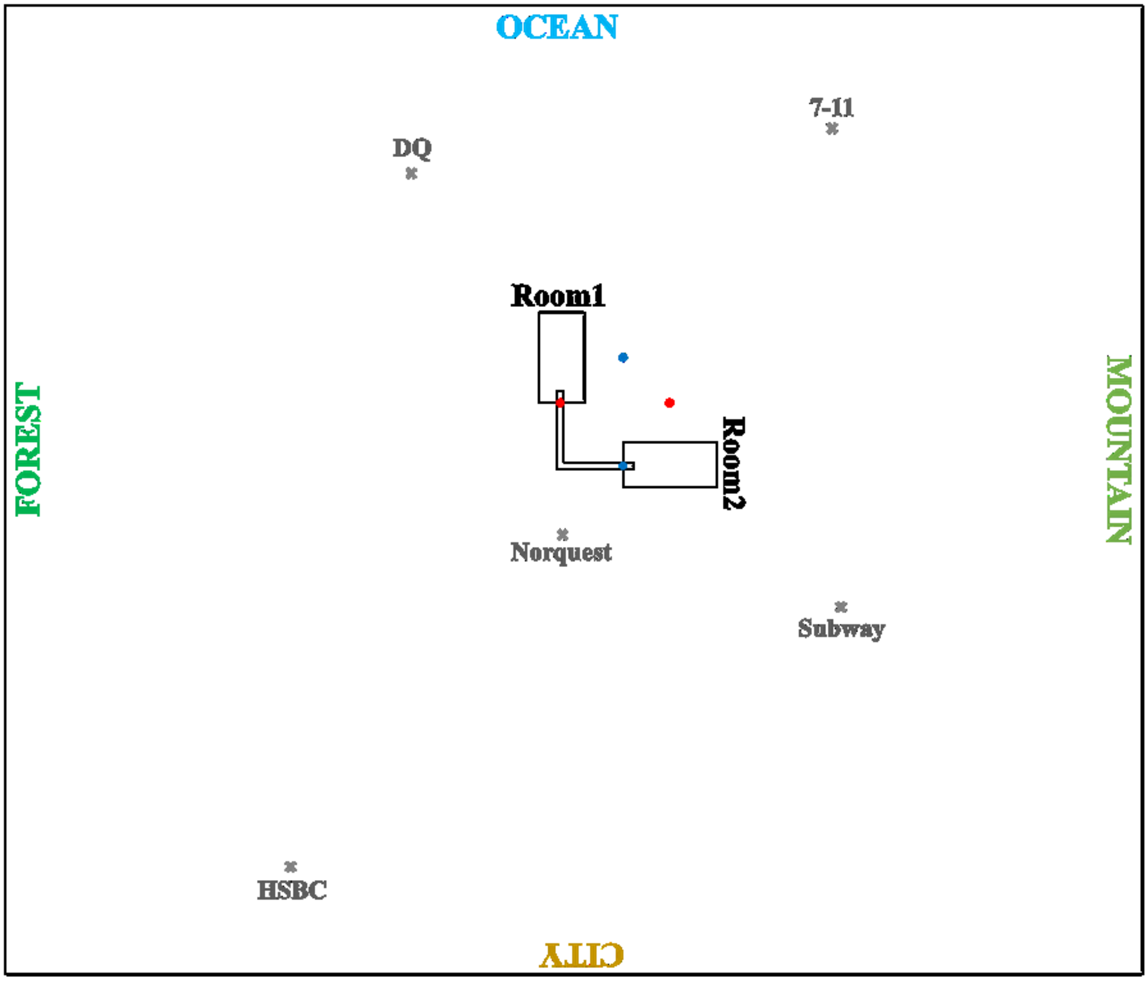

Figure 7. Schematic diagram of the experimental setup (bird's eye view) for Experiments 4 and 5. Compared to Figure 3, this setup includes a hallway, which has a roof, connecting the two rooms. In Experiment 5, participants locomoted between the two rooms through the hallway without seeing the global environment. In Experiment 4, participants learned five buildings' directions and then learned objects in the two rooms through the hallway. The red and blue dots are the five buildings' learning positions, with half of the participants learning from the two red dots and the other half learning from the two blue dots. When learning the five buildings, participants saw only one of the doorways. When participants were learning objects in the two rooms through the hallway, the five buildings remained there. The distal orientation cues were always shown.

