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Developing Global Spatial Representations through Across-boundary Navigation

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Abstract

This study investigated the extent to which people can develop a global representation of local environments through across-boundary navigation. 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 within the room; the views in two consecutive trials were from different rooms and locally or globally consistent (priming task). In some experiments, participants learned locations of five buildings before learning the objects in the rooms. In testing, after the priming task, they pointed to the buildings while adopting local views inside the rooms (across-boundary pointing task). Participants' estimated global headings were calculated from their pointing responses. The results showed that the priming effect from the globally consistent views occurred when participants learned the buildings and then locomoted between the rooms through a simple path. Consistent with the global priming effect, the means of participants' estimated global headings were accurate. In contrast, there was only the priming effect from the locally consistent views when participants did not learn the buildings before learning the objects inside the rooms or when participants were teleported between the rooms after learning the buildings. These results suggest that people can develop global representations of local environments through across-boundary navigation while travelling a simple path, provided there are prior global representations.

Keywords: global spatial representation; local spatial representation; across-boundary navigation; path integration

Developing Global Spatial Representations through Across-boundary Navigation

1. Introduction

In everyday life, people often move between two locations within a boundary (e.g., moving from a desk to a printer in an office). People also often move between two locations across boundaries (e.g., moving from a desk in an office to a desk in another office that is a few doors away). To efficiently navigate between locations within a boundary and across boundaries, people might form and rely on spatial memories of locations within and across boundaries. How people develop spatial memories during navigation within a boundary (within-boundary navigation) is quite well understood (e.g., Greenauer & Waller, 2010; Holmes, Newcombe, & Shipley, 2018; Kelly & McNamara, 2010; Shelton & McNamara, 2001; Yamamoto & Shelton, 2007). In contrast, how people develop spatial memories during navigation across boundaries (across-boundary navigation) is poorly understood (Marchette, Vass, Ryan, & Epstein, 2014; Shine, Valdés-Herrera, Hegarty, & Wolbers, 2016). The current study tackled this issue.

In navigation, people use two methods to encode spatial relations between two locations and update their own location in the environment. The first method relies on perception (primarily vision) and is referred to as piloting (or landmark-based navigation). Through piloting, people directly perceive spatial relations between two visible locations. People can also update their own location when they see familiar landmarks (Cheng & Spetch, 1998; Gallistel, 1990). The other method depends on self-movement cues (including optic flow and idiothetic cues) and is referred to as path integration (Etienne & Jeffery, 2004; Loomis, Klatzky, Golledge, & Philbeck, 1999; Rieser, 1989; Yamamoto & Shelton, 2005). Through path integration, people can calculate the Euclidian spatial relations between two locations on a circuitous path (Mittelstaedt & Mittelstaedt, 1980; Müller & Wehner, 1988; Wang, 2016). People can also update their own location relative to locations that they previously learned (Rieser, 1989).

In within-boundary navigation, people use both methods to develop spatial memories. A within-boundary space is usually a vista space (namely, an immediate visible surrounding, Montello, 1993). Using piloting, people directly perceive the shape of the boundary (e.g., the walls of a room) and the locations within the boundary. Locations can be encoded in terms of spatial reference frames based on the boundary geometry (e.g., Cheng, 1986; Doeller & Burgess, 2008; Shelton & McNamara, 2001) and the intrinsic structure of an object array (e.g., Mou & McNamara, 2002). People can even develop multiple micro-reference frames to encode spatial relations between objects within each object array, and a macro-reference frame to encode spatial relations between objects across different object arrays (Greenauer & Waller, 2010). Using path integration, people without vision can encode spatial relations between locations on the path that they have walked (Yamamoto & Shelton, 2005). While people change their viewpoints of an object array by walking around the array, they can also integrate spatial representations encoded at different viewpoints into a global spatial representation (Holmes et al., 2018).

However, it is not clear how people use piloting and path integration to encode spatial relations between locations in two local spaces across boundaries. The functions of piloting and path integration to develop spatial memoires could significantly differ in across-boundary navigation from those in within-boundary navigation. We propose two models to theorize it: the *global map model* and the *local map model*.

The global map model

In across-boundary navigation, as people cannot directly see the spatial relations between two locations in local spaces that are separated by boundaries, people primarily use path integration to calculate the spatial relations between these locations. Some researchers believe that path integration can support human spatial learning in a large-scale environment (Gallistel, 1990, p. 106; Gallistel & Matzel, 2013; Jacobs & Schenk, 2003; Loomis et al., 1999; McNaughton, Battaglia, Jensen, Moser, & Moser, 2006; Meilinger, 2008; see also Huebner & Mallot, 2007; Milford & Wyeth, 2008 for interesting computational theories of Robot navigation). One recent study showed that path integration functions equally well in across-boundary navigation and within-boundary navigation (Mou & Wang, 2015). This suggests that in across-boundary navigation, people primarily use path integration to integrate spatial representations of local spaces into a global spatial representation. We refer to this model as the *global map model*. According to this model, while people maintain the local spatial representations of individual local spaces, they also develop global representations of locations in across-boundary spaces.

The local map model

The *local map model* also states that people primarily rely on path integration rather than piloting to encode spatial relations between locations across boundaries, as they cannot see one local space while standing inside the other local space. However, the *local map model* stipulates that people cannot use path integration to calculate the spatial relations between the local spaces. Path integration is used to engage with the immediate local space. When people move from one local space to another local space, people *shift* maps of these two spaces instead of integrating the local maps into a global map (e.g., Wang, 2016; Wang & Brockmole, 2003). As path integration only functions within but not across boundaries, people only develop local spatial representations of individual local spaces but not a global spatial representation of both local spaces. We refer to this model as the *local map model*. According to this model, people maintain the local spatial representations of individual local spaces, but do not develop global representations of locations in across-boundary spaces.

These two models primarily differ in the function of path integration to encode global spatial relations between two locations in local spaces separated by boundaries. To differentiate these two models, we need to examine whether people can develop a global representation of two local environments through across-boundary navigation. Studies have examined whether people can develop a global representation of spatial relations between different routes (Ishikawa & Montello, 2006; Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014) and whether people can develop representations of spatial relations between indoor and outdoor environments (Burte & Hegarty, 2014; Sholl, Kenny, & DellaPorta, 2006; Wang & Brockmole, 2003). However, there are very few studies directly examining whether people can develop a global representation of two local environments through across-boundary navigation (Marchette et al., 2014; Shine et al., 2016).

In a recent study, Marchette et al. (2014) provided direct evidence that people do not develop a global representation of two separate spaces through across-boundary navigation while travelling a simple path. In a desktop virtual environment, the participants in Marchette et al. learned locations of objects in different rooms by visually travelling a simple path with one turn between rooms. During the test, the participants did a priming task. They were asked to adopt an imagined perspective inside a room and then judge the direction to an object in the same room. In two consecutive trials, the imagined perspectives 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 responses were facilitated if the perspective in the current trial was locally consistent with that in the preceding trial (i.e., local priming effect). This local priming effect was evident even when the two consecutive trials involved 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). In addition, Marchette et al. reported that there was neural activity sensitive to the local heading but no neural activity sensitive to the global heading (see also Spiers, Hayman, Jovalekic, Marozzi, & Jeffery, 2015 for a similar finding in rats).

In a follow-up study, Marchette, Ryan, and Epstein (2017) asked the participants to place the objects back into the original locations after learning the objects' locations in different rooms. The rooms had similar geometry but distinctive appearances. The results showed that the participants frequently went to the geometrically analogous location in the wrong room. This finding indicates that the participants might not have remembered the object's location in the global environment, although they did remember the local location in the room.

In contrast, Shine et al. (2016) have provided clear evidence that people can develop a global representation of vista spaces through across-boundary navigation. Similar to Marchette et al. (2014), the participants in Shine et al. learned pictures on different walls inside rooms by locomoting between the rooms. However, there are also important differences in the learning procedures between these two studies. First, the participants in Shine et al. were explicitly required to understand the headings of the paintings on the walls inside the rooms relative to the environment outside the rooms. If they incorrectly judged the global heading of a probed painting, they were required to walk outside the rooms to learn the correct global heading. Second, the participants in Shine et al. physically turned their bodies when they turned in the virtual environment, whereas the participants in Marchette et al. used a keyboard to turn their viewing orientations in the virtual environment. In the testing phase, the participants in Shine et al. judged whether the headings of two paintings from different rooms were globally consistent.

The behavioural results of Shine et al. showed that the participants were very accurate when judging global headings. In addition, there was neural activity that was sensitive to global headings (see also Carpenter, Manson, Jeffery, Burgess, & Barry, 2015 for a similar finding of rats).

Although the accurate judgments of global headings from two rooms in Shine et al. clearly favor the *global map model* over the *local map model*, one may argue that the *global map model* is valid only in a special situation when people are explicitly required and trained to learn their global headings inside rooms during navigation, whereas the *local map model* is valid whenever people are not explicitly required or trained to learn global headings. Actually, in everyday life, it is very rare that people are required and trained to learn global headings inside rooms when they move between rooms. Therefore, the *global map model* may be valid only in some exceptional cases rather than in a natural across-boundary navigation.

However, the lack of a global priming effect in Marchette et al. (2014) does not exclusively eliminate the possibility that people can develop global headings within a room in natural across-boundary navigation. The null global priming effect could be due to the following two possibilities. First, the participants in Marchette et al. used a keyboard to turn their orientations in the virtual environment but never physically turned their bodies. Thus, their path integration primarily relied on optic flow. Previous studies showed that idiothetic cues from physical body turning are important in path integration and spatial memories (Chrastil & Warren, 2013; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Rieser, 1989). Moreover, in real-life navigation, people turn their bodies physically. Therefore, the global priming effect could have appeared if the participants in Marchette et al. (2014) physically turned their bodies during navigation. Second, the participants in Marchette et al. (2014) might already have developed global headings within each room. However, the global priming trials might not reveal global headings. The participants judged the spatial relations of objects (i.e., the imagined facing object and the target object) within a local space. Thus, the global priming trials, as a within-boundary task, may not access global spatial representations. Therefore, it is plausible that participants, who might have both global and local spatial representations, only access the local representations to finish the global priming trials. To reveal the global spatial representations, we need across-boundary tasks in which participants are asked to judge the spatial relations of objects between local spaces (e.g., Shine et al., 2016).

As reviewed above, it is still not clear to what extent the *local map model* and the *global map model* can accurately stipulate how humans develop global spatial representations in a natural across-boundary navigation, similar to that in Marchette et al. (2014) but with the addition of physical body turning. The primary purpose of the current study was to address this issue. The key experiment (Experiment 3) would, with two important modifications, examine the global representations after across-boundary navigation using the paradigm of Marchette et al. (2014). The first modification is that, during learning, the participants would learn objects' locations in two misaligned rectangular rooms in an immersive virtual environment so that the participants physically turned their bodies. The second modification is that, during testing, the participants would have an across-boundary pointing task in addition to the priming task. If the key experiment showed that the participants could estimate their global headings accurately in the across-boundary pointing task, then the *global map model* would be favored in the natural across-boundary navigation; otherwise, the *local map model* would be favored. Supposing the participants could estimate their global headings accurately, the global priming trials could test whether these trials only access local spatial representations or also access global spatial representations. The lack of a global priming effect would support the former whereas the existence of a global priming effect would support the latter.

Table 1 summarizes the manipulations of all experiments in the current study. Experiment 1 was conducted to assure that the priming trials in the current study could demonstrate a local priming effect when participants did not have the across-boundary navigation. Participants were teleported between rooms. Experiment 2 was conducted to replicate Marchette et al., (2014) with the addition of physical body turning, to see whether physical body turning is critical to integrating a global representation. Experiment 3, as the key experiment, examined the *local map model* and the *global map model* using an across-boundary pointing task in addition to the priming task. In the across-boundary pointing task, the participants pointed to five buildings that they learned before locomoting between rooms. Experiment 4 was conducted to test whether directly seeing the two rooms while learning the five buildings is essential to forming global spatial representations. Experiment 5 investigated whether prior global spatial learning (i.e., learning the five buildings) is important to developing a global representation. Experiment 6 was conducted to investigate whether across-boundary navigation is essential to forming global spatial representations.

[Table 1]

2. Experiment 1

Experiment 1 was conducted to ensure that our priming task could demonstrate the local priming effect reported by Marchette et al. (2014) before we further investigated whether the participants could have a global representation of views in different rooms during across-boundary navigation. Our priming trials significantly differed from the trials used in Marchette et al. For example, to study global representations between rooms, our priming trials only included consecutive trials involving different rooms although Marchette et al. included consecutive trials involving the same room or different rooms. In Marchette et al., the local priming effect was observed in Experiment 1 but not in Experiment 2. According to the authors, the reason for this could be the longer inter-trial interval in Experiment 2, indicating that the local priming effect might be sensitive to slight changes in the experimental materials, design and procedure. As our trials differed from what was used in Marchette et al., it is important to make sure that our priming trials are valid to demonstrate the local priming effect before examining the global priming effect. Furthermore, to avoid cherry-picking when examining the global priming effects in the following experiments, it is important to make sure that we validate our priming trials independent of examining the global priming effect. The participants in the current experiment were teleported between two rooms and did not have the across-boundary navigation.

