Manuscript
Journal of Experimental Psychology: Learning, Memory, & Cognition, in press

Visual Re-anchoring in Misaligned Local Spaces Impairs Global Path Integration

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This study was not preregistered. Data and experimental materials are available upon reasonable request.

Abstract

It is a prevailing theoretical claim that path integration is the primary means of developing global spatial representations. However, this claim is at odds with reported difficulty to develop global spatial representations of a multiscale environment using path integration. The current study tested a new hypothesis that locally similar but globally misaligned rooms interfere with path integration. In an immersive virtual environment, participants learned objects' locations in one room and then physically walked, while being blindfolded, to a neighbouring room for testing. These rooms were rectangular but globally misaligned. Adopting different actual perspectives in the testing room, the participants judged relative directions (JRDs) from the imagined perspectives in the learning room. The imagined and actual perspectives were aligned or misaligned according to either *local* room structures or *global* cardinal directions. Prior to JRDs, participants did not conduct other tasks (Experiment 1) or judged relative global headings of the two rooms to activate global representations while seeing the testing room (Experiment 2) or in darkness (Experiment 3). Participants performed better at *locally* aligned than misaligned imagined perspectives in all experiments. Better performances for *globally* aligned imagined perspectives appeared only in Experiment 3. These results suggest that structurally similar but misaligned rooms interfered with updating global heading by path integration, and this interference occurred during but not after the activation of global representations. These findings help to settle the inconsistency between the theoretical claims and empirical evidence of the importance of path integration in developing global spatial memories.

Keywords: sensorimotor alignment effect; structural similarity; spatial representations; spatial updating; multiscale environment

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1. Introduction

During navigation, people update their self-location (i.e., their headings and positions) by using visual landmarks and self-motion cues including optic flow and idiothetic cues (e.g., vestibular, proprioceptive, and motor efference information). The method using visual landmarks is referred to as piloting (Cheng & Spetch, 1998; Etienne et al., 2004; Foo et al., 2005; Wehner et al., 1996) whereas the method relying on self-motion cues is referred to as path integration (Etienne & Jeffery, 2004; Loomis et al., 1999; Mittelstaedt & Mittelstaedt, 1980; Wang, 2017). Studies have demonstrated evidence supporting that people can use both methods not only in an immediate space (e.g., Cheng, 1986; Doeller & Burgess, 2008; Klatzky et al., 1998; Mou et al., 2004; Rieser, 1989; Waller et al., 2002) but also in multiscale spaces (Burte & Hegarty, 2004; Kelly et al., 2007; Lei & Mou, 2021; Riecke & McNamara, 2017; Sholl et al., 2006). However, whether and how these methods interact in multiscale spaces is not clear. This study addressed this issue.

In a multiscale environment with several across-boundary spaces (e.g., a building with several offices), people navigate within a space (e.g., within an office) and between spaces across boundaries (e.g., between different offices). Accordingly, people might update their self-location not only in the immediate space but also relative to the space which they just visited (the remote space). Lei and Mou (2021) proposed two means of updating self-locations relative to remote spaces. By the first means, people might rely on self-motion cues (i.e., path integration) to develop a global spatial representation between the immediate space and the remote space and update their self-location in the global representation (Lei & Mou, 2022; Lei et al., 2020; Shine et al., 2016). This means of updating based on path integration in across-boundary navigation is referred to as *global-path-integration*. By the second means, people re-anchor themselves in the remote space based on the visual similarity of structures in the immediate and the remote spaces (Kelly et al., 2007; Marchette et al., 2017; Marchette et al., 2014; Riecke & McNamara, 2017). For example, suppose we visit the office of our new colleague for the first time. The new office has visual features and a rectangular structure similar to our own offices (e.g., with a window on one short wall). Seeing the new office, we may spontaneously remember our own offices and superimpose our own offices onto the situated new office based on the visual similarity of the room structures. Specifically, facing the window in the new office would re-anchor ourselves to face the window in our own offices. Superimposing two rooms based on visual similarity, one ignores global location displacement and global heading change in two different rooms. This means of updating self-locations relative to the remote space based on visual similarity of the immediate and remote spaces is referred to as *visual re-anchoring*. As *visual re-anchoring* relies on recognizing familiar scenes, it is an instance of piloting (Lei & Mou, 2021).

Lei and Mou (2022) showed that people can use *global-path-integration* to update their self-location in the global spatial representations of two adjacent square rooms without unique orientations. In their study, participants learned locations of objects in one square room and then had one-time navigation from the learning room to another square room for testing. In the testing room, participants judged relative directions of objects (JRDs, for example, “imagine standing at object A and facing object B, point to object C”) based on the memories of the objects’ locations in the learning room. The results showed that JRD performances were better when the imagined perspective in the learning room and the actual perspective in the testing room were aligned according to cardinal directions (e.g., both perspectives were facing north) than when these two perspectives were misaligned (e.g., one was facing north and the other was facing south). This alignment effect determined by the global relationship between the actual perspective and the imagined perspective is termed as global sensorimotor alignment effect (Avraamides & Kelly, 2008; Kelly et al., 2007; Lei & Mou, 2021). The global sensorimotor alignment effect indicated that participants updated their actual heading in the representations of the global relations between the learning and testing rooms. Since the local structure of a square room (especially the testing room with four homogenous walls) was not decisively informative to determine orientations, participants could update self-location relative to the square learning room primarily by *global-path-integration*.

Meanwhile, Riecke and McNamara (2017) showed that people can use *visual re-anchoring* to update their actual heading in the testing room relative to the learning room without encoding the global spatial relations between the learning and testing rooms. In Riecke and McNamara (2017), participants learned objects' locations in a rectangular learning room and then were disoriented and led to another rectangular testing room to conduct JRDs based on the memories of the objects' locations. The results showed better performances when the imagined perspective in the learning room and the actual perspective in the testing room were aligned in terms of local room structures (e.g., imagining facing the door in the learning room while actually facing the door in the testing room) than when they were misaligned. This result suggests that people, who do not develop any global spatial representations, can update self-location relative to a remote space based on visual structural similarity between rooms (*visual re-anchoring*).

Although people can use either *global-path-integration* and *visual re-anchoring* in updating self-locations relative to a remote space (Lei & Mou, 2022; Riecke & McNamara, 2017), it is not clear whether these two means work separately or interactively. One may conjecture that these two means work separately (independence hypothesis) because of the following reasons. *Visual re-anchoring* and *global-path-integration* function on different environmental scales. *Visual re-anchoring* relies on structures in local spaces and updates self-location in local representations, whereas *global-path-integration* relies on global relations between spaces and updates self-location in global representations. These two means do not interact because they update self-location in different spatial representations of environmental scales. In addition, some studies examining cue combination have assumed that piloting and path integration are independent navigation systems to generate independent spatial estimates (Chen et al., 2017; Chen et al., 2019; Nardini et al., 2008; Sjolund et al., 2018), consistent with the independence hypothesis.

However, there are other theoretical insights supporting that these two means work interactively (interaction hypothesis). Although *visual re-anchoring* relies on the local similarity of rooms, it is possible that people may systematically treat two views from different rooms that are locally consistent (e.g., the views of windows in different offices) as globally consistent regardless of the real global relations between the two views. Therefore, when two rooms with similar structures are also globally aligned (e.g., both offices have windows facing north), *visual re-anchoring* may facilitate *global-path-integration*. In contrast, when two rooms with similar structures are globally misaligned (e.g., one office has a window facing north and the other has a window facing east), *visual re-anchoring* may interfere with *global-path-integration*. In addition, the theoretical insights that piloting is dominant over path integration regardless of the precision of spatial estimates based on individual cues (cue competition) (Zhao & Warren, 2015, see also Mou & Zhang, 2014; Zhang & Mou, 2017) are consistent with the interaction hypothesis. Although this hypothesis does not claim that *global-path-integration* never affects *visual re-anchoring*, the effect, if existing, should be smaller than the effect of *visual re-anchoring* on *global-path-integration* because the local alignment effect was consistently reported regardless of the global alignment effect (Kelly et al., 2007; Lei & Mou, 2021; Lei et al., 2020; Marchette et al., 2017; Marchette et al., 2014; Riecke & McNamara, 2017).

Empirical evidence for these two hypotheses is also mixed. Lei and Mou (2021) showed independent sensorimotor alignment effects attributed to *visual re-anchoring* and *global-path-integration* in a single experiment but with some restrictions. Their participants learned an environment with two rectangular rooms by navigating within and between the rooms. The two rooms were structurally the same (i.e., rectangular rooms with a window on one short wall) but faced different global (cardinal) directions with an angular difference of 90° (Marchette et al., 2014). Participants had developed local and global representations of the multiscale environment after extensively learning objects' locations in each room and walking between rooms before testing (Lei et al., 2020). During testing, participants navigated to adopt an actual view (i.e., an actual perspective) in one room and did a JRD trial in which they mentally adopted a view in the other room. The results constantly showed local sensorimotor alignment effects, which were attributed to *visual re-anchoring* (Riecke & McNamara, 2017). However, global sensorimotor alignment effects only occurred when participants did a global-relevant task (judging relative global headings of two views from different rooms) to activate the global representations prior to the JRD task. Thus, when the two local spaces were globally misaligned and structurally similar, global sensorimotor alignment effects occurred only when participants had developed global spatial representations after extensive learning and the global representations were activated on the sensorimotor level by global-relevant tasks.

On one hand, the independent local and global sensorimotor alignment effects may support that *visual re-anchoring* and *global-path-integration* are independent, favoring the independence hypothesis. On the other hand, the restrictions (existing global spatial representations in long-term memory and activated global spatial representations in working memory) to show the global sensorimotor alignment effects may suggest that *visual re-anchoring* in globally misaligned rooms interferes with *global-path-integration*, favoring the interaction hypothesis.