5.1.4 Data Analysis

When participants were learning five buildings' directions, their response directions for each building in the replacing-building task were recorded so that we could see whether participants learned five buildings' directions very well during the learning phase. We calculated the absolute direction error by using the angular difference between the correct building direction and the response building direction relative to the learning location.

Data analysis methods for the priming task and the across-boundary pointing task remained the same as in Experiment 3.

5.2 Results

5.2.1 Building learning accuracy

In the replacing-building task during the learning phase, the mean of the absolute direction error was 9.14º (*SD* = 10.54º), indicating that participants learned five buildings' directions very well.

5.2.2 Priming task

For trials with initial views, the overall accuracy was 94.24% (*SD* = 15.56%), and the overall mean reaction time was 5.88s (*SD* = 3.83s). There was no difference in accuracy across conditions, $F(4,188) = 0.245$, $p = .91$, $\eta_p^2 = .01$. Paired sample *t* tests contrasting *HG* and *HL* conditions with the (*None*+*PG*+*PL*) baseline condition were conducted to test the priming effects (see Figure 2). Participants responded significantly faster in the *HG* condition than in the baseline condition ($t(47) = 2.89$, $p = .006$, Cohen's $d = .59$), indicating a global heading priming effect. However, the difference between the *HL* condition and the baseline condition was not significant ($t(47) = 0.87$, $p = .39$, Cohen's $d = .18$), indicating no local heading priming effect.

5.2.3 Across-boundary pointing task

Figure 8 showed estimated standing positions and estimated global headings when participants imagined facing objects inside the rooms. This figure shows that the means of participants' estimated global headings were close to the correct headings, but their estimated positions were not accurate and they might not be able to distinguish the global locations of the two rooms.