2.1 Method

2.1.1 Participants

The study was approved by Ethics Committee of the University of Alberta. University students with normal or corrected-to-normal vision participated to partially fulfill the requirement for an introductory psychology course. Forty-eight participants (24 females) were used in all the experiments in the current study, and they were counterbalanced by gender, the learning order of the two rooms, and the order of the three blocks of priming trials.[1]

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[1] In Experiment 1, of the forty-eight participants, five were replaced because their accuracies were below 70% (following the criterion in Marchette et al., 2014). In each of the other experiments in the current study, about 10% of the participants were replaced because of low accuracy (i.e., below 70%), to ensure a counterbalance in the forty-eight participants.

In the first experiment of Marchette et al. (2014), Cohen's *d* of local direction effect was about 1.02[2]. Because the priming task in the current study has much fewer trials than that in Marchette et al. (63 vs. 384 trials), the effect size should decrease significantly. Assuming the effect size decreased to 0.50 (a medium effect), we used forty-eight participants to get the *power* 0.67 at the 0.05 level (for two-tailed paired *t* test, see the Matlab code for the power analysis at https://doi.org/10.7939/r3-vm8t-xy36).

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 the participants' viewing orientations in the virtual environment. In particular, the participants sat on a swivel chair in the centre of the room and physically turned their bodies to change their viewing orientations in the virtual environment; they used a joystick to move forwards or backwards along their viewing orientation in the virtual environment. The centre of the virtual environment overlapped with the centre of the physical room.

The virtual environment had an open field with a grass-textured ground. In the virtual environment there were two rectangular rooms, with a 90° angular difference between them (Figure 1A). Although the 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.

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[2] Cohen's *d* was calculated by $\sqrt{(\frac{2F}{N})}$. In Experiment 1 of Marchette et al. (2014), the *F* value for the local direction effect was 11.63 and N was 22.

These two rooms had identical geometry, with an aspect ratio of 0.6 (36m by 60m), but each had distinguishable interior and exterior textures and colours (Figure 1B). A large window was set on the back wall of each room. Both rooms had a long carpet stretching 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 the 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. To see each specific object, the participants had a fixed standing position and facing direction. Thus, specifying each view would determine both a standing position and a facing direction.

[Figure 1]

For each view, we could use local and global reference frames to code the location and heading of that view. The global reference direction (i.e., global north) in Figure 1A was arbitrarily defined. We assumed that the local reference direction of each room was from the door to the window and referred to it as local north. For example, for View 9, global position coding would be standing in the global northeast corner; global heading coding would be facing global east (90°); local position coding would be standing in the local northwest corner (i.e., the far-left corner in the room); local heading coding would be facing local north (0°).

The priming task occurred in a different physical room in the laboratory. There were three blocks of trials, 21 in each block (see the trials at https://doi.org/10.7939/R3H98ZW2V). In each trial, the participants were asked to imagine facing one object while standing on the corresponding stage, and to judge whether another target object in the same room was to their left or right. The target object was chosen randomly from six possible objects in the room (e.g., if the imagined facing object was the object at View 1, then possible target objects were the objects at Views 2, 3, 4, 5, 7, and 8). Across trials, the left and right target directions were balanced.

We made two major changes to the design of the consecutive trials in Marchette et al. (2014). First, in each block, the two consecutive trials were always between rooms. Within-room switching (used in Marchette et al.) was not included because it could not differentiate locally consistent headings from globally consistent headings and we were only interested in local/global priming effects between rooms. Second, the conditions based on the relationship between two consecutive trials were exclusive (Table 2). The conditions in Marchette et al. were not exclusive. For example, two views of consecutive trials could be both locally consistent in headings and globally consistent in positions. In the current study, in a global heading (*GH*) condition, only the global headings of consecutive trials were the same; in a local heading (*LH*) condition, only the local headings of consecutive trials were the same. We also used three other types of consecutive trials introduced in Marchette et al., but defined them exclusively as well. In a global position (*GP*) condition, only the global positions of consecutive trials were the same; in a local position (*LP*) condition, only the local positions of consecutive trials were the same; in a *None* condition, both the positions and headings were different globally and locally. The trial list in each block was created to have equal trials for these five conditions without repeating the facing-target object pairs (in particular, four trials in each condition and in each block).

To address the discrepancy in global heading representations between Marchette et al. (2014) and Shine et al. (2016), the current study still used the measures on the headings rather than those on the positions to examine the global and local heading representations. Consequently, in all experiments of the current study, the *GP*, *LP* and *None* conditions were combined to be a baseline condition in data analysis.

[Table 2]

2.1.3 Procedure

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

In the learning phase, the 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. The participants always started learning from the left corner under the window and then locomoted to the next corner clockwise. After five minutes of learning, all objects were removed and the participants replaced the objects from their memory. One probed object was shown at the corner of the HMD. The participants needed to locomote to the corresponding stage to face the corresponding alcove and then press a button to put the object back in the alcove. As feedback, the probed object reappeared in the correct alcove. If the participants made a mistake, they were informed about the correct alcove and were asked to locomote there to see the target. The participants replaced the objects in two blocks. In each block, all the objects were probed once and the order was randomized. The participants repeated the learning and the replacing tasks until they could correctly replace all the objects in the second block of the replacing task.

After learning the objects’ locations in one room, the participants were teleported to stand at the entrance and face the window of the other room to learn the other eight objects’ locations.

The room order during learning was counterbalanced across participants. Finally, the participants replaced all 16 objects in one block. The objects were randomly ordered and the feedback was given. During the replacement, the participants pressed a button to be teleported to the other room if necessary. After replacing all objects, the participants were allowed to see the objects' locations again. After the learning phase, the 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, the participants used the left and right arrow keys on a keyboard to judge whether a target object was 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"). The participants were told to respond broadly to the left or right, not just directly to the left or right (for example, when facing the object at View 1, the object at View 5 would be to the right). There was no feedback during testing. The trial ended as soon as the participants responded, and the inter-trial interval was 750 ms. The participants were required to respond as fast and accurately as possible (Marchette et al., 2014). The participants had 11 trials as practice to become familiar with the priming task before they had the three blocks of experimental trials.

2.1.4 Data analysis

Only the correct trials were used in data analysis of response latencies. Mean response latencies were calculated for each condition. If the response latency in the *LH* condition was shorter than the response latency in the baseline condition (*None* + *GP* + *LP*), the local priming effect was obtained. Since the 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 response latency in the *GH* condition than in the baseline condition.

2.2 Results

The overall accuracy was 93.23% (*SD* = 8.42%). The accuracies in *GH*, *LH* and baseline conditions were 93.58% (*SD*=10.35%), 92.19% (*SD*=10.65%), and 93.46% (*SD*=8.35%) respectively.

The response latency in *GH*, *LH* and baseline conditions is summarized in Table 3. To examine whether there were priming effects for the *GH* and *LH* conditions, paired sample *t* tests were conducted between these conditions and the baseline condition (*GH* versus baseline, *LH* versus baseline). No comparison was significant (*t*s(47) ≤ 0.36, *p*s ≥ .72, Cohen's *d*s ≤ .07). No correction of the *p* value was used as both comparisons were planned. The contrast between the local (*LH*) and global (*GH*) trials was not conducted as it is not theoretically meaningful.

Since there was no local priming effect when we analyzed trials for all views, we only analyzed the trials with facing objects at the initial views (i.e., Views 1, 2, 9 and 10). The initial views are the first views that the participants saw when they entered the room. We were interested in the initial views because the initial views could be used to establish the local reference direction (Shelton & McNamara, 2001) and the priming effect might reflect the facilitation between reference directions of different spaces (Marchette et al., 2017). Moreover, one previous study also reported that facilitative effects for taking the same perspective compared with taking a different perspective across environments occurred only for the initial views (Avraamides & Kelly, 2005).

For trials at the initial views, the overall accuracy was 96.08% (*SD* = 6.11%). The accuracies in *GH*, *LH* and baseline conditions were 97.22% (*SD*=9.31%), 95.14% (*SD*=13.73%), and 96.02% (*SD*=7.71%) respectively.

The response latency in *GH*, *LH* and baseline conditions in the trials at the initial views is summarized in Table 3. The paired sample *t* test contrasting the *LH* condition with the baseline condition showed a significantly shorter response latency in the *LH* condition ($t(47) = 2.09$, p =.04, Cohen's $d = .43$), indicating a local heading priming effect. The paired sample *t* test contrasting the *GH* condition with the baseline condition did not show a significant difference ($t(47) = .57$, $p = .57$, Cohen's $d = .12$), indicating no global heading priming effect (see Figure 2).

[Table 3]

[Figure 2]

2.3 Discussion

Only our priming trials at the initial views demonstrated the local heading priming effect reported in the study of Marchette et al. (2014). This indicates that the participants might have used the initial views to establish the local reference direction (Shelton & McNamara, 2001) and all the other views might have been specified in terms of the initial views (Avraamides & Kelly, 2005). Thus, the priming benefit from the preceding trial could only be seen at the initial views but could not be detected at the other views. As the other views might need to be inferred from the initial views, this inference eliminated the priming effect. We are not sure why Marchette et al. (2014) showed the local priming effect at collapsed views. This discrepancy might occur because the trials used in the current experiment differed significantly from those in Marchette et al.'s study. For example, Marchette et al. used consecutive trials involving the same room or different rooms whereas this study only used consecutive trials involving different rooms. Marchette et al. had many more trials than we used in this experiment (384 vs. 63 trials).

In Experiment 1, the local priming effect was only obtained in the trials at the initial view. Therefore, in all the following experiments, we will examine the global priming effects as well as the local priming effects only at the initial views. We still used the same list of the priming trials. Since this initial view analysis was set before the following experiments were conducted, it should not raise concerns about analysis flexibility regarding the results of the following experiments.

3. Experiment 2

Experiment 2 investigated whether people could develop a global representation of two separated local spaces by travelling a simple path between the local spaces. This is the same as in Marchette et al. (2014) but with the addition of physical body turning. The purpose of Experiment 2 was to investigate whether physical body turning in an immersive virtual environment is critical to developing a global representation. Unlike in Experiment 1 where the participants were teleported between the rooms in the learning phase, the participants in Experiment 2 locomoted between the two local rooms across the open field. In addition, distal orientation cues were presented in the open field. The same priming task was used to determine whether there was a global heading priming effect in addition to the local heading priming effect. A result of the global priming effect would indicate that physical body turning is critical to developing a global representation. A result of no global priming effect would suggest that physical body turning is not critical.

3.1 Method

3.1.1 Participants

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

3.1.2 Materials and design

The open field, the two local rooms, and the object arrangements inside the rooms remained the same as in Experiment 1, but there were distal orientation cues in the open field (i.e., ocean, mountain, forest, and city in Figure 3). Unlike in Experiment 1, the participants in the current experiment locomoted between the two rooms in the open field.

[Figure 3]

3.1.3 Procedure

At the beginning of the learning phase, the participants were at the centre of the virtual environment, with only distal orientation cues in the open field. Then the two local rooms appeared. Inside the rooms, the participants could see the distal orientation cues through the windows. The learning and testing procedures were the same as in Experiment 1, except that in the learning phase the participants locomoted from the center of the virtual environment to the first room and also locomoted between rooms rather than being teleported. The procedure in Experiment 2 primarily followed Marchette et al. (2014). The participants in Marchette et al. also saw the orientation cues through the windows while standing inside the rooms, as well as the spatial relations between rooms when they locomoted between the two rooms.

3.2 Results

For trials at the initial views, the overall accuracy was 93.63% (*SD* = 8.57%). The accuracies in *GH*, *LH* and baseline conditions were 93.75% (*SD*=16.35%), 93.75% (*SD*=14.84%), and 93.56% (*SD*=9.92%) respectively.

Paired sample *t* tests contrasting *GH* and *LH* conditions with the baseline condition were conducted to test the priming effects (see Figure 2). The responses in the *LH* condition were faster than those in the baseline condition ($t(47) = 2.25$, $p = .03$, Cohen's $d = .46$), indicating a local heading priming effect. However, the difference between the *GH* condition and the baseline condition was not significant ($t(47) = 1.13$, $p = .26$, Cohen's $d = .23$), indicating no global heading priming effect. To further qualify the null global priming effect, we also calculated the Bayes Factor (*BF*), measuring the ratio of the likelihood of no global priming effect to the likelihood of a global priming effect assuming a flat prior distribution using SPSS 25 (see Gallistel, 2009). The null global priming effect was supported ($BF = 4.77$).[3]

3.3 Discussion

Consistent with the findings of Marchette et al. (2014), the results in Experiment 2 indicate that even with physical body turning, people may not be able to encode global headings of local views in two separate rooms while travelling a simple path between the rooms. However, it is possible that the global headings are encoded but the priming task does not rely on the global representation. In the priming task, the imagined heading and the to-be-judged target are within the same local space; thus, the task may not rely on the global heading representations. As discussed in the Introduction, an across-boundary pointing task that requires judgments between different local spaces might be necessary to reveal a global representation.