The difficulty (the restrictions) in developing global representations of structurally similar but globally misaligned spaces (e.g., Lei & Mou, 2021; Marchette et al., 2014) might be caused by the lack of full idiothetic cues in path integration during navigation rather than the interference from *visual re-anchoring*. Lei and Mou (2021, see also Lei et al., 2020; Shine et al., 2016) used immersive virtual environments which allowed only physical rotation but visual translation during across-boundary navigation. Similarly, other studies that showed difficulty in developing global spatial representations of two misaligned rooms used desktop virtual environments which provided only visual translation and visual rotation during navigation (Marchette et al., 2017; Marchette et al., 2014). The importance of idiothetic cues on path integration and navigation has been demonstrated by previous studies (Chance et al., 1998; Klatzky et al., 1998; Rieser, 1989; Taube et al., 2013). In large-scale environments, body-based cues from active movement benefit spatial knowledge of directions (He et al., 2019; Waller et al., 2004). Idiothetic cues from physical translation may be more crucial than those from physical rotation to acquire spatial knowledge of directions and distances in large-scale environments (Ruddle et al., 2011). Therefore, the lack of idiothetic cues for physical translation and/or physical rotation during navigation may affect the function of path integration to develop global representations and update self-location relative to global relations (Lei & Mou, 2021; Lei et al., 2020; Marchette et al., 2017; Marchette et al., 2014). The difficulty (the restrictions) in developing global representations of structurally similar but globally misaligned spaces may disappear when participants have idiothetic cues for both physical translation and rotation during navigation, favoring the independence hypothesis.

The current study tested the interaction hypothesis and the independence hypothesis when people have one-shot walking with physical translation and rotation in a multiscale environment consisting of two globally misaligned but locally similar rooms. Differentiating these two hypotheses will significantly advance our understanding of the roles of visual and self-motion cues in updating self-location and developing global spatial memory in multiscale environments. The current study used the JRD task to reflect local sensorimotor alignment effects based on *visual re-anchoring* and global sensorimotor alignment effects based on *global-path-integration*. To accomplish a JRD trial, participants do not need to know the spatial relationship between their actual testing heading and the layout of objects used in JRDs. A JRD trial can be accomplished solely based on mental perspective-taking using the layout of objects (Lei & Mou, 2022; Lei, et al., 2022). Therefore, if there is a sensorimotor alignment effect, this will suggest that participants automatically encode and update their actual heading relative to the layout of objects during locomotion between learning and testing phases. It is the reason why a JRD task is widely used to test spontaneous spatial updating (e.g., Farrell & Robertson, 1998; Kelly et al., 2007; Lei et al., 2022; Rieser, 1989; Waller et al., 2002). In addition, Kelly et al. (2008) asked participants to point to target locations after each walking to test spatial updating. Participants in Kelly et al. (2008) immediately knew that they would need to update relative to the layout of objects after the first trial and then did so in each walking of the subsequent trials. Furthermore, participants could also develop the spatial relationship between their testing position and the target location during testing rather than during locomotion. Hence, this task of direct pointing used by Kelly et al. (2008) might not be ideal to test spontaneous spatial updating. Since the current study aimed to examine spontaneous use of *global-path-integration* and the effect of *visual re-anchoring* on spontaneous use of *global-path-integration*, the JRD task was used.

Experiment 1 was designed to test the interaction hypothesis and the independence hypothesis. As the results of Experiment 1 showed that *visual re-anchoring* in globally misaligned rooms interferes with *global-path-integration,* Experiments 2 and 3 were then designed to further understand the mechanisms through which *visual re-anchoring* in misaligned rooms interferes with *global-path-integration*.

2. Experiment 1

The purpose of Experiment 1 was to test the interaction hypothesis and the independence hypothesis. Participants learned objects' locations in one room, and then were blindfolded and led to walk to an adjacent testing room. The learning and testing rooms were two virtual rectangular rooms with globally misaligned principal axes, superimposed onto the real lab rooms (Figure 1). During testing, while they were facing actual perspectives in the testing room, they conducted the JRD task in which they adopted imagined perspectives and then pointed to target objects in the learning room. In the JRD task, the imagined perspectives in the learning room and the actual perspectives in the testing room were manipulated to be globally/locally aligned/misaligned, to examine global/local sensorimotor alignment effects. We assume that people can update their global headings relative to the learning room when walking to the testing room by *global-path-integration* with idiothetic cues for both physical translation and rotation during navigation (Lei & Mou, 2022). According to the interaction hypothesis, there would be no global sensorimotor alignment effects because when participants saw the testing room, *visual re-anchoring* in globally misaligned rooms interfered with the updated global heading representation from *global-path-integration*. In contrast, according to the independence hypothesis, there would be global sensorimotor alignment effects because seeing the testing room did not impair the updated global heading representation from *global-path-integration*. Local sensorimotor alignment effects would be expected regardless of the hypotheses, as consistently reported (Kelly et al., 2007; Lei & Mou, 2021; Lei et al., 2020; Marchette et al., 2017; Marchette et al., 2014; Riecke & McNamara, 2017).

2.1 Method

2.1.1 Participants

The study was approved by the Ethics Committee of the University of Alberta. Thirty-two university students (16 female) with normal or corrected-to-normal vision participated for credits in an introductory psychology course. This number of participants was the same as in Lei and Mou (2022), which showed global sensorimotor alignment effects when both learning and testing rooms were square rooms without unique orientations. In Experiment 6 of Lei and Mou (2022), Cohen's *d* of the global sensorimotor alignment effect was about 0.77. Using 32 participants led to the power value of 0.85 at the alpha level of .05 (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

In the real lab space, there were two lab rooms (4.4 m × 4.4 m each) and a hallway (Figure 1A). In each real lab room, an immersive virtual environment was generated by Vizard software (WorldViz, Santa Barbara, CA) and was presented in a head-mounted display (HMD, Oculus Rift, Oculus VR, LLC., Irvine, CA). Head motion tracking was carried out by an InterSense IS-900 motion tracking system (InterSense, Inc., Massachusetts). The participants physically walked and made turns to move in the virtual environment. In the learning phase, the participants replaced objects using a virtual pointer controlled by an InterSense Wand. In the testing phase, the participants did the JRD task using a joystick (Logitech Extreme 3D Pro, Newark, CA).

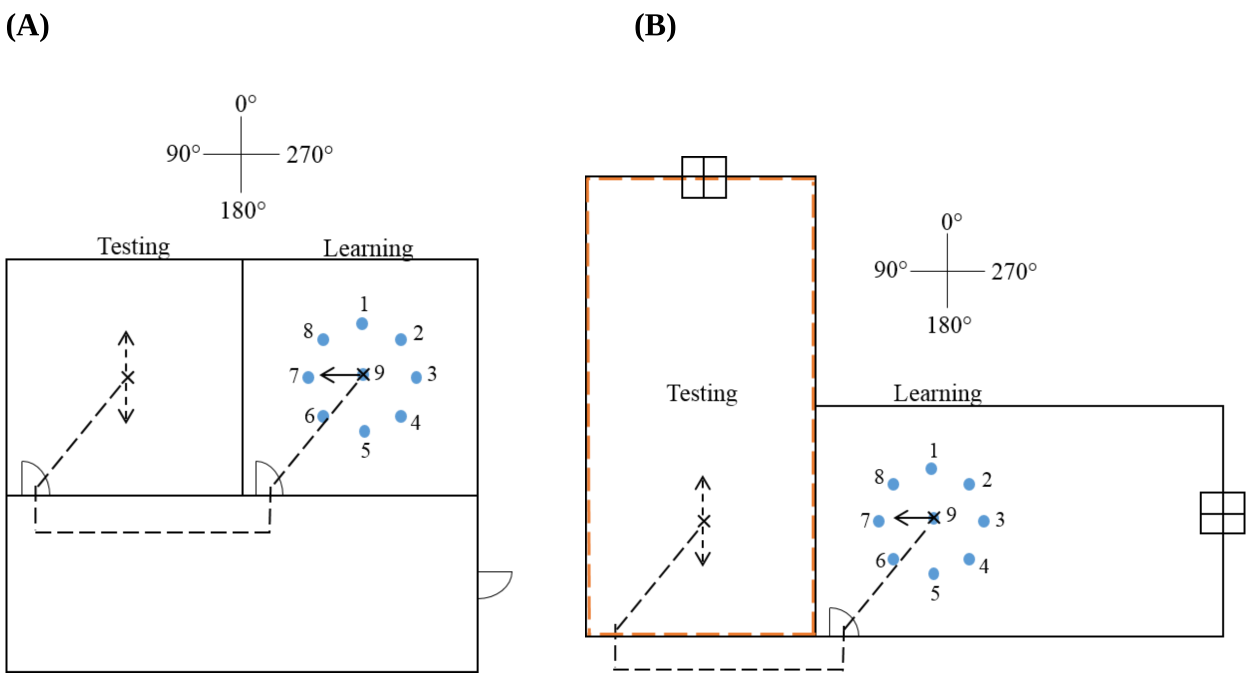

Figure 1. *Schematic experimental setup in the current study. (A) A real lab space with two lab rooms and a hallway. (B) Virtual rooms in an immersive virtual environment. The blue dots with numbers are objects. The crosses are the learning/testing positions. The solid arrow is the learning orientation (i.e., 90°). The dashed arrows are the actual perspectives in testing (i.e., 0° and 180°). The black dashed lines indicate the walking path from the learning position to the testing position. The red dashed lines along the virtual testing room indicate red walls. The compass indicates the labels for directions used in the current study.*

One real lab room was for the learning phase and the other was for the testing phase. The learning and testing positions were at the centers of the real lab rooms. The walking path was from the learning position to the testing position. However, although the participants moved in the real lab space, they never saw the real lab space; they saw only the virtual environments presented in each real lab room (Figure 1B). The virtual learning and testing rooms were structurally similar as both virtual rooms were rectangular (4.4 m × 8.8 m each) and had a window on one short wall, yet the virtual rooms were in different colors and textures. The principal axes and the orientations of the windows in the two virtual rooms were globally 90° apart so that the virtual learning and testing rooms were globally misaligned. In addition, the virtual learning room had a door, which overlapped with the door in the real lab room for learning, whereas the virtual testing room did not have a door. The virtual rooms were partially superimposed onto the real lab rooms. In particular, the left wall in the virtual learning room overlapped with the left wall in the real lab room for learning, whereas the bottom wall in the virtual testing room overlapped with the bottom wall in the real lab room for testing. Thus, the left half of the virtual learning room overlapped with the real lab room for learning, whereas the bottom half of the virtual testing room overlapped with the real lab room for testing.

In the learning phase, the participants learned locations of objects placed on the ground in the virtual learning room while standing at object 9 and facing object 7 (Figure 1). Eight objects formed a circular array (radius=1.8 m) in which the adjacent locations were 45° apart and one object was in the center of the circle (object 9, which was also the learning position). To increase the reality of the virtual environment, there were real objects placed at the same locations on the ground in the real lab room for the participants to touch.