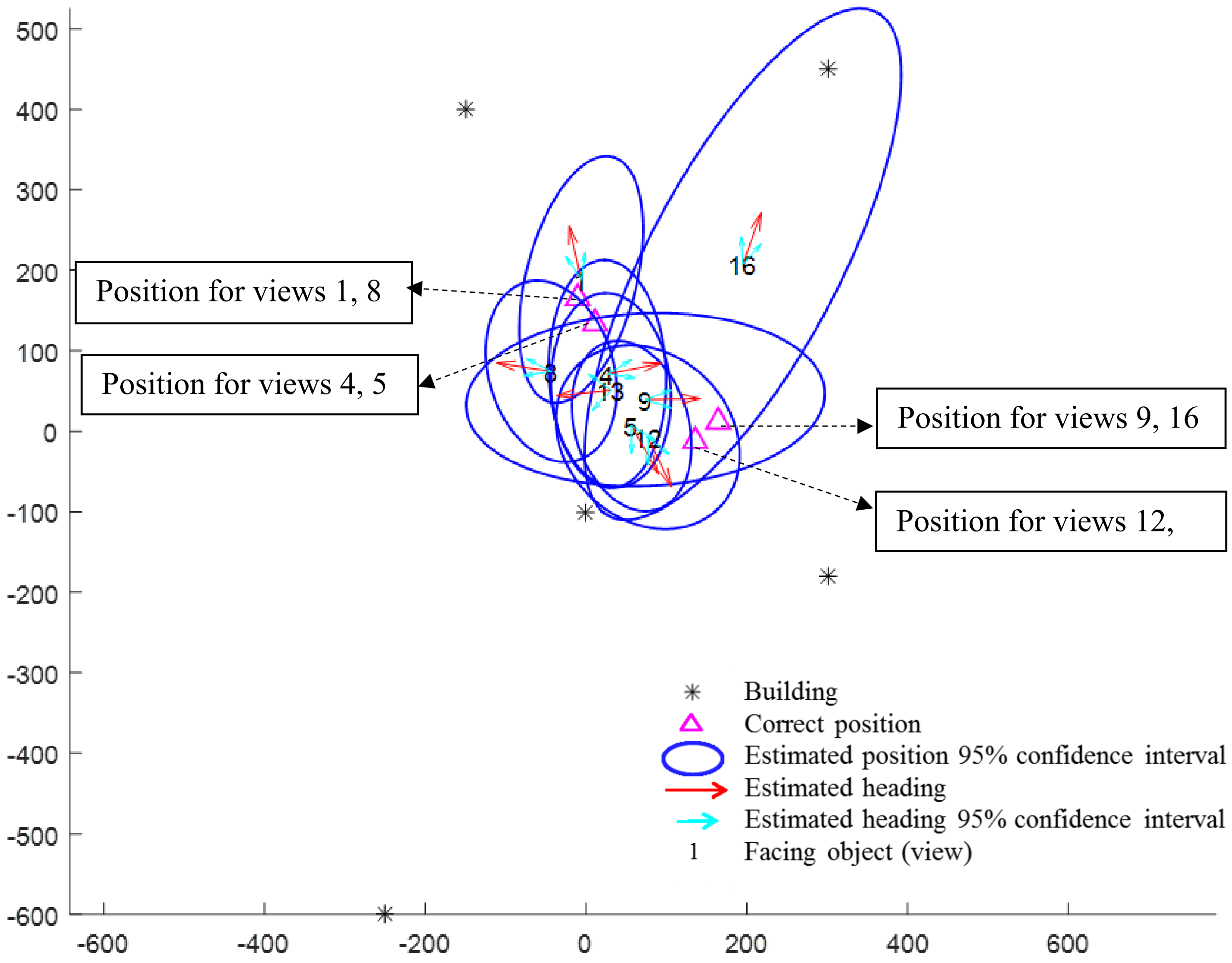

Figure 8. Estimated standing positions and headings when facing objects in the rooms in Experiment 4.

The correct and estimated global headings for each facing object are plotted in Figure 9. From the results we can see that the 95% confidence interval of the circular mean of each heading estimation included the corresponding correct heading. All circular means of heading estimations were close to the corresponding correct headings, which indicates that participants could accurately estimate their global headings at local views inside the rooms.