4. Experiment 3

In Experiment 3, except for the priming task, the participants also did an across-boundary pointing task to directly examine their global headings when they adopted different local views

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[3] The null effect is favored if the *BF* is larger than 3, and strongly favored if the *BF* is larger than 10, whereas the priming effect is favored if the *BF* is smaller than 1/3, and strongly favored if the *BF* is smaller than 1/10 (Rouder, Speckman, Sun, Morey, & Iverson, 2009). If the *BF* is between 1/3 and 3, neither is favored.

inside the rooms. Zhang and Mou (2018) developed a paradigm of measuring participants' estimates of their headings and positions. In their paradigm, participants learned the locations of five buildings and then pointed to the buildings after navigation. Participants' estimates of their headings and positions were calculated from their pointing directions. Following their paradigm, the participants in Experiment 3 learned five buildings before they learned objects in the two rooms as in Experiment 2 (see Figure 3). In the testing phase, after the priming task, the participants adopted views inside the rooms and then pointed to the five buildings. A best-fit method (see https://doi.org/10.7939/R3057D77Q for the Matlab code provided by Zhang and Mou, 2018) was used to calculate the participants' estimates of their global headings and positions from their pointing directions.

The results of Experiment 3 could differentiate the *local map model* and the *global map model* because these two models had different predictions on the across-boundary pointing accuracy and the priming effects. The *local map model* predicted that there was a local priming effect and the participants were not able to accurately estimate their global headings in the across-boundary pointing task, whereas the *global map model* predicted that the participants were accurate in estimating their global headings in the across-boundary pointing task and there was a local priming effect.

Comparing the results of the global heading priming effect with the across-boundary pointing task, we also tested whether the priming task as a within-boundary pointing task is sensitive to global representations. If the participants had accurate global headings as revealed by the across-boundary pointing task, but there was no global heading priming effect, these results would suggest that the priming task as a within-boundary pointing task is not sensitive to a global representation.

4.1 Method

4.1.1 Participants

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

4.1.2 Materials and design

The two local rooms and the distal orientation cues remained the same as in Experiment 2. Before seeing the two rooms, the participants learned the locations of five extra buildings (Figure 3) in the environment. The two rooms and the five buildings were never presented simultaneously. When the participants learned the five buildings, only the doorways (doorframes) of the two rooms were presented and the participants stood at each doorway to learn. Two learning positions (two doorways) were used to ensure that the participants could accurately encode the locations of the buildings. When the participants started to learn objects in the two rooms, 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, the participants also did an across-boundary pointing task using a joystick. The 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 object at a local view was presented in white letters on a black screen (e.g., “Imagine you are facing the vase”). After the participants pressed a button on the joystick, the name of the pointing building appeared (e.g., “point to 7-11”). The participants moved the joystick to point to the exact direction of the building.

To limit the experiment time to 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. Half of the participants conducted trials including views in the locally northwest and southeast corners in each room (Views 1, 8, 4, 5 and Views 9, 16, 12, 13), while the other half conducted trials including views in the locally northeast and southwest corners in each room (Views 2, 3, 6, 7 and Views 10, 11, 14, 15). For each view, the participants pointed to all five buildings (i.e., there were 40 trials in the across-boundary pointing task). The order of the trials was randomized for each participant.

4.1.3 Procedure

At the beginning of the learning phase, the participants stood at the centre of the virtual environment with only distal orientation cues in the open field. Both doorways of the rooms were then presented. The participants were asked to move towards one of the doorways. When the participants stood in the middle of a doorway, the five buildings appeared. The participants learned the locations of these buildings while standing at the doorway for one minute. After the learning session, all five buildings disappeared and the participants pointed, from memory, to the original direction of each building. Each building was probed by presenting a small model of it at the corner of the HMD. There was a red cursor in the middle of the HMD. The participants turned to aim the cursor in the direction of the building and then pressed a button on the joystick to confirm. After the participants responded, the probed building was presented as feedback at the correct location. There were two blocks of such pointing-feedback trials in this 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,[4] the same learning procedure (learning five buildings, followed by the replacing-building task) was repeated.

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[4] This happened when experimenters noticed any obvious discrepancy between the response direction (i.e., the cursor) and correct direction of the probed building (i.e., the feedback location) on two monitors showing the same views on the HMD.

Otherwise, the 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. The participants returned to the centre and closed their eyes for a three-minute rest break. After the break, the five buildings disappeared and the two complete rooms, including the doorway, appeared. The participants locomoted between the two rooms to learn the objects as in Experiment 2.

During the testing phase, the participants performed the priming task first, followed by the across-boundary pointing task. In the across-boundary pointing task, the participants were asked to respond as accurately as possible and take their time to think. We calculated the estimates of participants' headings using the pointing directions. Participants' response times were not relevant to the calculation of the heading estimates.

4.1.4 Data Analysis

For the across-boundary pointing task, at each testing view we calculated the participants' estimates of their global heading and global position using the least square of the errors in their response directions to the five buildings. A global heading is specified by an angular difference from the global north in Figure 1A 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 1A (E is x positive and N is y positive).

Particularly, at each testing view, for each target building, participants' response direction was measured by the travelling direction of the joystick in terms of the joystick front. Meanwhile, for any possible subjective global heading and any possible subjective global position, we calculated the direction from the given subjective global position to each of the five target buildings in terms of the given subjective global heading. We defined this calculated direction as the correct direction to that target building for this given global heading and position. Therefore, for any given subjective global heading and any given subjective global position, we obtained one response error for each building by subtracting the correct direction from the response direction. Participants' estimates of their global heading and global position for the given testing view were then determined by the least square of the response errors across the five buildings (see https://doi.org/10.7939/R3057D77Q for the Matlab code provided by Zhang & Mou, 2018).

Thus, we obtained the estimate of an allocentric heading 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 each position, we obtained the estimated coordinate for each testing view for each participant and then calculated the means of estimated coordinates for each view. Since there were two kinds of view lists, to simplify data analysis and increase the statistical power, we converted heading and position estimates of the participants who had testing views in the locally northeast and southwest corners in each room (Views 2, 3, 7, 6 and Views 10, 11, 15, 14) to the corresponding estimates at testing views in the locally northwest and southeast corners in each room (Views 1, 8, 4, 5 and Views 9, 16, 12, 13), respectively (see Table 4). As Views 2, 3, 7, and 6 were the mirror reflections of Views 1, 8, 4, and 5, respectively along the direction of global 0° (i.e., global north), we flipped the heading of Views 2, 3, 7, and 6 to those of Views 1, 8, 4, and 5 along the global 0° (i.e., converting H to -H). Similarly, as Views 10, 11, 15, and 14 were the mirror reflections of Views 9, 16, 12, and 13, respectively along the direction of global 90° (i.e., global east), we flipped the headings of Views 10, 11, 15, and 14 to those of Views 9, 16, 12, and 13, respectively along the direction of global 90° (i.e., converting H to 180-H). Therefore, we only used testing Views 1, 8, 4, and 5 and Views 9, 16, 12, and 13 to represent four global headings (0°, 90°, 180° and 270°) in each room.

[Table 4]

4.2 Results

4.2.1 Priming task

For trials at the initial views, the overall accuracy was 94.12% (*SD* = 8.75%). The accuracies in *GH*, *LH* and the baseline conditions were 96.53% (*SD*=10.29%), 94.44% (*SD*=15.88%), and 93.37% (*SD*=10.57%), respectively.

Paired sample *t* tests contrasting *GH* and *LH* conditions with the baseline condition were conducted to test the priming effects (see Figure 2). The participants responded significantly faster in both the *GH* and *LH* 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 the participants imagined facing objects at local views inside the rooms. From this figure, we can see that the circular means of participants’ estimated global headings were close to the correct headings, while the means of their estimated positions reveal that locations across rooms but not within the same room were distinguished. These observations were confirmed by the statistical analyses below.

[Figure 4]

4.2.2.1 Heading estimation

The correct and estimated global headings for each view 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 estimate included the corresponding correct heading.

Furthermore, all circular means of heading estimates were close to the corresponding correct headings, indicating that participants overall had accurate global heading estimates for each view inside the rooms.

Hotelling's paired tests contrasting the global headings of any two testing views were conducted to test whether the participants could distinguish between global headings at different testing views (the critical *p* value was reset to be .0018 (or .05/28) due to 28 comparisons in total) (Table 5A). The results showed that except for the marginal differentiation between View 4 (global east) and View 16 (global north) ($F(1, 46) = 7.38$, $p = .0020$), the participants could distinguish between any two different global headings (Fs ≥ 8.48, ps $\leq .0007$) but did not treat any two views with the same global heading as different headings (Fs ≤ 2.84, ps $\geq .0690$). These results indicate that the participants represented global headings accurately.

[Table 5]

[Figure 5]

4.2.2.2 Position estimation

Figure 4 shows the participants' estimated positions. For each standing position, we used the participants' estimated positions to calculate the 95% confidence interval of the mean of the estimated positions. If the 95% confidence interval only covers the corresponding correct standing position and does not cover any other standing position, then we may conclude that the participants could distinguish the corresponding standing position from others. However, Figure 4 shows that although each 95% confidence interval covered the corresponding correct standing position, it also covered the other standing position within the room, indicating that the estimated positions within rooms were not distinguishable.

Further analysis using Hotelling's T-squared test examined whether the participants could distinguish standing positions when facing different views (the critical *p* value was reset to be .0018 due to multiple comparisons) (Table 5B). The results showed that the participants could distinguish between positions in different rooms (except for standing positions for View 4 versus View 12 and View 4 versus View 13) (*F*s ≥ 8.09, *p*s ≤ .0010). However, there was no evidence that participants could distinguish between the positions within the same room (*F*s ≤ 4.92, *p*s ≥ .0116).

4.2.2.3 Global heading error and position error

The absolute global heading error was calculated by the angular difference between the estimated heading and the correct heading (Table 6). The range of the absolute global heading error was [0º, 180º]. There was no significant difference between the absolute global heading errors across different views after a Greenhouse-Geisser correction, *F*(4.789, 225.075) = 1.11, *p* = .36, η_p^2 = .02.

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. Thus, the position error was essentially the percentage error of the correct distance to the buildings (Table 6). There was no significant difference between the position errors across different views after a Greenhouse-Geisser correction, *F*(3.978, 186.977) = 1.16, *p* = .33, η_p^2 = .02.

There was a significant positive correlation between the absolute global heading error and the position error, *r*(48) = .48, *p* <.001.

[Table 6]

4.3 Experiment 3b

Since this was the first time to obtain a global heading priming effect, in contrast to the null global heading priming effect in Marchette et al. (2014) and in Experiment 2 of the current study, to ensure this was not a false positive result, we replicated Experiment 3 in Experiment 3b but only using the priming task during the testing. The learning phase in Experiment 3b was the same as in Experiment 3 where the participants learned the five buildings and then locomoted between the rooms to learn the objects. In the testing phase, the participants did the priming task to see whether we could replicate the priming results in Experiment 3.

For trials at the initial views, the overall accuracy was 92.52% (*SD* = 8.64%). The accuracies in *GH*, *LH* and baseline conditions were 90.97% (*SD*=17.85%), 93.06% (*SD*=15.31%), and 92.80% (*SD*=9.18%), respectively.

Paired sample *t* tests contrasting *GH* and *LH* conditions with the baseline condition were conducted to test the priming effects (see Figure 2). The participants responded significantly faster in both the *GH* and *LH* conditions than in the baseline condition ($t(47) = 2.60$, $p = .01$, Cohen's $d = .53$; $t(47) = 2.98$, $p = .005$, Cohen's $d = .61$, respectively), demonstrating both global and local heading priming effects as in Experiment 3.

4.4 Discussion

The results in Experiment 3 show that there are both local and global heading priming effects, and people at the group level can have an accurate estimation of their global headings at local views inside the rooms. These results support the *global map model*. People can develop a global representation after travelling a simple path between two across-boundary vista spaces. In addition, the global heading priming effect indicates that the within-boundary priming task can still reveal the existence of a global representation.

However, the global spatial representations might have developed prior to rather than during the across-boundary navigation between the two rooms. Following the paradigm of Zhang and Mou (2018) to measure estimates of the global headings, the participants learned the directions to five buildings at both doorways prior to learning objects in the two rooms through the across-boundary navigation. The doorways were presented simultaneously with the five buildings. Although Experiment 2 (where the participants locomoted between the rooms but showed no global priming effect) indicates that seeing the spatial relations between the rooms in across-boundary navigation does not provide sufficient information to form a global representation of local views inside the local spaces, it is possible that directly seeing the spatial relations between the doorways together with other buildings may help global integration. The buildings might serve as landmarks to help encode the spatial relations between the doorways and then the spatial relations between the local views inside the rooms. Experiment 4 was conducted to examine this possibility.