The global and local alignments were independently manipulated in the JRD trials and were within-subject variables. The participants physically faced different actual perspectives in the testing room while doing JRDs. The actual perspectives in the testing room were 0° and 180°, and the imagined perspectives in the learning room were 0°, 90°, 180° and 270° (Figure 1). Together, they formed globally/locally aligned/misaligned conditions (see Table 1). In the globally aligned/misaligned conditions, the actual and imagined perspectives were aligned/misaligned in terms of the global cardinal directions. For example, if the imagined perspective was 0°, then the actual perspective was also 0° in the globally aligned condition but was 180° in the globally misaligned condition. In the locally aligned/misaligned conditions, the actual and imagined perspectives were aligned/misaligned in terms of the local structures. For example, if the imagined perspective in the learning room was facing the window (270°), then the actual perspective in the testing room was also facing the window (0°) in the locally aligned condition but was facing the opposite wall of the window (180°) in the locally misaligned condition. The contrast between the globally aligned and globally misaligned conditions examined the global sensorimotor alignment effect, and the contrast between the locally aligned and locally misaligned conditions tested the local sensorimotor alignment effect. Note that in the globally (locally) aligned/misaligned conditions, the angular distance between the actual and imagined perspectives was locally (globally) 90° so that the global and local sensorimotor alignment effects did not confound each other. The dependent measures were the response latency and absolute pointing error in the JRD trials.

Table 1

Imagined and actual perspectives in four conditions of the JRD task (i.e., globally/locally aligned/misaligned). The directions of the perspectives refer to Figure 1.

Conditions		Imagined perspectives			
		0°	180°	270°	90°
Actual perspectives	0°	Globally aligned	Globally misaligned	Locally aligned	Locally misaligned
	180°	Globally misaligned	Globally aligned	Locally misaligned	Locally aligned

There were two blocks in the JRD task, with each of the two actual perspectives (i.e., 0° and 180°) tested in blocks. In each block, 16 trials were generated for each of the four imagined perspectives, leading to 64 trials (see Table 2 for the standing, facing and target objects used for the four imagined perspectives). The trials were randomized in each block. The order of the two blocks was counterbalanced across the participants.

Table 2

The standing, facing, and target objects for the four imagined perspectives. The object numbers refer to Figure 1.

Imagined perspective	Standing object	Facing object	Target object
0°	4	2	1, 3, 5
	5	9	2, 4, 6, 8
	6	8	1, 5, 7
	9	1	2, 3, 4, 6, 7, 8
90°	2	8	1, 3, 7
	3	9	2, 4, 6, 8
	4	6	3, 5, 7
	9	7	1, 2, 4, 5, 6, 8
180°	1	9	2, 4, 6, 8
	2	4	1, 3, 5
	8	6	1, 5, 7
	9	5	2, 3, 4, 6, 7, 8
270°	6	4	3, 5, 7
	7	9	2, 4, 6, 8
	8	2	1, 3, 7
	9	3	1, 2, 4, 5, 6, 8

2.1.3 Procedure

Before the experiment, participants were led into one room (not the lab room used in the formal experiment) and they signed consent forms, read instructions and practiced using the joystick. Then participants were blindfolded and guided to the real lab room for learning. They were led to stand at the learning position (i.e., object 9 in Figure 1) and face the learning orientation (i.e., facing object 7 which was 90°, indicated by the solid arrow in Figure 1). They closed their eyes, removed the blindfold and put on the HMD.

Participants saw the virtual learning room. To familiarize the room, they looked around and also walked to touch the real wall in front of them (i.e., the left wall in the learning room in Figure 1). Then participants returned to the learning viewpoint (i.e., standing at object 9 and facing object 7 in Figure 1), and the objects were presented. Participants named the objects with the help of an experimenter. After that, instructed by the experimenter, participants moved to touch three real objects on which the virtual objects were superimposed (object 7 in the front, object 6 on the walking path later on, and another random object in Figure 1). To touch each object, participants moved from the learning position and went back after touching. Moving to touch the wall and the objects helped participants calibrate their physical movement in the virtual environment and realize that the virtual environment was as stable as the real environment (Mohler et al., 2006; Siegel et al., 2017; Taube et al., 2013). Then participants returned to the learning viewpoint to learn the object's locations for three minutes. After that, the objects were removed and a probed object with its name appeared at the center of the HMD. Participants used a virtual pointer to replace the probed object. The probed object was then presented at the response location and also at the correct location as feedback. Participants replaced the objects in three blocks, with the objects randomly tested in each block. After that, the objects were presented. When participants notified the experimenter that they had memorized the objects' locations, the objects were removed and the learning phase was finished.

Before the testing phase, participants went through some procedures to make them further realize that the objects were stabilized relative to the environment rather than their bodies during navigation (Mou et al., 2008). After the learning phase, participants returned to the learning viewpoint (standing at object 9 and facing object 7 in Figure 1). They closed their eyes, took off the HMD and put on the blindfold. At the learning viewpoint, participants were instructed to use their fingers and point to some objects that were randomly named by the experimenter. Then they were instructed to turn and face object 6 (Figure 1). They used their fingers to point to some objects randomly named by the experimenter. After that, they closed their eyes to remove the blindfold and put on the HMD. They saw the virtual environment from a new viewpoint (i.e., standing at object 9 and facing object 6 in Figure 1) and replaced all the objects at the original locations. Each object was tested once without feedback. Then participants closed their eyes to take off the HMD and put on the blindfold. They were led to walk from object 9 to object 6 (Figure 1). Again, they used their fingers to point to some objects and then put on the HMD to replace all the objects from the new viewpoint (standing at object 6 and facing the walking direction from object 9 to object 6 in Figure 1). Seeing the virtual environment from new viewpoints helped participants realize that the virtual environment was as stable as the real environment. Replacing the objects from new viewpoints helped participants realize that the objects were stable in the virtual environment and were not moving along with their bodies.

Then participants closed their eyes to take off the HMD and put on the blindfold. Prior to walking to the testing position, participants were instructed that they would walk to another room and should pay attention to the walking and track the objects. Before leaving the learning room, participants touched the door of the learning room to ensure that they would walk outside. They were guided to the testing position along the walking path (the black dashed lines in Figure 1) and oriented to face one actual perspective (0° or 180°, the dashed arrows in Figure 1). Participants were told that they had walked into a new room.

In the testing room, participants put on the HMD and saw a new virtual room. They held the joystick in their hands and conducted the first block of the JRD trials after facing the first actual perspective. They were required to maintain their actual perspective in the JRD trials. In each trial, a sentence to instruct an imagined perspective was shown at the center of the HMD (e.g., "standing at the bottle, facing the paperclip"). If the participants adopted the imagined perspective, they clicked the trigger on the joystick and the sentence disappeared. The duration between the appearance of the imagined perspective and the clicked trigger was recorded as orientation latency. Then another sentence was shown to instruct a target object (e.g., "point to the mug"). The participants pointed to the target from the imagined perspective. They were required to point as fast as possible without sacrificing accuracy. The sentence disappeared after pointing. The duration between the appearance of the target and the pointing response was recorded as response latency. The response pointing direction was recorded and was compared with the correct direction to get the absolute angular pointing error. The intertrial interval was 750 ms. The participants finished the first block of the JRD trials and then they were turned to the other actual perspective to finish the second block.

2.1.4 Data analysis

For each of the four conditions (i.e., globally/locally aligned/misaligned), we calculated the mean orientation latency, mean response latency and mean absolute angular pointing error. To test the global/local sensorimotor alignment effects, paired-sample *t* tests were conducted in IBM

SPSS 26 to compare performances between globally/locally aligned and globally/locally misaligned conditions. We also calculated the Bayes factor favoring the null effect over the alternative effect (BF_{01})[1].

Although previous studies suggested that response latency might be more sensitive than pointing error to sensorimotor alignment effects, sensorimotor alignment effects were found in either latency (e.g., Avraamides & Kelly, 2005) or pointing error (e.g., Riecke & McNamara, 2017, Experiment 2) if not both (see a discussion in Lei et al., 2022). Hence, sensorimotor alignment effects were concluded based on either response latency or pointing error in the current study as long as the results in response latency and pointing error do not show reversed alignment effects.

2.2 Results

The results from orientation latency were not significant in all experiments of the current study (Figure S1 in supplementary materials). Thus, the detailed results from response latency and absolute pointing error were reported as follows.

2.2.1 Response latency

Figure 2 plots the mean response latency for each condition in all experiments. The response latency in the globally aligned condition was not significantly different from that in the globally misaligned condition, $t(31) = 1.21$, $p = .234$, Cohen's $d = 0.30$, $BF_{01} = 3.62$, indicating a null global sensorimotor alignment effect. The responses in the locally aligned condition were significantly faster than those in the locally misaligned condition, $t(31) = 5.26$, $p < .001$, Cohen's $d = 1.32$, $BF_{01} < 0.01$, indicating a local sensorimotor alignment effect.

[1] The null effect is favored if the BF_{01} is larger than three, and strongly favored if the BF_{01} is larger than 10. The alternative effect is favored if the BF_{01} is smaller than 1/3, and strongly favored if the BF_{01} is smaller than 1/10 (Rouder et al., 2009). If the BF_{01} is between 1/3 and three, neither is favored.