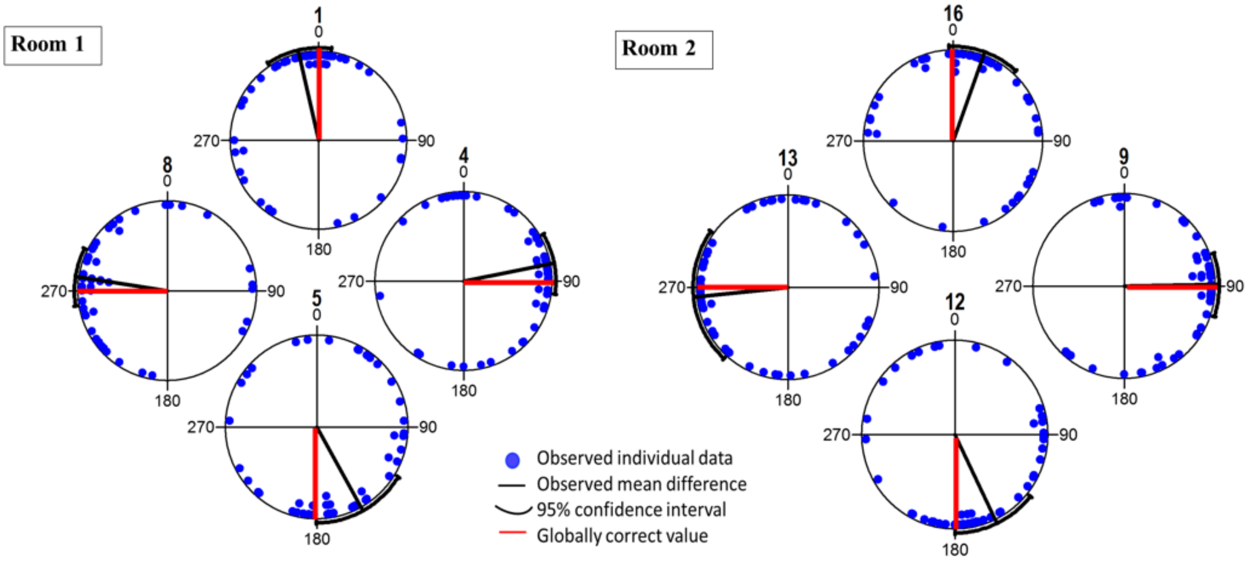

Figure 9. Correct global headings and estimated global headings for each facing object in each room based on the response pointing of buildings in Experiment 4.

The above results in Experiment 4 show an accurate global heading representation as well as the global heading priming effect, demonstrating that people can develop a global representation through the path integration system when minimum piloting cues are provided. The global heading priming effect in Experiments 3 and 4 suggests that the within-boundary priming task was also sensitive to the global representation of the two rooms. This raises the question of why Experiment

2, in which participants locomoted between the two rooms in the open field, did not show the global heading priming effect. We speculated that acquiring some global knowledge about the environment, such as learning five buildings' directions, may be important for participants to develop a global representation through the path integration system. Experiment 5 tested this speculation.

6. Experiment 5

The purpose of Experiment 5 was to test whether the learning of five buildings played an important role in developing a global representation through path integration. Experiment 5 was the same as Experiment 4 except that we removed the five buildings' learning phase and participants conducted only the priming task. If learning some global knowledge of the environment is important for developing a global map through the path integration system, then we may not see the global heading priming effect.

6.1 Method

6.1.1 Participants

Thirty-six university students (18 females) with normal or corrected-to-normal vision were recruited. Their participation was counted as partial fulfillment of a requirement for an introductory psychology course.

6.1.2 Materials and design

The two local rooms and the hallway remained the same as in Experiment 4.

6.1.3 Procedure

In the beginning of the learning phase, participants were standing at the entrance to one room, facing the window in the room. They then entered the room to learn objects. Participants still locomoted through the hallway between the two rooms. After learning, participants conducted the priming task in another experimental room.

6.1.4 Data Analysis

Data analysis for the priming task remained the same as in previous experiments.

6.2 Results

For trials with initial views, the overall accuracy was 94.44% (*SD* = 15.07%), and the overall mean reaction time was 4.56s (*SD* = 2.02s). There was no difference in accuracy across conditions, $F(4,140) = 0.05$, $p = .99$, $\eta_p^2 = .002$. Paired sample *t* tests contrasting *HG* and *HL* conditions with the baseline condition were conducted to test the priming effects (see Figure 2). Participants responded significantly faster in the *HL* condition than in the baseline condition ($t(35) = 3.48$, $p = .001$, Cohen's $d = .82$), indicating a local heading priming effect. However, the difference between the *HG* condition and the baseline condition is not significant ($t(35) = 0.65$, $p = .52$, Cohen's $d = .15$), indicating no global heading priming effect.

7. General Discussion

The important results of all experiments are summarized in Table 2. There are three important findings. First, participants could develop a global representation of two rooms through the path integration system while locomoting between rooms using a simple path. Second, developing a global map of the two rooms might require some prior representations of the global environment. Third, participants could maintain both global and local maps of the rooms, which might require significant cognitive resources.

First, the accurate global heading estimation and the global heading priming effect in Experiment 3 and Experiment 4 clearly indicate that after travelling a simple path between local spaces, people can use the path integration system to develop a global representation of local spaces that are separated by boundaries. This sort of demonstration of the global representations observed in the current study, as well as in Shine et al. (2016), is theoretically significant.

A prevailing theory stipulates that the path integration system is critical to the global representation of an environmental space (Gallistel, 1990, p. 106; Gallistel & Matzel, 2013; Jacobs & Schenk, 2003; Loomis et al., 1999; McNaughton et al., 2006; Meilinger, 2008). However, the previous empirical evidence showed that participants might not be able to develop a global representation of two local spaces even when they walked a simple path between the two rooms (Kelly, et al., 2007; Marchette, et al., 2014; Marchette, et al., 2017). These previous findings challenged the importance of path integration in developing a global representation across boundaries. In fact, the findings were more consistent with a local-map hypothesis, suggesting that the path integration system stops tracking the original environment when people cross boundaries towards a new environment (Wang & Brockmole, 2003).