5. Experiment 4

The purpose of Experiment 4 was to examine the development of a global representation through across-boundary navigation when participants never learned the relations between two rooms together with the buildings. There were four changes from Experiment 3. First, one of the doorways and one pole (see the two blue dots or the two red dots in Figure 6), instead of the two doorways, were presented to indicate the locations to learn the five buildings. The learning location that was indicated by the pole was a location that was different from either room and was a location that the participants would never visit or notice after learning the buildings. It was only used so that the participants still had two learning positions to ensure that they accurately perceived the locations of the buildings. Therefore, the relations between the doorway and the pole did not indicate the relations between the rooms. Second, the 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 presented in the hallway so that the participants could not see both rooms simultaneously, even at the turning corner of the hallway. Fourth, the windows in the two rooms were opaque so that the participants could not see the distal orientation cues outside.

In the testing phase, the participants still conducted the priming task, followed by the across-boundary pointing task. As indicated by the previous experiments, there should be a local heading priming effect. Importantly, if people cannot develop a global representation through across-boundary navigation without directly seeing the two rooms simultaneously while learning the five buildings, then there would be neither a global heading priming effect nor accurate global heading estimates. Otherwise, both a global heading priming effect and accurate global heading estimates would be expected.

5.1 Method

5.1.1 Participants

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

5.1.2 Materials and design

The open field, distal orientation cues, and five buildings remained the same. During learning the buildings, only one doorway was presented to indicate the first learning position. The second learning location was indicated by a pole and differed from the locations of the rooms. There were two possible locations for the pole, each associated with one doorway (see

Figure 6 for the exact location). The location of the pole was a place that would not be visited or noticeable after participants learned the buildings so that the pole could not indicate the spatial relations between the two rooms. Half of the participants learned from one pair of a doorway and a pole (red dots in Figure 6) and the other half learned from the other pair (blue dots in Figure 6).

The two local rooms remained the same as in previous experiments except that the windows of the two rooms were opaque so that the 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 6). As a result, when the 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 90° turning corner. Opaque fog was presented 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 priming task and the across-boundary pointing task also remained the same as in Experiment 3. In addition, a virtual blue stick associated with an Intersense Wand was used as a pointer.

5.1.3 Procedure

At the beginning of the learning phase, the participants were at the centre of the virtual environment with only distal orientation cues in the open field (see Figure 6). Then one doorway of the room was presented, and the participants were asked to move to the doorway, where they learned the directions to the five buildings as in Experiment 3. The participants pointed to each building from their memory using the pointer of the virtual stick. The participants' response directions were recorded so that after the experiments we could check whether participants had accurately learned the directions to the five buildings. After that, the doorway remained in place and a pole was shown in the environment. The participants moved towards the pole and then learned the directions to the five buildings and finished the replacing-building task there again. After learning, the participants moved back to the doorway and closed their eyes to have a three-minute rest break.

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

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

[Figure 6]

5.1.4 Data Analysis

When the participants were learning the directions to the five buildings, their response directions for each building in the replacing-building task were recorded so that we could see whether they learned the 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 5.83º (*SD* = 3.55º), indicating that the participants accurately learned the directions to the five buildings.

5.2.2 Priming task

For trials at the initial views, the overall accuracy was 94.73% (*SD* = 8.69%). The accuracies in *GH*, *LH* and baseline conditions were 95.14% (*SD*=15.36%), 95.83% (*SD*=11.14%), and 94.32% (*SD*=9.31%) respectively.

Paired sample *t* tests contrasting *GH* and *LH* conditions with the baseline condition were conducted to test the priming effects (see Figure 2). Participants responded significantly faster in the *GH* condition than in the baseline condition ($t(47) = 2.75$, $p = .008$, Cohen's $d = .56$), indicating a global heading priming effect. However, the difference between the *LH* condition and the baseline condition was not significant ($t(47) = 0.92$, $p = .36$, Cohen's $d = .19$), indicating no local heading priming effect.

5.2.3 Across-boundary pointing task

Figure 7 showed estimated standing positions and estimated global headings when the participants imagined facing objects at local views inside the rooms. This figure shows that the circular means of the participants' estimated global headings were close to the correct headings, but the means of their estimated positions were not accurate.

[Figure 7]

5.2.3.1 Heading estimation

The correct and estimated global headings for each view are plotted in Figure 8. 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 estimates were close to the corresponding correct headings, which indicates that overall the participants could accurately estimate their global headings at local views inside the rooms.

Hotelling's paired tests contrasting the global headings of any two testing views were conducted as in Experiment 3 (Table 5A). The results showed that except for the marginal differentiation between View 5 (global south) and View 9 (global east), and between View 9 (global east) and View 12 (global south) (*F*s(1, 46) $\leq$ 7.45, *p*s $\geq$ .0020), the participants could distinguish between any two different global headings (*F*s $\geq$ 7.881, *ps* $\leq$ .0010) but did not treat any two views with the same global heading as different headings (*F*s $\leq$ 3.343, *ps* $\geq$ .0440). These results indicate that the participants represented global headings accurately.

[Figure 8]

5.2.3.2 Position estimation

Figure 7 shows the participants' estimated positions. From the figure we can see that the 95% confidence intervals of the mean position estimate covered more than one standing position, indicating that the participants' global position estimation was noisy.

Further analysis using Hotelling's T-squared test as in Experiment 3 showed that there was no evidence that the participants could distinguish between positions either in different rooms (*F*s $\leq$ 6.355, *p*s $\geq$ .0037) or within the same room (*F*s $\leq$ 4.567, *p*s $\geq$ .0155) (Table 5B).

5.2.3.3 Global heading error and position error

The absolute global heading error and the position error were calculated in the same ways as in Experiment 3 (Table 6). There was no significant difference among the absolute global heading errors across different views after a Greenhouse-Geisser correction, *F*(4.780, 224.666) = 1.91, *p* = .10, η_p^2 = .04. There was no significant difference among the position errors across different views after a Greenhouse-Geisser correction, $F(1.309, 61.509) = 0.923$, $p = .37$, $\eta_p^2 = .02$.

There was a significant positive correlation between the absolute global heading error and the position error, $r(48) = .46$, $p =.001$.

5.3 Discussion

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 across-boundary navigation without directly perceiving the spatial relations between the two rooms, especially when learning the five buildings. The global priming effect in Experiment 4, in which the participants did not see any relations between the two rooms, was at least as large as (if not larger than) that in Experiment 3, in which the participants saw spatial relations between the two rooms in the open field (Cohen's *d* of the global priming effect was .56 in Experiment 4 and .44 in Experiment 3). This suggests that seeing both rooms together with buildings in Experiment 3 does not seem critical to developing global representations of local spaces through across-boundary navigation.

The lack of the local priming effect in Experiment 4 was inconsistent with the findings in the previous experiments and Marchette et al. (2014). It might be because participants in Experiment 4 travelled over the hallway between the two rooms, and thus may have been more likely to perceive that the two rooms belonged to the same environment, as the rooms were connected. This could have led the participants to focus on the global spatial relations but not on the local spatial relations.

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 the 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 the directions to the five buildings, may be important for the participants to develop a global representation through across-boundary navigation. Experiment 5 tested this speculation.

6. Experiment 5

The purpose of Experiment 5 was to test whether learning the directions to the five buildings played an important role in developing a global representation through across-boundary navigation. Experiment 5 was the same as Experiment 4 except that we removed the five buildings' learning phase and the participants only conducted the priming task. If learning some global knowledge of the environment is important for developing a global representation through across-boundary navigation, then there should be no global heading priming effect in Experiment 5.

6.1 Method

6.1.1 Participants

Forty-eight university students (24 females) with normal or corrected-to-normal vision were used in data analysis. Their participation was counted as partial fulfillment of the 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

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

6.2 Results

For trials at the initial views, the overall accuracy was 94.73% (*SD* = 7.70%). The accuracies in *GH*, *LH* and baseline conditions were 94.44% (*SD*=15.88%), 95.14% (*SD*=11.89%), and 94.70% (*SD*=7.92%) respectively.

Paired sample *t* tests contrasting *GH* and *LH* conditions with the baseline condition were conducted to test the priming effects (see Figure 2). The participants responded significantly faster in the *LH* condition than in the baseline condition ($t(47) = 3.01$, $p = .004$, Cohen's $d = .61$), indicating a local heading priming effect. However, the difference between the *GH* condition and the baseline condition was not significant ($t(47) = 1.86$, $p = .07$, Cohen's $d =.38$), indicating no clear evidence for a global heading priming effect. To further qualify the null global priming effect, we calculated *BF* (the null over the alternative). The *BF* analysis (*BF* = 1.73) did not provide clear evidence on whether there was a global priming effect. As the global priming effect was the main focus of the current study, we conducted Experiment 5 again in Experiment 5b.

6.3 Experiment 5b

For trials at the initial views, the overall accuracy was 94.49% (SD = 7.32%). The accuracies in GH, LH and baseline conditions were 97.92% (SD=8.15%), 94.44% (SD=12.55%), and 93.56% (SD=8.79%) respectively.

Paired sample *t* tests contrasting *GH* and *LH* conditions with the baseline condition were conducted to test the priming effects (see Figure 2). The participants responded significantly faster in the *LH* condition than in the baseline condition ($t(47) = 4.28$, $p < .001$, Cohen's $d = .87$), indicating a local heading priming effect. However, the difference between the *GH* condition and the baseline condition was not significant ($t(47) = 0.46$, $p = .65$, Cohen's $d = .09$). The null global priming effect was supported by the *BF* analysis (*BF* = 7.98).

6.4 Discussion

The results in Experiment 5 showed a local heading priming effect but weak or null global heading priming effect, indicating that the participants might not have developed a global representation without prior learning the five buildings. A comparison of the weak or null global priming effect in Experiments 2 and 5 (where the participants locomoted between local spaces without prior global learning of the buildings) and the strong global heading priming effect in Experiments 3 and 4 (where the participants learned the five buildings before locomoting between the rooms) suggests that prior global learning is critical to developing a global representation through across-boundary navigation. Prior global learning may provide a reference frame to scaffold subsequent spatial information in the local rooms (Kelly & McNamara, 2010).

We speculated that the lack of local priming effect in Experiment 4 occurred because participants in Experiment 4 travelled over the hallway between the two rooms and thus may have been more likely to perceive that the two rooms belonged to the same environment, as the rooms were connected. However, the clear local priming effect in Experiment 5 rejected this speculation as participants in Experiment 5 also travelled over the hallway. Because the local priming effect is not the main focus of the current study, the exact reason for the null local priming effect in Experiment 4 will be examined in future studies.

The strong global heading priming effect in Experiments 3 and 4, compared with Experiments 2 and 5, suggests that prior global learning together with across-boundary navigation can lead to the development of a global representation. The null global priming effect in Experiments 2 and 5 suggests that the across-boundary navigation between local spaces cannot sufficiently lead to the development of a global representation. However, it is not clear whether prior global learning itself sufficiently leads to the development of a global representation or whether across-boundary navigation is still essential to the development of global representations. Therefore, in Experiment 6, we removed the across-boundary navigation between the rooms but kept prior global learning of the five buildings, to test whether prior global learning would sufficiently demonstrate a global representation.

7. Experiment 6

Experiment 6 investigated whether prior global learning (i.e., learning the buildings) would sufficiently lead to the development of a global representation without the across-boundary navigation between local spaces. Experiment 6 was the same as Experiment 3 except that in Experiment 6 the participants were teleported between the two rooms after learning the buildings in the learning phase and there was only the priming task in the testing phase. If there was a global heading priming effect, the indication is that prior global learning is sufficient to the development of a global representation; whereas if there was no global heading priming effect, the indication is that prior global learning is not sufficient and across-boundary navigation is essential to the development of a global representation.

7.1 Method

7.1.1 Participants

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

7.1.2 Materials and design

The two local rooms and the open field with distal orientation cues were the same as in Experiment 3.

7.1.3 Procedure

The learning phase was similar to that in Experiment 3, in which the participants learned the five buildings' directions from two doorways and then entered the two rooms to learn the objects. The only difference was that when learning the objects in the two rooms, the participants were teleported between the rooms as in Experiment 1, so that there was no across-boundary navigation between the local spaces. In the testing phase, participants only conducted the priming task.

7.2 Results

7.2.1 Building learning accuracy

In the replacing-building task during the learning phase, the mean of the absolute direction error was 6.13º (*SD* = 6.44º), indicating that the participants accurately learned the directions to the five buildings.

7.2.2 Priming task

For trials at the initial views, the overall accuracy was 95.71% (*SD* = 5.66%). The accuracies in *GH, LH* and baseline conditions were 95.83% (*SD*=11.14%), 93.75% (*SD*=14.84%), and 96.21% (*SD*=6.72%) respectively.