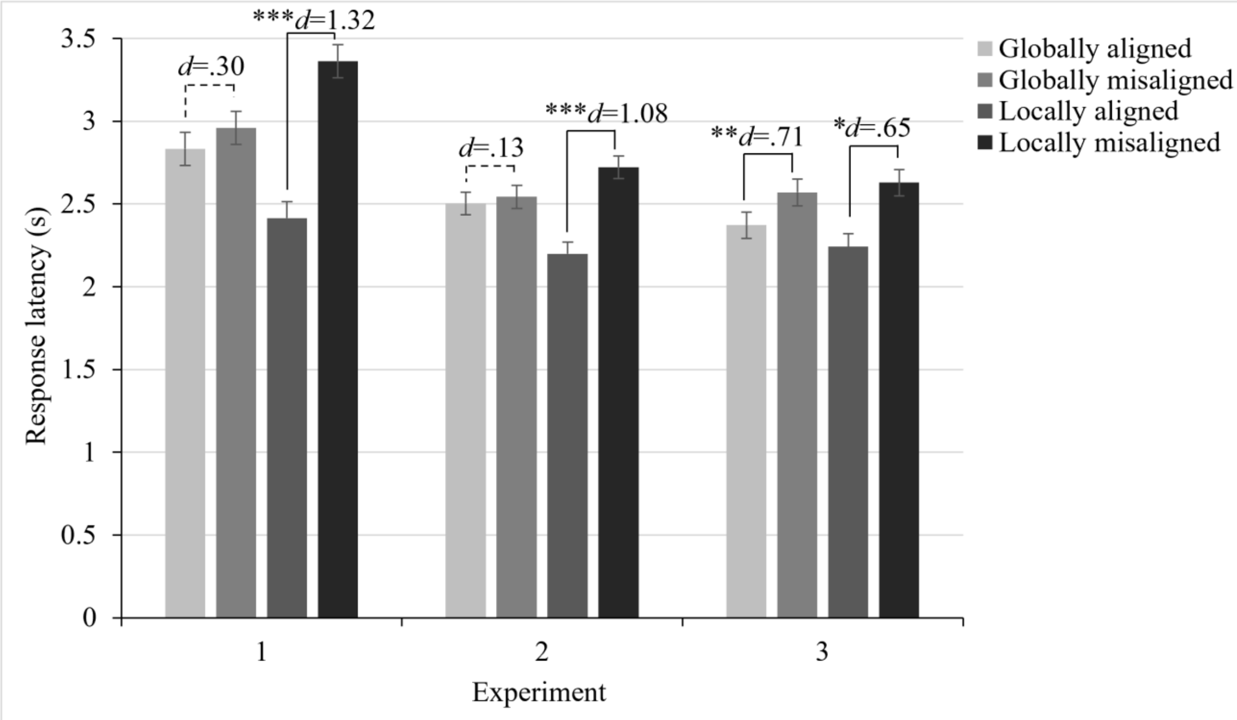

Figure 2. The mean response latency for each condition in all experiments. Error bars represent ±1 SE removing the variance from individual differences[2]*. The solid lines indicate significant comparisons, and the dashed lines indicate insignificant comparisons. Cohen's d values are listed (* p< .05; ** p< .01; *** p< .001).*

2.2.2 Absolute pointing error

Figure 3 shows the mean absolute angular pointing error for each condition in all experiments. The absolute pointing error in the globally aligned condition was not significantly different from that in the globally misaligned condition, $t(31) = 0.71$, $p = .483$, Cohen's $d = 0.18$, $BF_{01} = 5.72$, indicating a null global sensorimotor alignment effect. The responses in the locally aligned condition were significantly more accurate than those in the locally misaligned condition,

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[2] *SE* removing the variance from individual differences was obtained in the following equation: $SE = \sqrt{\frac{MSE}{N}}$, where *MSE* was the within-subject MSE in ANOVA with the four conditions of globally/locally aligned/misaligned and *N* was the number of subjects contributing to the means (Lei & Mou, 2022).

t(31) = 3.10, *p* = .004, Cohen's *d* = 0.77, BF_{01}= 0.12, indicating a local sensorimotor alignment effect.

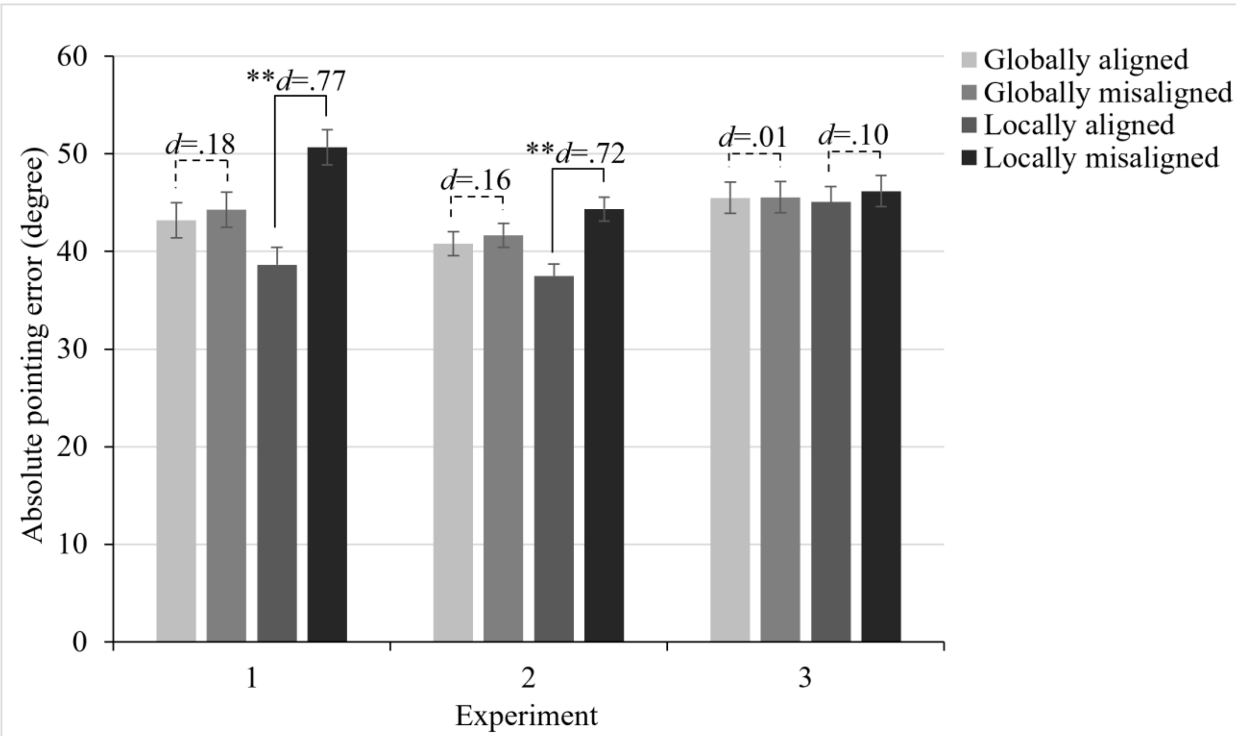

*Figure 3. The mean absolute pointing error for each condition in all experiments. Error bars represent ±1 SE removing the variance from individual differences. The solid lines indicate significant comparisons, and the dashed lines indicate insignificant comparisons. Cohen's d values are listed (** p< .01).*

There was no speed-accuracy trade-off (i.e., no negative correlation between response latency and absolute pointing error in globally/locally aligned/misaligned conditions). The response latency and the absolute angular error across participants and globally/locally aligned/misaligned conditions (i.e., 32 participants and four conditions leading to 128 pairs of latency and error) were not significantly correlated, *r*(126)=.11, *p*=.210.

2.3 Discussion

Experiment 1 showed only local sensorimotor alignment effects but no global sensorimotor alignment effects (see individual data patterns of local and global sensorimotor alignment effects in Figure S2 in supplementary materials), indicating that after one-shot walking from the learning room to the testing room, the participants only updated their headings relative to the learning room by *visual re-anchoring*. This result supports the interaction hypothesis. The following experiments further examined the mechanisms through which *visual re-anchoring* interferes with *global-path-integration*.

The difficulty in utilizing global spatial representations in self-localization after seeing the testing room might occur because *visual re-anchoring* interferes with *global-path-integration* by prioritizing the local spatial representations (and deprioritizing the global spatial representations) on the sensorimotor level (Lei & Mou, 2021; Wang, 2016). Experiment 2 tested this possibility.

3. Experiment 2

Previous studies have shown that relative heading judgments can activate global representations and bring them onto the sensorimotor level (Burte & Hegarty, 2004; Lei & Mou, 2021; Sholl et al., 2006). In those studies, relative heading judgments involved participants in the testing room being asked, for example, to face the global direction of a probed view in the learning room. Inspired by these findings, Experiment 2 added a relative heading judgment prior to the JRD task. If *visual re-anchoring* interferes with *global-path-integration* by prioritizing the local spatial representations (and deprioritizing the global spatial representations) on the sensorimotor level, then the interference will disappear when the global spatial representations are activated by the relative heading judgment, producing global sensorimotor alignment effects in the JRD task following the relative heading judgment.

3.1 Method

3.1.1 Participants

Thirty-two university students (16 female) with normal or corrected-to-normal vision participated for credits in an introductory psychology course.

3.1.2 Materials and design

The virtual environments and the JRD trials were the same as in Experiment 1.

There was one trial in the relative heading judgment task. Participants were asked to turn and face the cardinal direction of the original learning orientation in the virtual learning room (standing at object 9 and facing object 7 in Figure 1, which was an allocentric direction of 90°). Participants did one trial of relative heading judgment only from the first actual perspective of the JRD task (either 0° or 180°).

3.1.3 Procedure

The learning phase and the walking procedure were the same as in Experiment 1. In the testing phase, after participants put on the HMD and saw the testing room, they did one trial of the relative heading judgment. A sentence was presented at the center of the HMD to instruct the probed direction ("Imagine the experimenter is standing at the brush, facing the clock. Turn to face the same direction." Note that the brush was object 9 and the clock was object 7 in Figure 1). Participants were instructed to physically turn to face the cardinal direction of the probed direction, and they were allowed to take their time to think. They notified the experimenter after responding and the experimenter pressed a key on the keyboard to record participants' facing direction (recorded by the motion tracker on the HMD). The sentence on the HMD then disappeared. Participants were turned back to the initial actual perspective (i.e., 0° or 180°), and continued to conduct the JRD task.

3.2 Results

3.2.1 Response latency in JRD

Figure 2 plots the mean response latency for each condition. The response latency in the globally aligned condition was not significantly different from that in the globally misaligned condition, $t(31) = 0.53$, $p = .603$, Cohen's $d = 0.13$, $BF_{01} = 6.38$, indicating a null global sensorimotor alignment effect. The responses in the locally aligned condition were significantly faster than those in the locally misaligned condition, $t(31) = 4.31$, $p < .001$, Cohen's $d = 1.08$, $BF_{01} = 0.01$. This shows a local sensorimotor alignment effect.

3.2.2 Absolute pointing error in JRD

Figure 3 plots the mean absolute angular pointing error for each condition. The absolute pointing error in the globally aligned condition was not significantly different from that in the globally misaligned condition, $t(31) = 0.66$, $p = .516$, Cohen's $d = 0.16$, $BF_{01} = 5.92$, demonstrating a null global sensorimotor alignment effect. The responses in the locally aligned condition were significantly more accurate than those in the locally misaligned condition, $t(31) = 2.89$, $p = .007$, Cohen's $d = 0.72$, $BF_{01} = 0.20$, indicating a local sensorimotor alignment effect.

The response latency and the absolute angular error across participants and globally/locally aligned/misaligned conditions (i.e., 32 participants and four conditions leading to 128 pairs of latency and error) were negatively correlated, $r(126)=-.21$, $p=.018$, indicating speed-accuracy trade-off. However, in each of the four conditions, the response latency and the absolute angular error were not significantly correlated (rs(30) $\leq$-.29, ps$\geq$.105).