The current finding and that of Shine et al. (2016), however, indicate that people can track their global heading when they walk into local rooms, consistent with the recent finding that the path integration system is not sensitive to boundary crossing (Mou & Wang, 2015). To sum up, the current finding and that of Shine et al. (2016) support the hypotheses claiming a global map (multiscale-map hypothesis, global-map-only hypothesis).

Second, the current study indicates that some spatial learning of the global environment may be critical in developing a global representation of local spaces using the path integration system. Participants who learned five extra buildings' directions before entering local spaces were able to develop a global map (Experiments 3 and 4). In contrast, participants who did not learn the five buildings were not able to develop a global map (Experiments 2 and 5). This indicates that some spatial learning of the global environment may be important to integrating local spaces into a global map. Furthermore, the spatial learning of the global environment may need to include memory tasks rather than just familiarization of the environment. Participants in Marchette et al. (2014) were also instructed to familiarize themselves with the global environment before they learned the objects inside rooms, but they did not do any memory task in this familiarization, which might explain why there was no global priming effect in their study. In the current study, participants did a replacing-building task when learning five buildings' directions. The memory of the global spatial relationships of the buildings might provide a global frame to integrate local spaces afterwards.

Meanwhile, the current study also identifies several factors that were thought to be but actually are not critical to explain the discrepancy in findings about global representations acquired through path integration. (1) The global heading priming effect in Experiments 3 and 4 indicates that the global map is accessed by a priming task as well as by an across-boundary pointing task, undermining the speculation that global representation is only accessed by the across-boundary tasks (see Table 1). (2) One possible explanation for why no global priming effect was observed in Marchette et al. (2014) but there was a global representation in Shine et al. (2016) is the desktop virtual environment used in the former and the immersive virtual environment in the latter. However, Experiments 2 and 5 in the current study, where participants could physically rotate in the immersive virtual environment, did not show evidence of a global representation. Thus the body-based self-motion cues, such as vestibular and proprioceptive cues, may not be the only reason to develop a global map. (3) Shine et al. (2016) reported that participants could estimate their global heading inside a room after they were explicitly instructed and trained to do so. Participants in the current study were not explicitly instructed or trained to learn the global headings inside rooms. This suggests that explicit instruction and training to learn global relationships may not be essential to the development of a global spatial representation.

Third, the coexistence of local and global heading priming effects together with the accurate global heading estimation in Experiment 3 demonstrates that people can develop multiscale cognitive maps. Participants in Experiment 3 established a local reference system using the room orientation (the principal axis) to represent the locations inside the room, whereas they established a global reference system outside the rooms to integrate the two rooms into a global representation (McNamara, Sluzenski, & Rump, 2008; Meilinger & Vosgerau, 2010; Poucet, 1993; Zhang, Mou, McNamara, & Wang, 2014). Importantly, they maintained both the local and global spatial representations separately, which had not been clearly demonstrated in previous studies.

By contrast, participants in Experiment 4 had only a global priming effect but did not have a local priming effect. We speculated that developing multiscale maps might require significant cognitive resources/efforts. Compared with Experiment 3, there were minimal piloting cues in Experiment 4 as participants never saw the two rooms simultaneously and could not see the global environment while walking in the hallway. Therefore, it was much harder for participants in Experiment 4 to integrate the two rooms in the same global representation. Participants might have used most of the cognitive resources to integrate the global representation of these two rooms; as a result, they did not have resources to simultaneously maintain separate local maps of the rooms. In contrast, the relatively rich piloting cues in

Experiment 3 might have reduced the difficulty of global integration so that participants could still have enough cognitive resources to maintain local maps simultaneously with a global map.