Paired sample *t* tests contrasting *GH* and *LH* conditions with the baseline condition were conducted to test the priming effects (see Figure 2). The participants responded significantly faster in the *LH* condition than in the baseline condition (*t*(47) = 2.15, *p* = .04, Cohen's *d* = .44), indicating a local heading priming effect. However, the difference between the *GH* condition and the baseline condition was not significant (*t*(47) = 1.21, *p* = .23, Cohen's *d* =.25), indicating no global heading priming effect. The null global priming effect was supported by the *BF* analysis (*BF* = 4.38).

7.3 Discussion

The null global heading priming effect in Experiment 6 suggests that, without across-boundary navigation between the local spaces, prior global learning cannot sufficiently lead to the development of a global representation. Thus, across-boundary navigation is essential to the development of a global representation of locations in local spaces.

7. General Discussion

The important results of all the experiments are summarized in Table 1. There are two important findings. First, the participants could develop a global representation of two rooms through across-boundary navigation while walking on a simple path. Second, developing a global representation of the two rooms through across-boundary navigation might require some prior representations of the global environment.

First, the accurate mean global heading estimation and the global heading priming effect in Experiments 3 and 4 suggest that after navigation between local spaces that are separated by boundaries, people can develop a global representation of local spaces. This sort of demonstration of the global representations observed in the current study, as well as in Shine et al. (2016), is theoretically significant.

One prevailing theory of human spatial memories and navigation stipulates that people develop the global representation of an environmental space through path integration (Gallistel, 1990, p. 106; Gallistel & Matzel, 2013; Jacobs & Schenk, 2003; Loomis et al., 1999; McNaughton et al., 2006; Meilinger, 2008). This theory is based on the insights that in an environmental space, piloting sometimes may not operate well due to the lack of valid piloting cues. For example, when people cross boundaries, the boundaries separate the current space from the previous space and block the views of the previous space. Therefore, to develop a global representation when piloting cues are minimal, people have to primarily rely on path integration to calculate the Euclidean relations between the two spaces. Furthermore, people can use path integration equally well during navigation within a boundary and across boundaries (Mou & Wang, 2015). According to these theoretical insights and empirical evidence, people should be able to form a global representation through across-boundary navigation with the support of path integration (i.e., the *global map model*). In contrast, some researchers have argued that path integration cannot function in across-boundary navigation (Wang, 2016; Wang & Brockmole, 2003). Consequently, people cannot form a global representation through across-boundary navigation (i.e., the *local map* model). Studies have showed that the 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, Avraamides, & Loomis, 2007; Marchette, et al., 2014; Marchette, et al., 2017). These previous findings challenged the *global map model*. In fact, these findings were more consistent with the *local map model*. However, Shine et al. (2016) showed that participants could be instructed and trained to develop a global representation between two rooms, favoring the *global map model* over the *local map model*.

The current findings, for the first time, indicate that people can track their global headings when they walk into local rooms even without any explicit instruction of learning the global headings. These findings are consistent with the recent finding that path integration is not sensitive to boundary crossing so it can support spatial learning in across-boundary navigation (Mou & Wang, 2015). In that sense, the current findings seem more consistent with the *global map model*.

The global spatial representations were not formed as a result of participants directly seeing the spatial relations between two rooms during navigation. In Experiment 3, the participants could directly see spatial relations between the two rooms when they travelled between them in the open field. Do these perceived spatial relations provide sufficient information to form the global headings of local views inside rooms? We speculate that the answer is no. We acknowledge that the perceived spatial relations between the two rooms could provide an approximate indication of the global positions of views inside rooms as the size of each room was significantly smaller than the distance between the two rooms. However, it is hard to understand how the participants could know the headings of views in one room relative to the headings of views in the other room from only the spatial relations between the two rooms that they perceived outside the rooms. Furthermore, the participants in Experiment 2 of the current study as well as the participants in Marchette et al. (2014) could also see the spatial relations between the two rooms when they travelled between the two rooms. In neither Experiment 2 nor Marchette et al. (2014) did the results show any significant global heading priming effect. Hence, the spatial relations between the two rooms perceived outside the rooms during navigation might not provide sufficient information to form the global headings of views inside the rooms.

Furthermore, the global spatial representations were not formed by directly seeing the spatial relations between two rooms when participants learned buildings before navigation. In Experiment 3, the participants could directly see spatial relations between the two rooms when they learned buildings before they travelled between rooms in the open field. Are these perceived spatial relations together with buildings, critical to forming the global headings of local views inside rooms? Based on the findings of Experiments 4 and 6, the answer is no. The global priming effect in Experiment 4, in which participants did not see any relations between the two rooms while learning the buildings, was at least as large as that in Experiment 3, in which the participants saw the spatial relations between the two rooms when learning the buildings. This suggests that perceiving spatial relations between two rooms together with buildings was not essential to forming the global headings. There was no global priming effect in Experiment 6, in which the participants perceived spatial relations between the two rooms together with the buildings but were teleported between the rooms. Hence, perceiving spatial relations between two rooms together with the buildings was not sufficient to forming the global headings. This suggests that in Experiment 3, across-boundary navigation rather than directly seeing the spatial relations between two rooms before or during navigation was critical to developing global spatial representations.

The second important finding of the current study indicates that some prior spatial learning of the global environment may be critical in developing a global representation of local spaces through across-boundary navigation. The participants who learned the directions to the five extra buildings before entering local spaces were able to develop a global representation (Experiments 3 and 4). In contrast, the participants who did not learn the five buildings were not able to develop a global representation (Experiments 2 and 5). This indicates that some prior spatial learning of the global environment may be important to integrating local spaces into a global representation. Furthermore, the prior spatial learning of the global environment may need to include memory tasks rather than just familiarization of the environment. The 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, the participants did a replacing-building task when learning five buildings' directions. The memory of the global spatial relations of the buildings might provide a global frame of reference to integrate local spaces afterwards.

We speculate that the mechanism in which the global reference system contributes to the integration of local spaces afterwards might be similar to using an existing reference system as scaffolding for the subsequent learning of new spatial information from a new perspective in a vista space (e.g., Kelly & McNamara, 2010). Kelly and McNamara (2010) showed that the participants in a vista space used a reference frame selected from one visual perspective to represent a new layout learned from another visual perspective. Although in Experiments 3 and 4 of the current study, the participants could not visually see the global reference frame that had been acquired to represent the buildings when they entered the rooms, they might still tend to use the global reference frame to represent the spaces inside the rooms.

Philbeck and colleagues (Arthur, Philbeck, & Chichka, 2007; Philbeck & O'Leary, 2005; see also Rieser, 1999) provided empirical evidence to support that people use the global reference frame that has been remembered to guide their subsequent path integration (or spatial updating). They reported that a visual preview of the testing environment significantly improved the accuracy of path integration even without online visual input during locomotion. One explanation for the facilitating effect of spatial memory of the environment on subsequent path integration is that the spatial memory of the environment can also provide the internal reference frame to guide path integration. Following this explanation and that in Kelly and McNamara (2010), we speculate that when entering the rooms, the participants in Experiments 3 and 4 tended to use the global reference frame that had been established to encode spatial information of the buildings to encode spatial information inside the rooms. While the global reference frame representing spatial relations of the buildings guided path integration, path integration kept track of the relations between the vista spaces and the global reference frame. This indicates that prior learning of five buildings facilitated learning global headings of views inside the rooms through path integration in Experiments 3 and 4.

Although prior spatial learning is critical, it is not sufficient in forming global spatial representations. The participants in Experiment 6, without directly locomoting between the rooms, did not show the global priming effect after learning the buildings. This suggests that both prior spatial learning and across-boundary navigation were critical to forming global spatial representations in Experiments 3 and 4. In the sense that across-boundary navigation itself did not definitely lead to global spatial representations, the current findings do not fully favor the *global map model* over the *local map model*. Both models might be valid in different situations. Future studies should further investigate the conditions to qualify these two models.

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 across-boundary navigation in Marchette et al. (2014) and Shine et al. (2016). (1) The global heading priming effect in Experiments 3 and 4 indicates that global representation is accessed by a priming task as well as by an across-boundary pointing task, questioning the speculation that global representation is only accessed by the across-boundary tasks. (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. This explanation is based on the findings that idiothetic information in physical turning is important to path integration and the development of survey knowledge (e.g. Chrastil & Warren, 2013). However, Experiments 2 and 5 in the current study, in which the participants could physically rotate in the immersive virtual environment, did not show evidence of a global representation. Thus, the body-based self-motion cues available in an immersive virtual environment may not be the only reason to develop a global representation. (3) Shine et al. (2016) reported that participants could know their global headings inside a room after they were explicitly instructed and trained to do so. The 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 relations may not be essential to the development of a global spatial representation.

In the current study, both the global and local priming effects were observed only when the testing views were the initial views but not the other views. This indicates that the participants might have used the initial views of each room to establish the local reference direction (Shelton & McNamara, 2001) and also encode the global relations between the local reference directions (i.e., initial views) (Greenauer & Waller, 2010; Zhang, Mou, McNamara, & Wang, 2014). All the other views might have been specified in terms of the local reference direction (i.e., initial views) (Avraamides & Kelly, 2005). Therefore, when the participants saw two views, locally or globally consistent, they needed more steps to figure out the consistency between the two views for trials at non-initial views than for trials at initial views. This extra step might have eliminated the priming effect for trials when testing views were not the initial views. We acknowledge that the local priming effect in the current study might only be due to the initial views of the local rooms rather than the similar local environmental structures (e.g., Marchette et al., 2014). Indeed, both local environment structures and the initial views of the local rooms are just different types of cues that can be used to establish local reference systems (Mou & McNamara, 2002; Shelton & McNamara, 2001). Therefore, the local priming effect should be attributed to consecutively retrieving two local reference directions, whether participants use local environment structures or initial views to establish the local reference directions (Marchette et al., 2017).

The local and global heading priming effects together with the accurate global heading estimates in Experiment 3 indicate multiscale spatial representations (Han & Becker, 2014). The 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 et al., 2014). They maintained both the local and global spatial representations. In contrast, the participants in Experiment 4 had only a global priming effect but did not have a local priming effect. The lack of the local priming effect in Experiment 4 might be due to a Type I error as the other seven experiments showed clear local priming effects.

The findings of both global and local heading priming effects at the group level in Experiment 3 suggest that the participants could have developed multiscale spatial representations. However, the findings of both the global and local heading priming effects at the group level in Experiment 3 could also have occurred if one group of the participants only developed the global representation and the other group of the participants only developed the local representation. To test this possibility, we analyzed the correlation between the global heading priming effect (i.e., response latencies for the global heading trials minus those for the baseline trials) and the local heading priming effect (i.e., response latencies for the local heading trials minus those for the baseline trials) in Experiment 3. The correlation would be negative if one group of the participants had a global heading priming effect but no local heading priming effect, whereas the other group of the participants had no global heading priming effect but a local heading priming effect. However, as illustrated in Table 7, the correlation was 0.65 and significantly larger than 0 (i.e., a positive correlation), which undermined the possibility of two groups of the participants having only local or global representations. The positive correlation might be attributed to the possibility that the participants who more efficiently used the global representation in the global priming trials also more efficiently used the local representation in the local priming trials.

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 8). However, the variance of the estimated heading was large. The large variance could be attributed to individual differences in developing the global headings or to the noise in determining the global headings from the pointing responses to the five buildings. For each test view in the across-boundary pointing task, participants pointed to the five buildings once. Then one estimation of the global heading was derived from these five responses. Random errors could be involved when the participants used global representations to guide their responses, when the participants executed their pointing responses, and when we derived the global heading estimation from their five responses. Therefore, the estimation of the global headings in the current study could be noisy even if the participants had an accurate global representation.

To determine the source of the large variance in the global heading estimation, we analyzed the correlations between the error in estimating global headings and the global heading priming effect. The error in estimating global headings is indicated by the absolute global heading error (the angular difference between the estimated global heading and the correct global heading) for the initial views (i.e., Views 1 and 9). The global heading priming effect was calculated by subtracting the response latencies in the baseline trials from the response latencies in the global heading trials (a smaller value indicates a larger priming effect). If the individual differences in encoding an accurate global heading were the common cause of the variance of errors in the global heading estimation and the variance of the global priming effect, then we would expect a significant positive correlation between the global heading error and the global priming effect. However, as illustrated in Table 7, there was no significant correlation in either Experiment 3 or Experiment 4. We therefore speculate that the large variance in the global heading estimation might be primarily due to the noise in measuring the global heading rather than to the individual differences in forming an accurate global heading. The noisy global position estimation could also be due to random noise involved in determining the global position from the pointing responses to five buildings rather than to the inaccurate global position representations.

[Table 7]

The current findings indicate that the participants can develop a global representation of two rooms through across-boundary navigation on a simple path between two separated spaces. In real-life environments, a complicated path may link many across-boundary local spaces. Although people may have accurate representations of the relations between two nearby local spaces linked by a simple path, they might not encode accurate spatial relations between two distant spaces linked by a complicated path (Wang & Brockmole, 2003). Therefore, their global representations of all spaces along the path might not be a single cognitive map; rather, the global representations might be a cognitive collage (Tversky, 1993) or a cognitive graph (Warren, Rothman, Schnapp, & Ericson, 2017). Despite the structure of spatial representations of an environmental space (e.g., cognitive maps, cognitive collages, or cognitive graphs), path integration might be the mechanism to encode spatial relations between two nearby but across-boundary spaces linked by a simple path.