3.2.3 Relative Heading Judgment

Figure 4A plots the response directions in the relative heading judgment task. The correct allocentric response direction was 90° (i.e., standing at object 9 and facing object 7 in Figure 1).

The circular mean of the allocentric response directions from all participants was 131.02°, and the 95% confidence interval of the mean direction was [105.37°, 156.69°], which did not cover the correct direction of 90°. Instead, the responses were biased toward 180°, which was the direction if the participants relied on local structures to respond. These results indicate that participants did not respond accurately according to the global relations between the learning and testing rooms, but rather they tended to respond based on the local structural similarity between the rooms.

To test if participants who performed accurately in relative heading judgment exhibited global sensorimotor alignment effects in JRD, we divided the participants into two groups based on their response errors in the relative heading judgment task (i.e., absolute distance between the response direction and the correct direction of 90°). We used 45° as an arbitrary criterion, with response errors smaller than or equal to 45° indicating accurate global representations (accurate group) and response errors larger than 45° indicating inaccurate global representation (inaccurate group). There were 12 participants in the accurate group, and global sensorimotor alignment effects were not significant in either response latency or absolute pointing error ($t(11) = 0.42$, $p = .681$, Cohen's $d = 0.17$; $t(11) = 1.21$, $p = .251$, Cohen's $d = 0.49$, respectively). There were 20 participants in the inaccurate group, and global sensorimotor alignment effects were not significant in either response latency or absolute pointing error ($t(19) = 1.10$, $p = .284$, Cohen's $d = 0.35$; $t(19) = 0.41$, $p = .689$, Cohen's $d = 0.13$, respectively).

In addition, we calculated the correlation between the response error in the relative heading judgment task (i.e., absolute distance between the response direction and the correct direction of 90°) and the global sensorimotor alignment effects (i.e., response latency/absolute pointing error in globally misaligned conditions minus that in globally aligned conditions) (Figures S3A and S3B in supplementary materials). There was no significant correlation in either response latency or absolute pointing error ($r(30) = 0.08$, $p = .673$; $r(30) = -0.14$, $p = .457$, respectively).

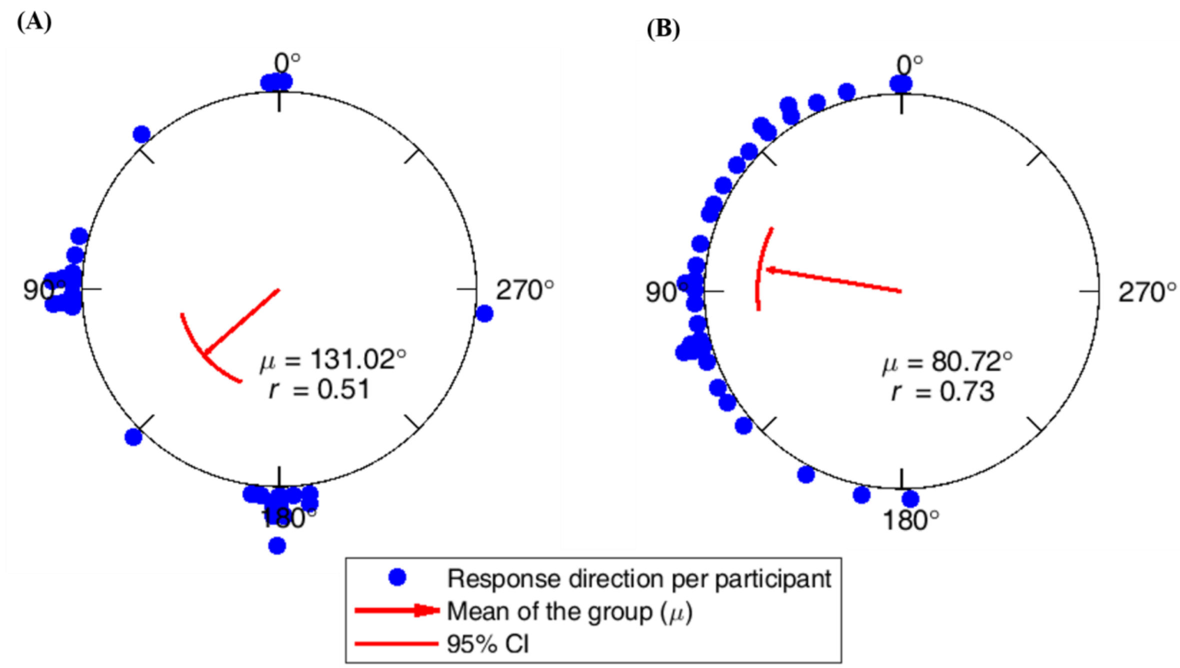

Figure 4. Response heading directions in the relative heading judgment task of Experiment 2 (A) and Experiment 3 (B). The correct heading direction is 90°. Each dot indicates the response direction from one participant. The red arrow shows the circular direction (μ) and the length (r) of the mean vector across all participants. The red arc indicates the 95% confidence interval of the mean direction.

3.3 Discussion

Experiment 2 still showed only local sensorimotor alignment effects as in Experiment 1, even when the participants in Experiment 2 conducted the relative heading judgment prior to the JRD task. Therefore, *visual re-anchoring* interferes with *global-path-integration* not just by prioritizing local spatial representations and deprioritizing global spatial representations on the sensorimotor level (Lei & Mou, 2021; Wang, 2016). This finding differs from that in Lei and Mou (2021), which showed the global sensorimotor alignment effect when participants conducted the relative heading judgment prior to the JRD task. This discrepancy will be addressed in the General Discussion.

Even though Experiment 2 showed the interference from *visual re-anchoring* on *global-path-integration* in the JRD task following the relative heading judgment, it is not clear whether *visual re-anchoring* interferes with activating the global representations onto the sensorimotor level or disrupts the global representations that have been activated by the relative heading judgment. The first possibility, which suggests that *visual re-anchoring* does not disrupt global representations that have been activated, indicates that people can develop a global spatial representation of two misaligned rooms by path integration in some conditions. In contrast, the second possibility, which indicates that *visual re-anchoring* universally interferes with *global-path-integration,* predicts that a global spatial representation of two misaligned rooms cannot be developed by path integration. Because misaligned rooms are very common in real environments, testing these two possibilities is critical to testing the theoretical debates on whether people can develop cognitive maps of a large-scale environment and the function of path integration in developing global cognitive maps. Some researchers claim that *global-path-integration* is the primary means of developing global cognitive maps (e.g., Gallistel, 1990). However, other researchers suggest that people may not be able to develop global cognitive maps but only develop local spatial representations (e.g., Marchette et al., 2014) or global cognitive graphs (e.g., Meilinger, 2008). In addition, testing these two possibilities can further reveal the mechanism of interference from *visual re-anchoring* on *global-path-integration*. Experiment 3 tested these two possibilities.

4. Experiment 3

In Experiment 3, participants conducted the relative heading judgment in darkness without the presentation of the virtual testing room. Therefore, possible interference from *visual re-anchoring* in misaligned rooms could only occur after the relative heading judgment activated the global relations on the sensorimotor level. If the global sensorimotor alignment effect appeared, then this result would support that *visual re-anchoring* interferes with activation of the global representations by the relative heading judgment; *visual re-anchoring* does not disrupt the global representations that have been activated by the relative heading judgment.

4.1 Method

4.1.1 Participants

Thirty-two university students (16 female) with normal or corrected-to-normal vision participated for credits in an introductory psychology course.

4.1.2 Materials, design and procedure

The materials, design and procedure were the same as in Experiment 2, except for the following change in the relative heading judgment task. After participants were led to the testing position and oriented to the actual perspective, they put on the HMD and saw a dark screen. Participants conducted one trial of relative heading judgment in darkness. After they finished responding, they were turned back to the initial actual perspective. Then the virtual testing room was presented and participants conducted the JRD task.

4.2 Results

4.2.1 Response latency in JRD

Figure 2 plots the mean response latency for each condition. The responses in the globally aligned condition were significantly faster than those in the globally misaligned condition, $t(31)$ =

2.84, p = .008, Cohen's d = 0.71, BF_{01}= 0.22. This shows a significant global sensorimotor alignment effect. The responses in the locally aligned condition were significantly faster than those in the locally misaligned condition, $t(31)$ = 2.60, p = .014, Cohen's d = 0.65, BF_{01}= 0.37, indicating a significant local sensorimotor alignment effect.

4.2.2 Absolute pointing error in JRD

Figure 3 plots the mean absolute angular pointing error for each condition. The absolute pointing error in the globally aligned condition was not significantly different from that in the globally misaligned condition, $t(31)$ = 0.03, p = .980, Cohen's d < 0.01, BF_{01}= 7.30, indicating a null global sensorimotor alignment effect. The absolute pointing error in the locally aligned condition was not significantly different from that in the locally misaligned condition, $t(31)$ = 0.39, p = .700, Cohen's d = 0.10, BF_{01}= 6.78, indicating a null local sensorimotor alignment effect.

There was no speed-accuracy trade-off. The response latency and the absolute angular error across participants and globally/locally aligned/misaligned conditions (i.e., 32 participants and four conditions leading to 128 pairs of latency and error) were not significantly correlated, $r(126)$=-.08, p=.349.

4.2.3 Relative Heading Judgment

Figure 4B plots the response directions in the relative heading judgment. The correct response direction was 90°. The circular mean of the response directions across all participants was 80.72° and the 95% confidence interval of the mean direction was [65.11°, 96.34°], which covered the correct direction of 90°. These results indicate that participants responded accurately according to the global relations between the learning and testing rooms. In addition, we conducted a Watson-Williams F-test (Mardia & Jupp, 2000, p.129) to test whether the response directions differed between Experiments 2 and 3. The result showed that the mean response directions in

Experiments 2 and 3 were significantly different, $F(1, 62) = 11.43$, $p = .001$, suggesting that the responses in the relative heading judgment were better in Experiment 3 than in Experiment 2. The participants in Experiment 3 relied on the global representations of the learning and testing rooms to judge headings in the two rooms when there was no interference from local structural similarity (i.e., in darkness before the testing room was presented).