It is important to note that we used the circular mean of the estimated global heading in the across-boundary pointing task to examine the fidelity of the global representation. The small angular difference between the circular mean of the estimated heading and the correct global heading indicates that participants developed an overall accurate global heading representation (see Figure 5 and Figure 9). However, the variance of the estimated heading was large. This large individual difference in global heading estimation indicates that the development of a global representation, even while walking a simple path between two separated spaces, is not effortless. This echoes our above speculations that significant cognitive resources/efforts are required for the development of a global map, especially for the development of multiscale maps. It seems that whether a local map, a global map, or multiscale maps can be developed through path integration depends on how much cognitive resources/efforts participants can devote to the process. By expending the least amount of cognitive resources/efforts, people can develop local maps; by expending an intermediate amount of cognitive resources/efforts, people can develop a global map without local maps; by expending the greatest amount of cognitive resources/efforts, people can develop multiscale maps.

Although the current findings indicate that participants can develop a global representation of two rooms using path integration, the findings do not undermine the importance of the piloting system in the development of a global map. Due to the difficulty of developing a global map using path integration, we acknowledge that the piloting system may play a more important role in developing a global representation in an environmental space than what is stipulated by the prevailing theory (Gallistel, 1990, p. 106; Gallistel & Matzel, 2013; Jacobs &

Schenk, 2003; Loomis et al., 1999; McNaughton, et al., 2006). It has been reported that the piloting system can remove the accumulated error in the path integration system (Etienne et al., 2004; Foo et al., 2005; Kelly et al., 2007; Mou & Zhang, 2014; Zhang & Mou, 2016; Zhao & Warren, 2015a, 2015b). More directly, using the piloting system, people may perceive common reference objects and directions (e.g., a high building, a mountain) while standing in different local spaces. This suggests that the piloting system can establish a global reference system to integrate the local spaces into a global representation (Ishikawa & Montello, 2006; Sholl et al., 2006; Weisberg et al., 2014; see Table 1). In addition, Han and Becker (2014; see also Kelly et al., 2007) observed that participants developed a global spatial representation of two neighbourhoods simply because the neighborhoods shared a common appearance. Meilinger et al. (2016) showed that walking a path while seeing a common boundary at all legs of the path significantly facilitates the development of a global representation of the traversed path. Moreover, the discrepant findings in Experiments 3 and 4 of the current study suggest that the piloting system might also be important to developing multiscale maps.

In the current study, both the global and local priming effects were only observed when the testing views were the initial views but not the other views. This indicates that participants might have used the initial views of each room to establish the local reference direction (Shelton & McNamara, 2001) and also encode the global relationships between the local reference directions (i.e., initial views) (Greenauer & Waller, 2010; Zhang et al., 2014). All the other views might have been specified based on the local reference direction (i.e., initial views). Therefore, when participants saw two other views, which were locally or globally consistent, they did not know the direct relationship between these two views and had to infer the relationship. This extra inference might have eliminated the priming effect for the views other than the initial ones.

Moreover, as participants might have encoded the spatial relations of some views between the rooms but inferred the spatial relations of some other views between the rooms during global judgments, the global representations observed in Experiments 3 and 4 included not only those directly encoded during path integration but also those inferred during judgments (Meilinger, 2008).

A local position priming effect was also reported in Marchette et al. (2014). The local position priming effect is that participants responded faster if their imagined testing positions in two consecutive trials were locally consistent. However, we did not observe any local position priming effect. One possible reason may be due to the interior features in the local rooms. In Marchette et al. (2014), virtual museums had windows, carpets and architectural features such as facades, columns and plinths, which might have acted as local landmarks to facilitate participants to code local positions. In contrast, in our virtual environment set-ups, the two rooms had no rich visual features, only windows, carpets and room geometry to help participants perceive the principal axis of the space, the axis of the entrance to the window or the elongation of the carpet. The perceived principal axis could precisely encode a local heading but not a local position.

In summary, the present findings indicate that people can develop a global spatial representation of local spaces across boundaries using path integration. A prior representation of the global environment may be important to integrating local spaces to a global representation. Both the global and local representations can be separately maintained in multiscale cognitive maps, although maintaining multiscale cognitive maps requires significant cognitive resources.

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