Meanwhile, in an environmental space with piloting cues available, piloting may play a more important role than what is stipulated in developing a global representation (Gallistel, 1990, p. 106; Gallistel & Matzel, 2013; Jacobs & Schenk, 2003; Loomis et al., 1999; McNaughton, et al., 2006). Using piloting, people may perceive common reference objects and directions (e.g., a high building, or a mountain) while standing in different local spaces. Hence, piloting can establish a global reference system to integrate the local spaces into a global representation (Han & Becker, 2014; Ishikawa & Montello, 2006; Meilinger, Strickrodt, & Bülthoff, 2016; Sholl et al., 2006; Weisberg et al., 2014). Moreover, as mentioned above, the prior spatial memory of buildings acquired by piloting may also provide an internal reference system to facilitate path integration even when the piloting cues are no longer available (Arthur et al., 2007; Philbeck & O'Leary, 2005; Kelly et al., 2007).

In summary, the present findings indicate that people can develop a global spatial representation of two adjacent local spaces across boundaries through navigation on a simple path. A prior representation of the global environment is important to integrating local spaces into a global representation.

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Tables

Table 1

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

Experiment	Learning phase	Testing phase	Priming effect		Estimated global heading
			Local	Global	
1	Be teleported between two rooms	Priming task	Yes	No	N/A
2	Locomote between two rooms in the open field	Priming task	Yes	No	N/A
3	Learn five buildings and then locomote between two rooms in the open field	Priming task; Pointing task	Yes	Yes	Accurate
3b		Priming task	Yes	Yes	N/A
4	Learn five buildings and then locomote between two rooms in the hallway	Priming task; Pointing task	No	Yes	Accurate
5	Locomote between two rooms in the hallway	Priming task	Yes	No	N/A
5b			Yes	No	N/A
6	Learn five buildings and then be teleported between two rooms in the open field	Priming task	Yes	No	N/A

Table 2

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

Condition		Example views
GH (global heading)		2→15
LH (local heading)		1→10
Baseline	GP (global position)	1→14
	LP (local position)	2→11
	None	1→12

Table 3

The response latency (M ± SE, in seconds) in GH, LH, and baseline conditions for all views and initial views in Experiment 1.

	GH	LH	Baseline
All views	5.80 ± 0.31	5.65 ± 0.44	5.75 ± 0.35
Initial views	6.13 ± 0.44	4.93 ± 0.56	5.94 ± 0.36

Table 4

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 3 7 6	(x, y)	H	1 8 4 5	(-x, y)	-H
10 11 15 14	(x, y)	H	9 16 12 13	(x, -y)	180-H

Table 5

(A) P values from Hotelling's paired tests used to examine global headings' differentiation (critical p= .0018 or .05/28) in Experiments 3 and 4. A p value smaller than the critical p indicates differentiation. Views 1, 4, 5 and 8 are in Room 1, and Views 9, 12, 13 and 16 are in Room 2.

Experiment	View / *p*	1 Global north	4 Global east	5 Global south	8 Global west	9 Global east	12 Global south	13 Global west	16 Global north
3	1	-----	0.0004	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.2900
	4		-----	<0.0001	<0.0001	0.0690	<0.0001	<0.0001	0.0020
	5			-----	<0.0001	<0.0001	0.7140	<0.0001	<0.0001
	8				-----	<0.0001	<0.0001	0.1980	0.0010
	9					-----	<0.0001	<0.0001	<0.0001
	12						-----	<0.0001	<0.0001
	13							-----	0.0007
	16								-----
4	1	-----	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0010	0.1300
	4		-----	0.0010	<0.0001	0.7220	0.0004	<0.0001	0.0010
	5			-----	<0.0001	0.0020	0.9120	0.0009	<0.0001
	8				-----	<0.0001	<0.0001	0.0440	<0.0001
	9					-----	0.0020	<0.0001	<0.0001
	12						-----	0.0001	<0.0001
	13							-----	0.0003
	16								-----

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

(B) P values from Hotelling's T-squared tests used to examine global positions' differentiation (critical p= .0018 or .05/28) in Experiments 3 and 4. A p value smaller than the critical p indicates differentiation. Views 1, 4, 5 and 8 are in Room 1, and Views 9, 12, 13 and 16 are in Room 2.

Experiment	View / *p*	1	4	5	8	9	12	13	16
3	1	-----	0.1242	0.0116	0.1724	⬚ <0.0001	⬚ 0.0006	⬚ 0.0010	⬚ 0.0004
	4		-----	0.4732	0.0164	⬚ 0.0001	0.0020	0.0064	⬚ 0.0007
	5			-----	0.0183	⬚ <0.0001	⬚ <0.0001	⬚ 0.0007	⬚ 0.0001
	8				-----	⬚ <0.0001	⬚ <0.0001	⬚ <0.0001	⬚ <0.0001
	9					-----	0.7872	0.1999	0.3884
	12						-----	0.3845	0.8292
	13							-----	0.7888
	16								-----
4	1	-----	0.1339	0.0155	0.3090	0.0302	0.0252	0.0996	0.0037
	4		-----	0.5792	0.2362	0.7577	0.4731	0.9615	0.0965
	5			-----	0.0632	0.8146	0.9227	0.6794	0.2642
	8				-----	0.4363	0.0609	0.2832	0.0281
	9					-----	0.7966	0.8300	0.3289
	12						-----	0.4407	0.2619
	13							-----	0.2057
	16								-----

⬚ Indicates pairs of standing positions that the participants could distinguish.

Table 6

Absolute global heading error (M ± SE, in degrees) and position error (M ± SE, in percentage) when facing different views in Experiments 3 and 4. Views 1, 4, 5 and 8 are in Room 1, and Views 9, 12, 13 and 16 are in Room 2.

Experiment	View	1	4	5	8	9	12	13	16
3	Global 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
	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
4	Global heading error (°)	48.69 ± 7.45	48.04 ± 6.41	63.77 ± 8.03	47.19 ± 7.21	47.50 ± 5.87	59.33 ± 7.75	68.71 ± 7.36	54.38 ± 7.19
	Position error (%)	63.20 ± 9.86	62.69 ± 6.37	58.23 ± 3.81	57.23 ± 3.51	78.02 ± 21.73	67.66 ± 10.82	70.99 ± 7.52	101.92 ± 37.91

Table 7

Correlations and p values between the global and local heading priming effects, between the global heading priming effect and absolute global heading error, between the local heading priming effect and absolute global heading error for the initial views (N=48 in each experiment).

Experiment/ r (*p*)	1	2	3	3b	4	5	5b	6
Global priming effect & Local priming effect	-.12 (.40)	.04 (.81)	.65*** (<.001)	.08 (.61)	.36* (.01)	.36* (.01)	.51* (<.001)	.24 (.10)
Global priming effect & Global heading error	N/A	N/A	.04 (.78)	N/A	.14 (.34)	N/A	N/A	N/A
Local priming effect & Global heading error	N/A	N/A	-.11 (.48)	N/A	.09 (.54)	N/A	N/A	N/A

* *p*<.05. *** *p*<.001.

Figures

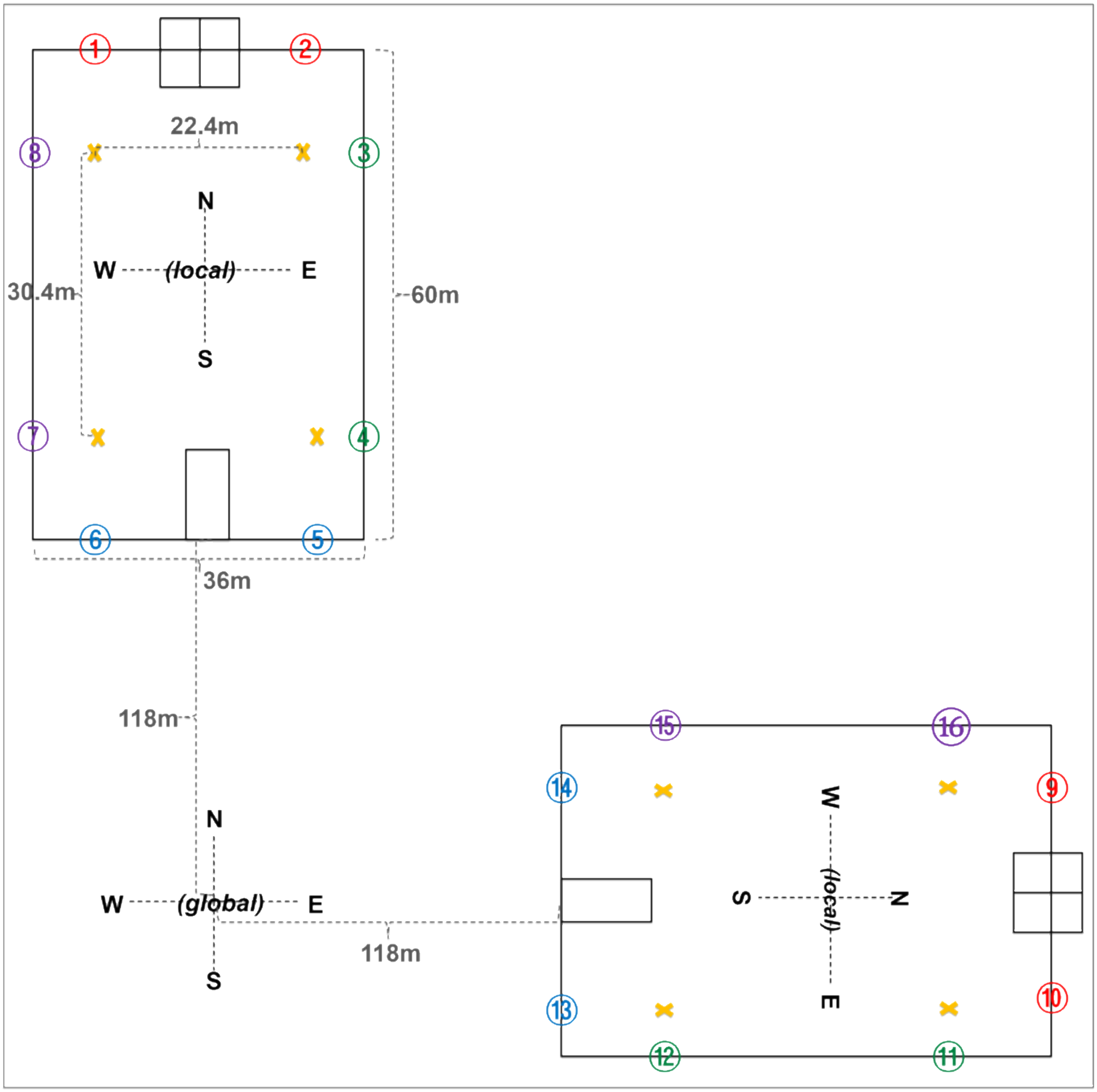

Figure 1A. Schematic diagram of the room setup and object arrangements (bird's eye view). The numbers are views (objects located in the alcoves) in the rooms. The yellow crosses are the participants' standing positions when learning objects in the rooms. Each room also has a long carpet from the entrance to the back wall. The two rooms have different interior and exterior textures and colors. The participants needed to stand on the yellow cross and faced the view to *see the object at that view. The measures of the room size, distances between adjacent standing positions, and distances between the room and the centre of the virtual environment are illustrated.*

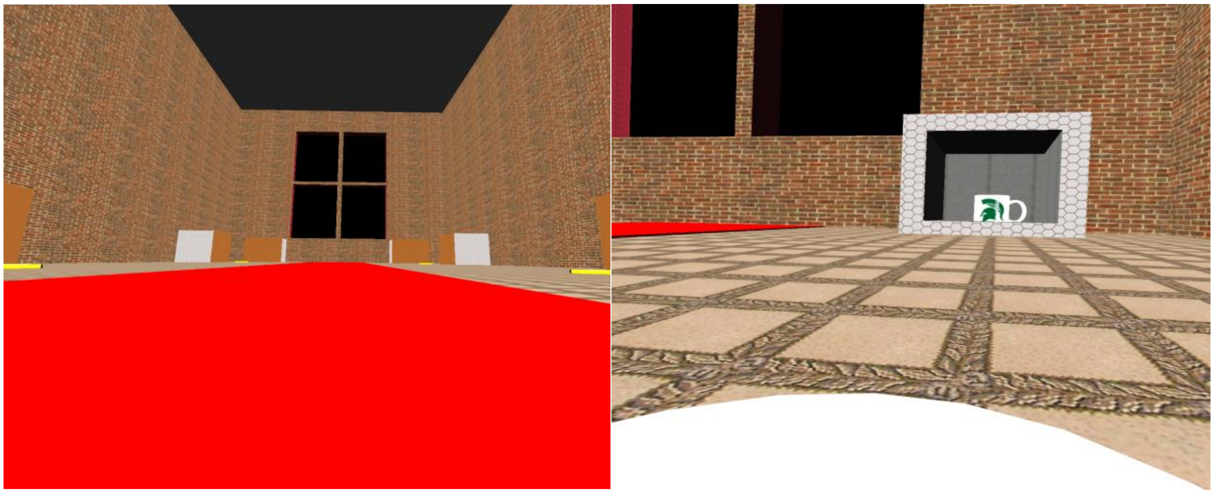

Figure 1B. *Examples of one virtual room in Experiment 1 from participants' perspective that is consistent with the principle direction of the room (left) and when participants saw one object, i.e., object at View 2 (right).*