As in Experiment 2, we divided the participants into the accurate group and inaccurate group according to their performance in relative heading judgments. There were 21 participants in the accurate group, and global sensorimotor alignment effects were significant in response latency ($t(20) = 2.64$, $p = .016$, Cohen's $d = 0.82$) but not significant in absolute pointing error ($t(20) = 0.60$, $p = .552$, Cohen's $d = 0.19$), suggesting that participants updated global headings after the global representations were activated. There were 11 participants in the inaccurate group, and global sensorimotor alignment effects were not significant in either response latency or absolute pointing error ($t(10) = 1.17$, $p = .268$, Cohen's $d = 0.50$; $t(10) = 0.82$, $p = .430$, Cohen's $d = 0.35$, respectively).

In addition, as in Experiment 2, we calculated the correlation between the response error in the relative heading judgment task and the global sensorimotor alignment effects (Figures S3C and S3D in supplementary materials). There was no significant correlation in either response latency or absolute pointing error ($r(30) = -0.16$, $p = .376$; $r(30) = -0.12$, $p = .508$, respectively).

4.3 Discussion

Experiment 3 showed the global sensorimotor alignment effect in addition to the local sensorimotor alignment effect, suggesting that participants updated headings by *global-path-integration* in addition to *visual re-anchoring*. These results indicate that the interference from *visual re-anchoring* in the misaligned rooms on *global-path-integration* occurs during rather than after activating global spatial representations on the sensorimotor level. After the global representations were successfully activated onto the sensorimotor level, the sensorimotor global representations were immune to the interference from *visual re-anchoring* in the misaligned rooms. Participants could then update their headings in the global representations with the presence of the testing room in the JRD task.

5. General Discussion

The current study examined whether and how visual re-anchoring in misaligned local spaces interferes with updating people's global headings by one-shot across-boundary walking between the spaces. There are two main findings. First, visual re-anchoring in misaligned local spaces interfered with updating people's global headings by one-shot across-boundary walking between the spaces. Second, visual re-anchoring interfered with activation of global spatial representations but did not disrupt the global spatial representations after they had been activated.

To the best of our knowledge, the current study demonstrated, for the first time, that visual re-anchoring in misaligned local spaces interfered with updating global headings from self-motion. Previous studies have shown local sensorimotor alignment effects attributed to *visual re-anchoring* and have demonstrated that people can re-anchor themselves in a remote space based on the similar visual structures of the current space and the remote space (Riecke & McNamara, 2017). Previous studies have also shown global sensorimotor alignment effects attributed to *global-path-integration* and have demonstrated that people can update their headings in the global representations of two square rooms by one-shot across-boundary walking between the rooms (Lei & Mou, 2022). Lei and Mou (2021) showed both local sensorimotor alignment effects attributed to *visual re-anchoring* and global sensorimotor alignment effects attributed to *global-path-integration.* However, before the current study, there was no study directly testing whether *visual* *re-anchoring* interferes with *global-path-integration* (interaction hypothesis) or these two means are independent (independence hypothesis). The findings that the global sensorimotor alignment effect did not appear in Experiments 1 and 2 of the current study but only appeared in Experiment 3 clearly favor the interaction hypothesis over the independence hypothesis.

The finding that *visual re-anchoring* interfered with *global-path-integration* can explain the difficulty in developing global representations and updating global headings shown in the previous studies (see Table 3 for a summary of studies). In a multiscale environment containing structurally similar spaces, developing global representations by across-boundary navigation is difficult and requires preconditions such as prior global learning (Lei et al., 2020; Marchette et al., 2017; Marchette et al., 2014). Furthermore, even after people develop global spatial representations, they still need to perform relative heading judgments to bring the global spatial representations onto the sensorimotor level so that they can update global headings (Lei & Mou, 2021). Unfortunately, these studies did not enable full-body movement during across-boundary navigation, which confounds with the existence of globally misaligned local structural similarity to explain the difficulty in developing global representations of spaces with similar structures. In the current study, participants physically walked from the learning position to the testing position, enabling full-body movement during across-boundary navigation. The null global sensorimotor alignment effect in Experiments 1 and 2 of the current study and the global effect only in Experiment 3 replicated the difficulty of using across-boundary navigation to develop global representations of structurally similar spaces. Thus, the difficulty was not necessarily due to the lack of full idiothetic cues in across-boundary navigation, but rather primarily due to the interference from visual re-anchoring in misaligned local spaces.

Table 3

Summary of studies on results of global representations or global spatial updating by across-boundary navigation between local spaces. The key variables summarized from the studies are explicit instruction to encode global relations, misaligned local similarity, full-body movement during across-boundary navigation, prior global learning, extensive or one-shot navigation across boundaries, extra global-relevant task to activate global representations, and whether testing occurred in the original learning virtual environment or not (i.e., onsite or offsite testing). (Exp is short for Experiment.)

Study	Instruction	Misaligned local similarity	Full-body movement	Prior global learning	Extensive/ one-shot navigation	Extra global task	Onsite/ offsite testing	Results
Shine et al., 2016	√	×	×	×	extensive	×	offsite	√
Lei et al., 2020, Exp 2; Marchette et al., 2014	×	√	×	×	extensive	×	offsite	×
Marchette et al., 2017	×	√	×	×	extensive	×	onsite	×
Lei et al., 2020, Exps 3&4	×	√	×	√	extensive	×	offsite	√
Lei & Mou, 2021, Exp 1	×	√	×	√	extensive	×	onsite	×
Lei & Mou, 2021, Exps 2&3	×	√	×	√	extensive	√	onsite	√
Strickrodt et al., 2019	×	√	√	×	extensive	×	onsite	√
Lei & Mou, 2022	×	×	√	×	one-shot	×	onsite	√
Current study, Exp 1	×	√	√	×	one-shot	×	onsite	×
Current study, Exp 2	×	√	√	×	one-shot	√ while seeing the test room	onsite	×
Current study, Exp 3	×	√	√	×	one-shot	√ before seeing the test room	onsite	√

The interaction hypothesis can reconcile the discrepancy between theoretical claims and empirical evidence regarding the function of *global-path-integration* in developing global spatial memories. It is a prevailing theoretical claim that *global-path-integration* is the primary means of developing global spatial representations (Gallistel, 1990; Jacobs & Schenk, 2003; Loomis et al., 1999; McNaughton et al., 2006; Wang, 2016; but see Meilinger, 2008). However, this theoretical claim is at odds with empirical evidence showing that it is difficult to develop global spatial representations of a multiscale environment using *global-path-integration* (Lei et al., 2020; Marchette et al., 2017; Marchette et al., 2014). Researchers have attributed this difficulty to the minimal visual information in across-boundary navigation (Mou & Wang, 2015), the error-prone nature of path integration (Etienne & Jeffery, 2004), and the disengagement from spatial updating in remote spaces when people move in an immediate space (Wang, 2016). The interaction hypothesis proposed in the current study suggests that the misaligned but structurally similar local spaces might critically contribute to the difficulty in developing global representations of a multiscale environment using *global-path-integration.*

Importantly, the current study showed that *visual re-anchoring* in misaligned rooms interferes with *global-path-integration* because *visual re-anchoring* interferes with the activation of the global representations rather than disrupts the global representations that have been activated by relative heading judgments. In Experiment 2, participants conducted the relative heading judgment with the testing room presented, prior to the JRD task. The results still showed only local sensorimotor alignment effects. In Experiment 3, participants conducted the relative heading judgment task without the testing room presented (i.e., in darkness). The results showed that there were both global and local sensorimotor alignment effects. These findings indicate that *visual re-*

anchoring in misaligned local spaces interferes with *global-path-integration* because it interferes with activation of the global representations to the sensorimotor level by the relative heading judgment. If global representations are successfully activated to the sensorimotor level, no further interference from *visual re-anchoring* in misaligned local spaces occurs. This finding sheds light on the mechanism through which *visual re-anchoring* interferes with *global-path-integration.*

The current study shows that the global representations need to be activated by relative heading judgments, to support updating headings in the global representations with the presence of misaligned local rooms (Experiment 3). This is consistent with the previous finding that the global representations in long-term memory need to be retrieved as sensorimotor global representations in working memory so that people can rely on the global representations to update self-location (Lei & Mou, 2021). However, participants who conducted the relative heading judgment while viewing the misaligned rooms prior to the JRD task showed the global sensorimotor alignment effects in Lei and Mou (2021) but not in Experiment 2 of the current study. This discrepancy might occur because the participants in Lei and Mou (2021) had extensive across-boundary navigation and prior global learning whereas the participants in the current study had only one-shot across-boundary navigation without any prior global learning. Some previous studies have shown that extensive navigational experiences and prior global learning may be critical to developing global representations in large-scale environments (Han & Becker, 2014; He et al., 2019; Lei et al., 2020; Starrett et al., 2019). As the participants in Lei and Mou (2021) had both extensive across-boundary navigation and prior global learning, they should have developed relatively enduring global representations in their long-term memory. Activation of enduring global representations on the sensorimotor level might be resistant to the interference from *visual re-anchoring* in misaligned rooms.

By contrast, in the current study, participants only had a one-time walking experience between the learning and testing rooms in a novel environment. The global representations developed by one-shot across-boundary walking might have been primitive and transient. For example, participants might have encoded the origin of the walking path relative to the learning room and also their self-location relative to the origin of the walking path (the homing vector). Extra steps were needed to turn the primitive global representations into relatively enduring global representations. These steps could be invoked by any task that tapped into global spatial relations (e.g., relative heading judgments). However, these steps were prone to the interference from *visual re-anchoring*. In Experiment 2 of the current study, seeing the structurally similar but globally misaligned testing room before and during the relative heading judgment might have disrupted the process of developing enduring global representations. Importantly, the participants in Experiment 3 conducted the relative heading judgment task without the testing room presented (i.e., in darkness), and the results showed both global and local sensorimotor alignment effects. Thus, one trial of judging relative headings in darkness could turn the primitive global representations into the relatively enduring global representations that were immune to the interference from *visual re-anchoring*.

It is still not clear whether extensive across-boundary navigation with full-body movement (but without prior global learning) can sufficiently overcome the interference from *visual re-anchoring* in misaligned local rooms and lead to the development of enduring global representations. On one hand, the reciprocal interaction between navigation and spatial memory during extensive across-boundary navigation may contribute to developing global representations, and with more navigational experiences, the primitive global representations may become more integrated and mature to support navigation. On the other hand, Lei et al. (2020) showed that global prior learning might be essential to developing global representations. The prior global learning may provide a common global reference system to turn primitive global representations into enduring global representations. Without prior global learning, the primitive global representations may be washed out by *visual re-anchoring* after each across-boundary walk. Consequently, no enduring global representations can be formed regardless of the number of across-boundary walks. Note that the participants in Lei et al. (2020) did not have full idiothetical cues. Therefore, it is not clear whether prior global knowledge is still essential to resisting to interference from *visual re-anchoring* when participants have full idiothetical cues. Future studies are needed to address this issue.