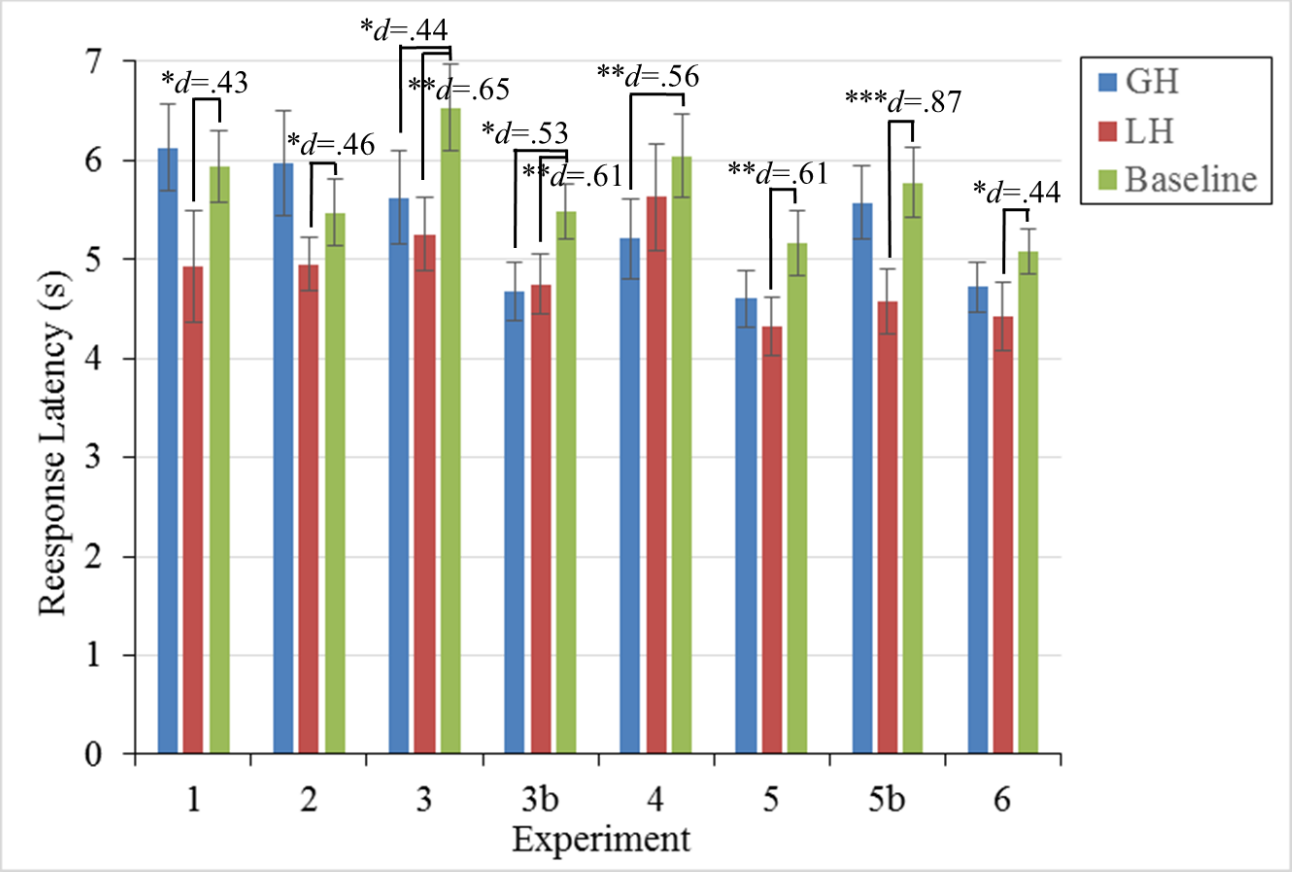

*Figure 2. Response latency of the priming task for trials at the initial views in three conditions (GH, LH, and baseline (None + GP + LP)) in all eight experiments. The solid line means a significant difference of GH and LH from the baseline (*p < .05; ** p < .01; *** p < .001). Cohen's d values are listed for significant comparisons. Error bars are the standard errors for the mean response latency in each condition without removing variances of the individual differences.*

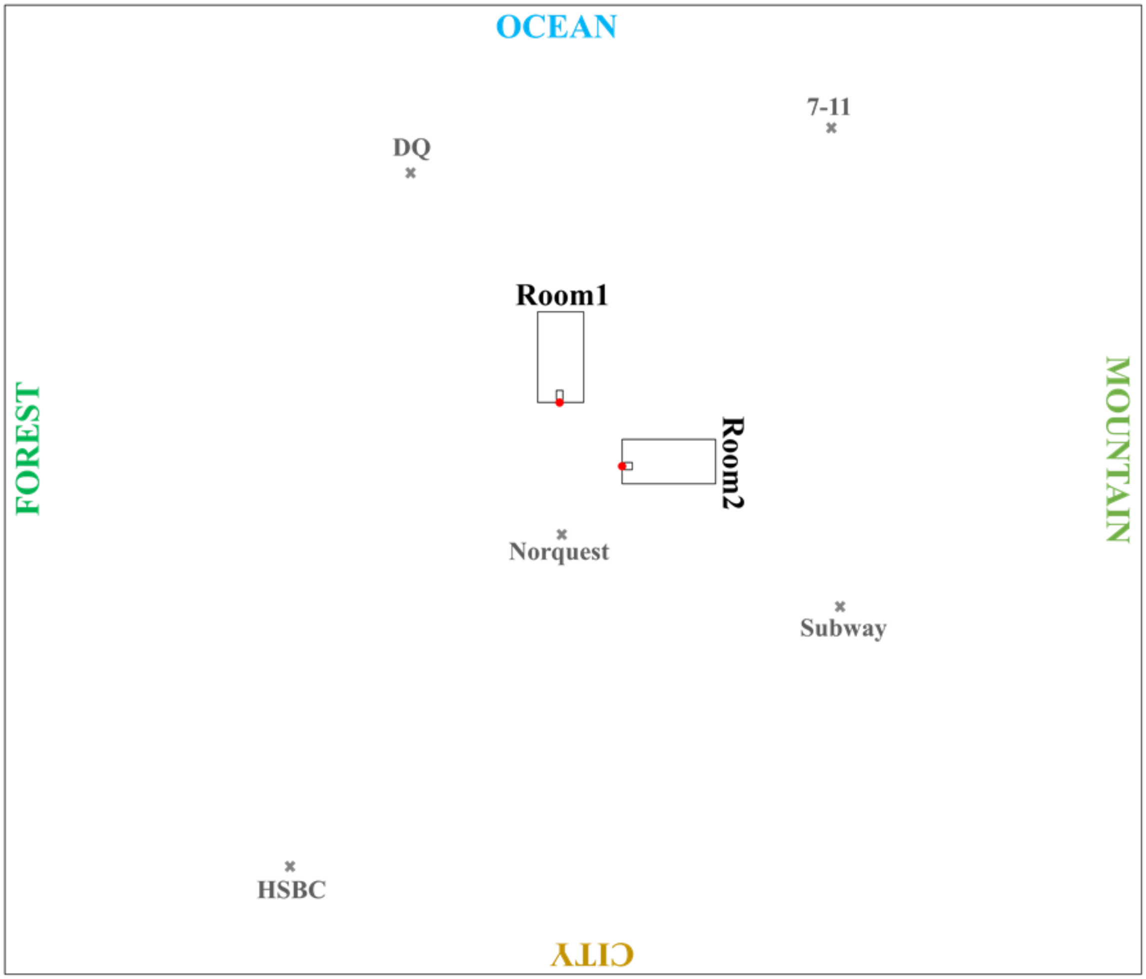

Figure 3. *Schematic diagram of the experimental setup (bird's eye view) in Experiments 2, 3, 3b and 6. The ground was covered with grass. Four distal (in an infinite distance) orientation cues (ocean, mountains, city scene, and forest) were always presented. The five buildings (DQ, 7-11, Subway, Norquest College, and HSBC) were presented in Experiments 3, 3b and 6, but not in Experiment 2. For Experiments 3, 3b and 6, before viewing the two rooms, the participants learned the five buildings. 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, the participants only saw the doorways of the two rooms, whereas when the participants started to learn objects in the two rooms, the five buildings disappeared.*

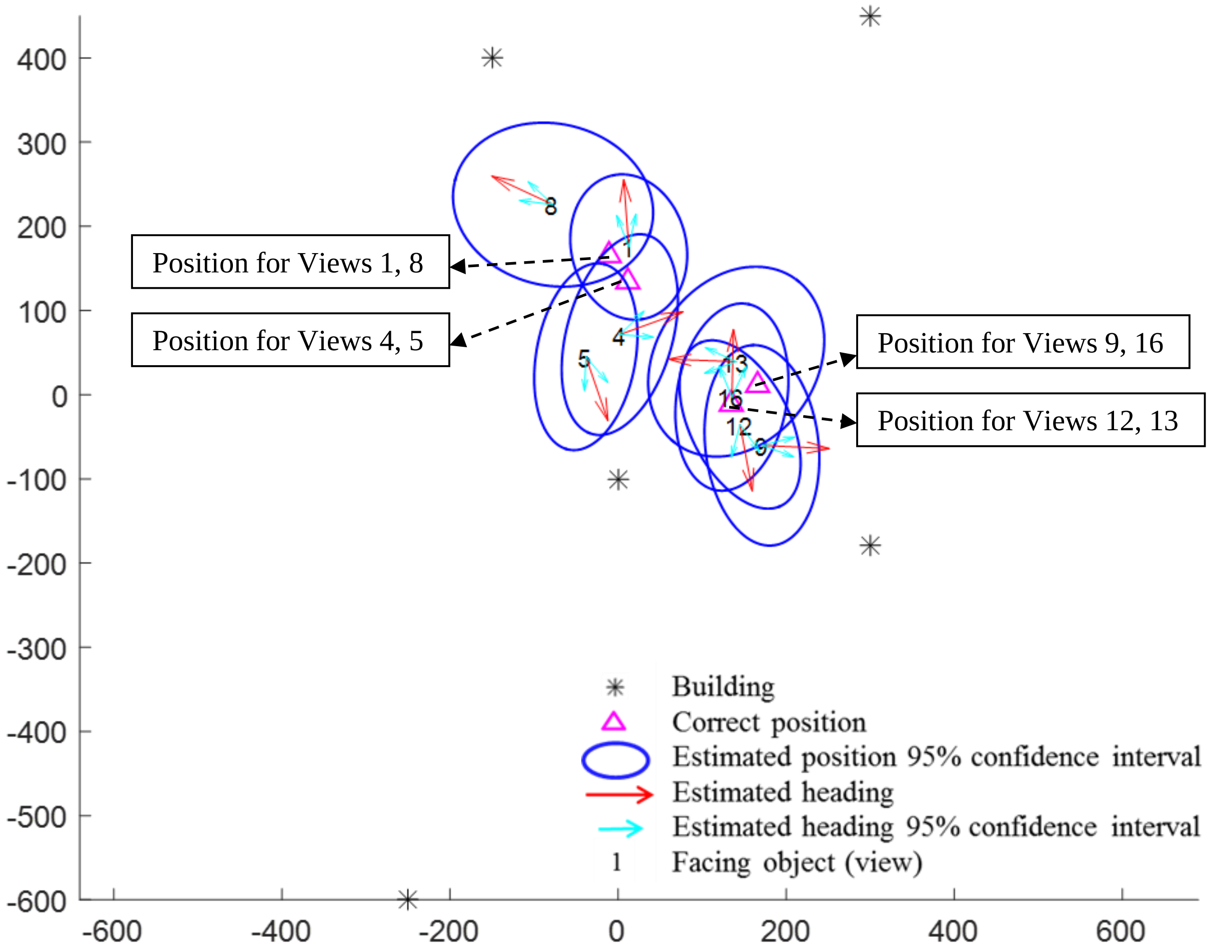

Figure 4. *Estimated standing positions and headings when facing views in the rooms in Experiment 3. The blue ovals represent 95% confidence intervals of the mean of the participants' estimated positions when they imagined facing views in the rooms. The locations of the view numbers represent the centre 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 view. The cyan arrows are the 95% confidence intervals of the mean of the participants' estimated headings.*

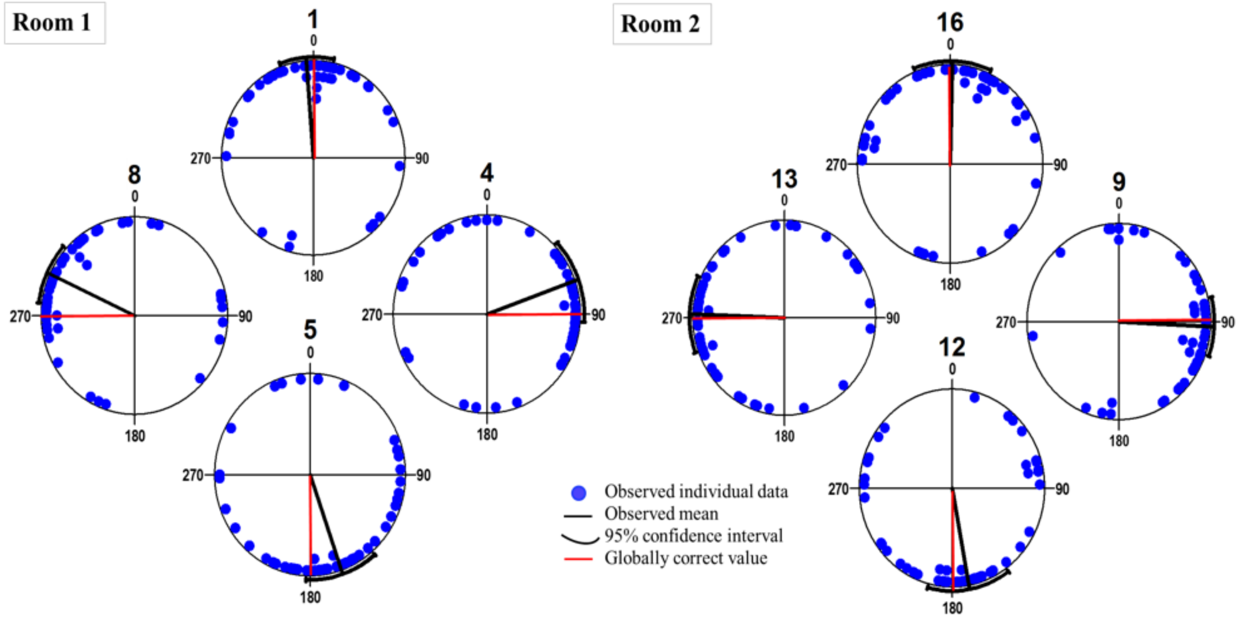

Figure 5. *Correct global headings and estimated global headings for each view in each room based on the response pointing of buildings in Experiment 3. The confidence interval is for the mean of the estimated global headings at each view.*

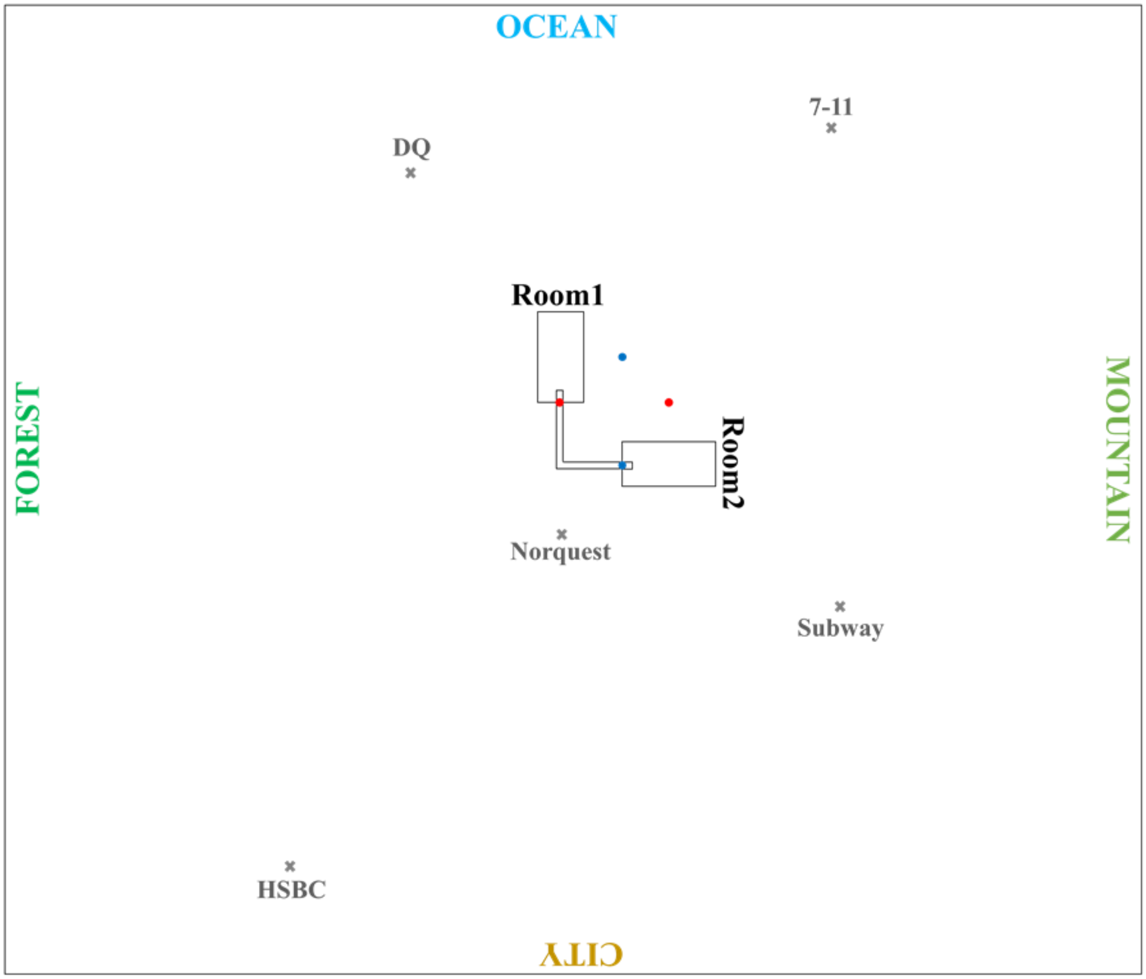

Figure 6. *Schematic diagram of the experimental setup (bird's eye view) for Experiments 4, 5 and 5b. Unlike Figure 3, this setup includes a hallway, which has a roof, connecting the two rooms. The five buildings were only presented in Experiment 4 but not in Experiments 5 and 5b. In Experiment 4, the participants learned the directions to the five buildings 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, the participants saw only one of the doorways. When the participants were learning objects in the two rooms through the hallway, the five buildings remained there. The distal orientation cues were always shown.*

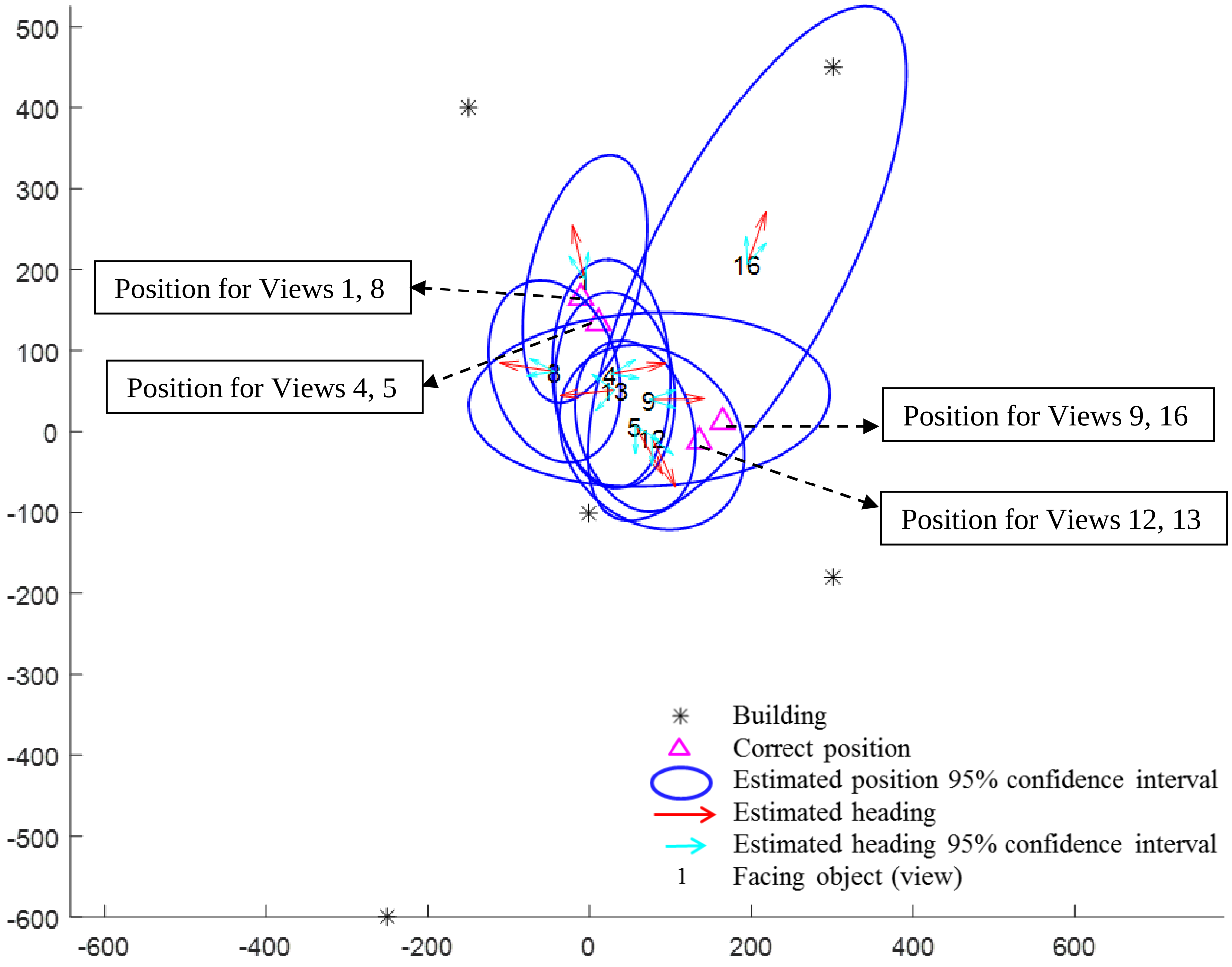

Figure 7. *Estimated standing positions and headings when facing views in the rooms in Experiment 4. Confidence intervals are for the mean of the individual estimations.*

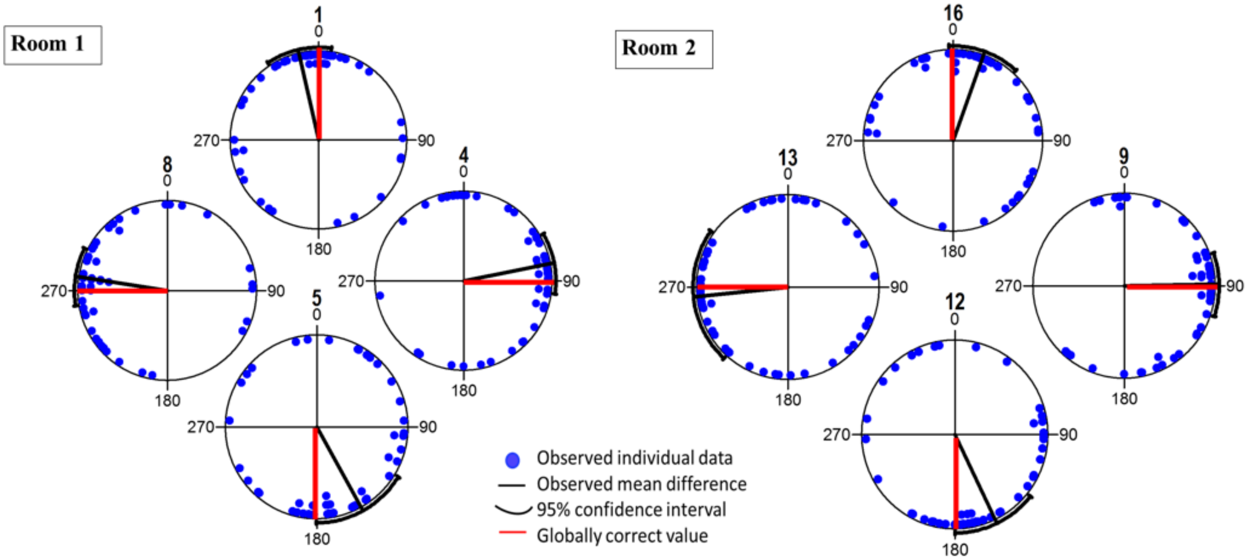

Figure 8. *Correct global headings and estimated global headings for each view in each room based on the response pointing of buildings in Experiment 4. The confidence interval is for the mean of the estimated global headings at each view.*