The key difference between the independence and the interaction hypotheses is that while the independence hypothesis stipulates that *visual re-anchoring* does not interfere with *global-path-integration*, the interaction hypothesis stipulates that *visual re-anchoring* interferes with *global-path-integration*. The interaction hypothesis does not claim that *global-path-integration* interferes with *visual re-anchoring*. Therefore, evidence (or no evidence) of *global-path-integration* interfering with *visual re-anchoring* is not critical to distinguishing these two hypotheses. Indeed, the results of the current study provided unclear evidence of *global-path-integration* interfering with *visual re-anchoring*. On one hand, the local sensorimotor alignment effects constantly shown in all three experiments suggest that *global-path-integration* might not have interfered with *visual re-anchoring*. On the other hand, the effect sizes of the local sensorimotor alignment effect decreased across the three experiments when participants were increasingly encouraged to use global representations. In addition, the local sensorimotor alignment effects in Experiments 1 and 2 were observed in both response latency and angular pointing error, but in Experiment 3, the effect was observed only in response latency. These results suggest that *global-path-integration* might also have interfered with *visual re-anchoring*. When people maintain the global representations on the sensorimotor level (using working memory), it might impair sensorimotor representations of the immediate room (also using working memory), reducing the local sensorimotor alignment effect. Future studies are required to directly investigate whether *global-path-integration* interferes with *visual re-anchoring*.

Following previous studies on alignment effects which showed effects in either response latency and/or pointing error (e.g., Avraamides & Kelly, 2005; Kelly et al., 2007), the current study relied on either response latency or pointing error to conclude sensorimotor alignment effects. This practice of data analyses was consistently used in our previous studies (Lei & Mou, 2021, 2022; Lei et al., 2022), as summarized in Table 4. The results of these previous studies showed that sensorimotor alignment effects occurred only in response latency or only in pointing error, if not in both. However, in general, response latency appears to be more sensitive than pointing error to sensorimotor alignment effects. These results are consistent with other findings in the literature (see a discussion in Lei et al., 2022). In the current study, the global sensorimotor alignment effect, as well as the local sensorimotor alignment effect, was found in response latency but not absolute pointing error in Experiment 3, whereas local sensorimotor alignment effects were found in both response latency and absolute pointing error in Experiments 1 and 2. These results also suggest that response latency appears to be more sensitive than pointing error to sensorimotor alignment effects when sensorimotor alignment effects do not appear in both response latency and pointing error. Because local sensorimotor alignment effects were also only found in response latency in Experiment 3, sensorimotor alignment effects (both local and global effects) in Experiment 3, seem smaller than sensorimotor alignment effects (local effect only) in Experiments 1 and 2. This might have occurred because spatial representations were weaker or less accessible when participants needed to maintain or use both global and local representations in Experiment 3.

Table 4

*Summary of our recent studies on local/global sensorimotor alignment effects in latency/error and conclusions. Ticks indicate significant effects, and crosses indicate null effects. Cohen's d and partial eta squared (η_p^2) are listed (*p< .05; **p<.01; ***p<.001).*

Study	Local Effect		Global Effect		Conclusion	
	Latency	Error	Latency	Error	Local	Global
Lei & Mou, 2021, Exp 1	√ **d=.64	× d=.36	× d=.09	× d=.27	√	×
Lei & Mou, 2021, Exp 2	√ **d=.84	√ *d=.50	× d=.09	√ *d=.54	√	√
Lei & Mou, 2021, Exp 3	√ ***d=1.18	√ *d=.68	× d=.12	√ **d=.81	√	√
Lei & Mou, 2022, Exp 1 (across boundary)	N/A	N/A	√ *d=.55	√ *d=.51	N/A	√
Lei & Mou, 2022, Exp 1 (within boundary)	N/A	N/A	√ *d=.71	× d=.45	N/A	√
Lei & Mou, 2022, Exp 2	N/A	N/A	√ *d=.60	√ *d=.64	N/A	√
Lei & Mou, 2022, Exp 3	N/A	N/A	√ *d=.60	× d=.36	N/A	√
Lei & Mou, 2022, Exp 4 (including learning orientation)	N/A	N/A	√ *d=.54	× d=.41	N/A	√
Lei & Mou, 2022, Exp 4 (excluding learning orientation)	N/A	N/A	√ **d=.69	√ *d=.51	N/A	√
Lei & Mou, 2022, Exp 5	N/A	N/A	√ *d=.53	× d=.32	N/A	√
Lei & Mou, 2022, Exp 6	N/A	N/A	√ **d=.77	√ *d=.53	N/A	√
Lei et al., 2022, Exp 1	N/A	N/A	× η_p^2=.05	× η_p^2=.00	N/A	×
Lei et al., 2022, Exp 1b	N/A	N/A	× η_p^2=.00	× η_p^2=.02	N/A	×
Lei et al., 2022, Exp 2	N/A	N/A	√ ** η_p^2=.45	√ * η_p^2=.20	N/A	√
Lei et al., 2022, Exp 2b	N/A	N/A	√ * η_p^2=.25	× η_p^2=.00	N/A	√
Lei et al., 2022, Exp 3	N/A	N/A	√ ** η_p^2=.49	× η_p^2=.14	N/A	√
Current study, Exp 1	√ ***d=1.32	√ **d=.77	× d=.30	× d=.18	√	×
Current study, Exp 2	√ ***d=1.08	√ **d=.72	× d=.13	× d=.16	√	×
Current study, Exp 3	√ *d=.65	× d=.10	√ **d=.71	× d=.01	√	√

In the current study, participants walked with both physical rotation and translation instead of lacking physical translation and/or physical rotation in the previous studies (Lei & Mou, 2021; Lei et al., 2020; Marchette et al., 2017; Marchette et al., 2014; Shine et al., 2016). Thus, path integration in the current study is closer to that during navigation in real environments. We acknowledge that path integration in the current study is still not identical to that in real environments. The current study still presented virtual learning and testing rooms to create globally misaligned but locally similar rooms. When participants walked from the learning room to the testing room, they had to un-don the HMD in the learning room and don the HMD in the testing room. These extra steps might have interfered with the path integration process. Future studies should consider avoiding these extra steps if possible.

In conclusion, the current study demonstrated that globally misaligned but locally similar structures in local spaces interfere with developing global representations and updating self-location in the global representations, after one-shot across-boundary walking in a novel environment. In particular, misaligned local structural similarity interferes with activating the global representations on the sensorimotor level. When global-relevant tasks successfully activate global representations on the sensorimotor level, people can develop global representations and update self-location globally with the presence of misaligned local structural similarity. The demonstrated interference from misaligned local structural similarity on updating global self-location contributes to our experiences of difficulty in developing and relying on global representations in daily life.

Acknowledgments

This work was supported by NSERC funding provided to Weimin Mou. We thank Subekshya Adhikari, Jarlo Alganion, Aradhna Chawla, Lara Pereira, Mujtaba Siddique and Qingyao Xue for their contribution to data collection.

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Supplementary Materials

1. Results from Orientation Latency

Figure S1 shows the mean orientation latency for each condition in all experiments. None of the global or local sensorimotor alignment effect was significant in any experiment.

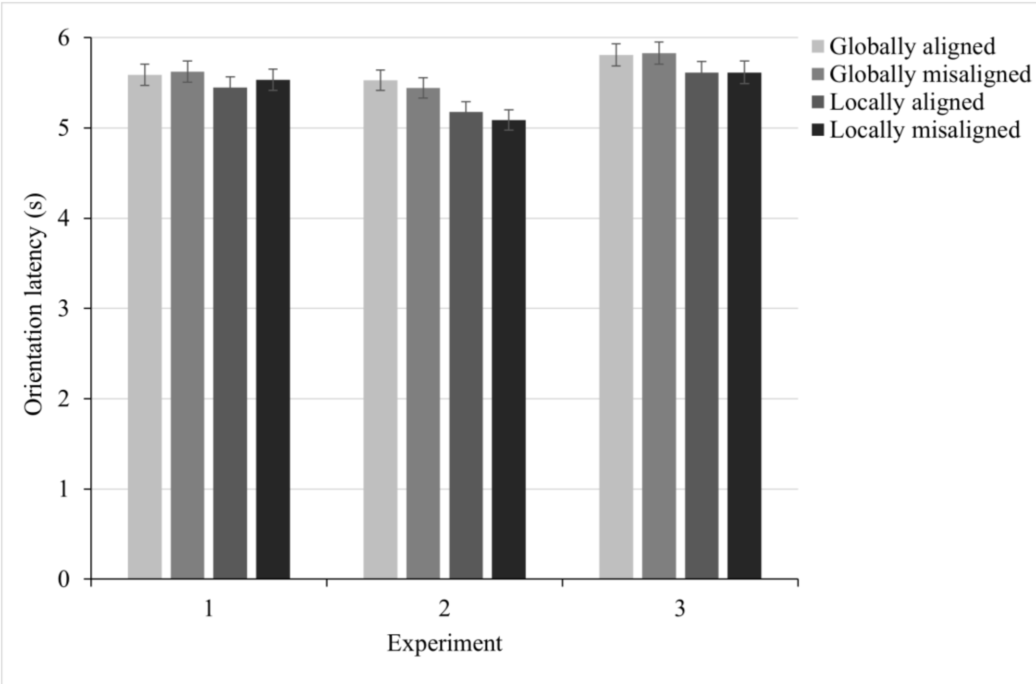


Figure S1. The mean orientation latency for each trial type in all experiments. Error bars represent ±1 SE removing the variance from individual differences.

1.1 Experiment 1

The orientation latencies in the globally aligned condition and the globally misaligned conditions were not significantly different, $t(31) = 0.20$, $p = .846$, Cohen's $d = 0.05$, $BF_{01} = 7.16$, indicating a null global sensorimotor alignment effect. The orientation latencies in the locally aligned condition and the locally misaligned conditions were not significantly different, $t(31) = 0.48$, $p = .637$, Cohen's $d = 0.12$, $BF_{01} = 6.53$, indicating a null local sensorimotor alignment effect.

1.2 Experiment 2

The orientation latencies in the globally aligned condition and the globally misaligned conditions were not significantly different, $t(31) = 0.69$, $p = .494$, Cohen's $d = 0.17$, $BF_{01} = 5.79$, indicating a null global sensorimotor alignment effect. The orientation latencies in the locally aligned condition and the locally misaligned conditions were not significantly different, $t(31) = 0.57$, $p = .570$, Cohen's $d = 0.14$, $BF_{01} = 6.22$, indicating a null local sensorimotor alignment effect.

1.3 Experiment 3

The orientation latencies in the globally aligned condition and the globally misaligned conditions were not significantly different, $t(31) = 0.10$, $p = .920$, Cohen's $d = 0.03$, $BF_{01} = 7.26$, indicating a null global sensorimotor alignment effect. The orientation latencies in the locally aligned condition and the locally misaligned conditions were not significantly different, $t(31) = 0.02$, $p = .988$, Cohen's $d < 0.01$, $BF_{01} = 7.30$, indicating a null local sensorimotor alignment effect.

2. Individual Local and Global Sensorimotor Alignment Effects

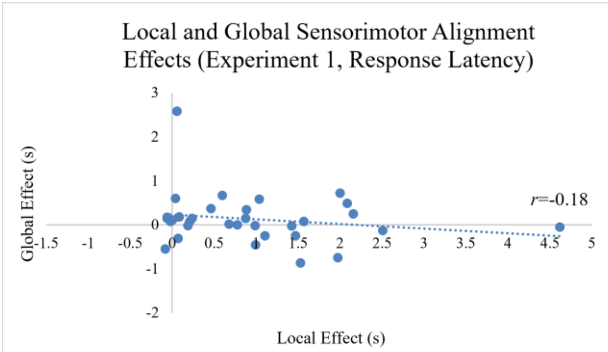
For all experiments of the current study, we plotted individual data patterns of local and global sensorimotor alignment effects in response latency and absolute pointing error (Figure S2). Local/global sensorimotor alignment effects were defined by the measures in locally/globally misaligned conditions subtracting those in locally/globally aligned conditions.

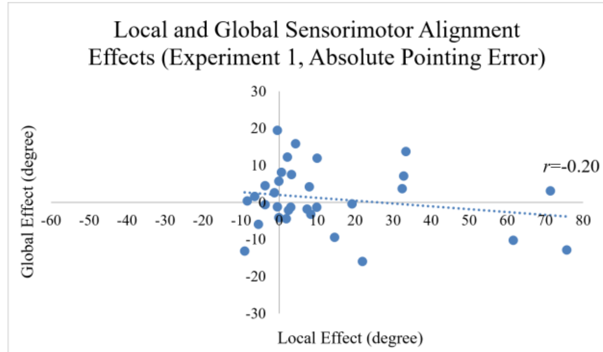
For Experiment 1, local and global sensorimotor alignment effects were not significantly correlated in either response latency or absolute pointing error ($r(30) = -0.18$, $p = .313$; $r(30) = -0.20$, $p = .274$, respectively).

For Experiment 2, local and global sensorimotor alignment effects were not significantly correlated in either response latency or absolute pointing error ($r(30) = -0.08$, $p = .665$; $r(30) = 0.07$, $p = .704$, respectively).

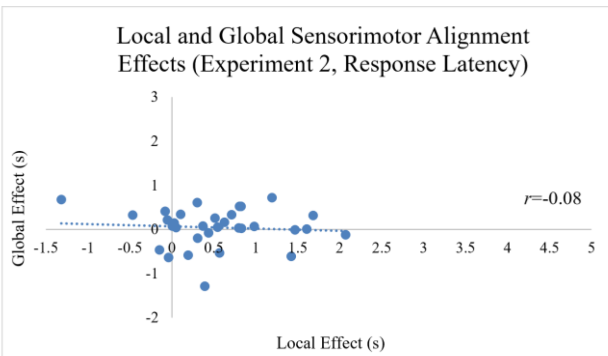
For Experiment 3, in response latency, local and global sensorimotor alignment effects were positively correlated, $r(30) = 0.37$, $p = .036$, suggesting that participants who showed larger local effects tended to exhibit larger global effects (see also Lei, Mou, & Zhang, 2020). In absolute pointing error, local and global sensorimotor alignment effects were not significantly correlated, $r(30) = -0.06$, $p = .742$.

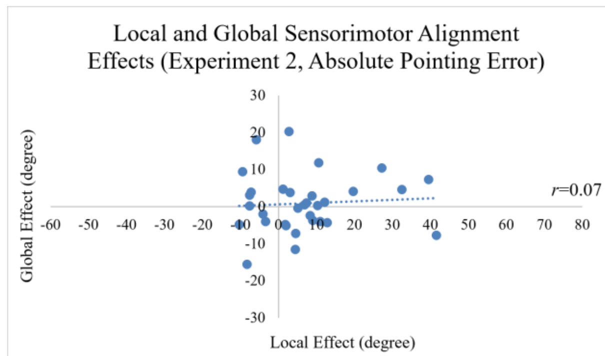
(A) (B)



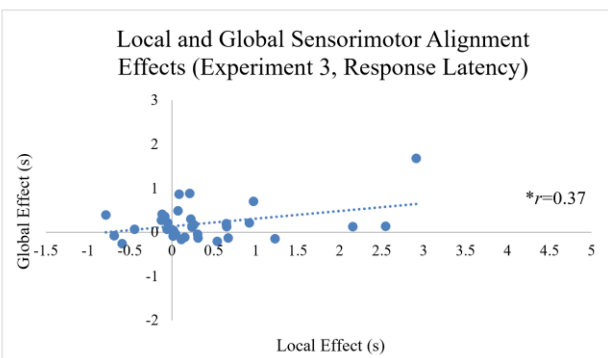


(C) (D)





(E) (F)



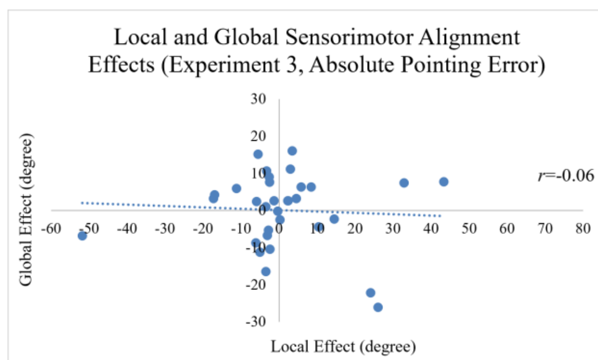
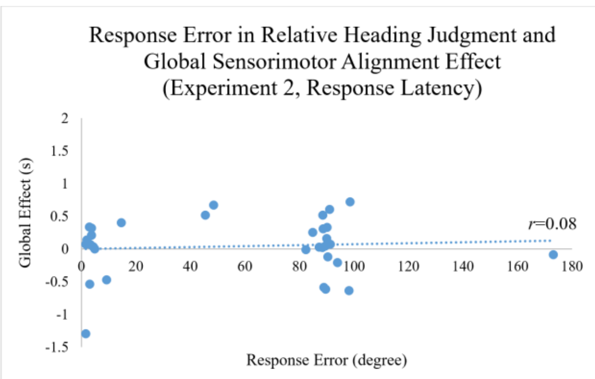


Figure S2. Individual local and global sensorimotor alignment effects in response latency and absolute pointing error of Experiment 1 (A and B), Experiment 2 (C and D), and Experiment 3 (E and F). Local/global sensorimotor alignment effects are calculated by subtracting measures in locally/globally aligned conditions from measures in locally/globally misaligned conditions. Each *dot represents one participant. The dotted line is the linear trendline. Correlation values (i.e., r) are listed (* p<.05).*

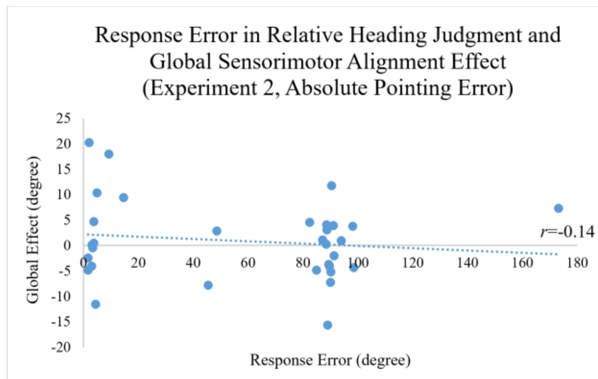
3. Relative Heading Judgment and Global Sensorimotor Alignment Effect

Figure S3 shows the correlation between the response error in the relative heading judgment task (i.e., absolute distance between the response direction and the correct direction of 90°) and the global sensorimotor alignment effects (i.e., response latency/absolute pointing error in globally misaligned conditions minus that in globally aligned conditions) in Experiments 2 and 3. None of the correlation was significant.

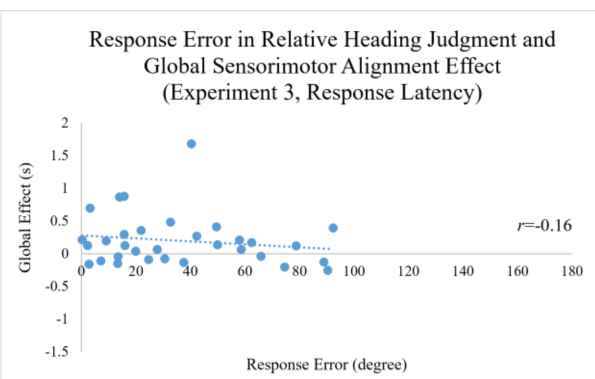
(A)



(B)



(C)



(D)

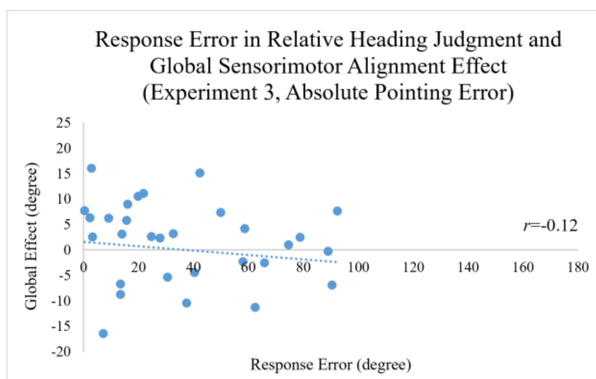


Figure S3. Response error in the relative heading judgment task and the global sensorimotor alignment effect in response latency and absolute pointing error of Experiments 2 (A and B) and 3 (C and D). Response error is the absolute distance between the response direction and the correct direction of 90°, and the global sensorimotor alignment effect is calculated by subtracting measures in globally aligned conditions from measures in globally misaligned conditions. Each dot represents one participant. The dotted line is the linear trendline. Correlation values (i.e., r) are listed.