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The Influence of Environmental Geometry and Spatial Symmetry on Spatial Updating During Locomotion

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This study was not preregistered. Data and experimental materials are available upon reasonable request.

Abstract

Spatial updating based on self-motion cues is important to navigation in the absence of familiar landmarks. Previous studies showed that spatial updating without vision was automatic. The goal of the current study was to investigate whether ambiguous orientations indicated by visual cues affect spatial updating based on self-motion. Participants learned an object array in a rectangular room. After the objects were removed, participants maintained their actual perspective or turned 180° to face opposite walls of the room. Participants judged relative directions from imagined perspectives based on the memories of the object array. The actual and imagined perspectives were aligned or misaligned. Better performance for aligned than misaligned perspectives (sensorimotor alignment effects) was used to indicate spontaneous updating of ones' headings relative to the object array. In Experiment 1, participants turned their bodies in the middle of the room so that their distances to the walls of the room looked similar before and after turning (spatial symmetry at the turning position with the rectangular room shape). In Experiments 2-3, participants turned their bodies in a location so that the distances to the facing walls looked different before and after turning (spatial asymmetry at the turning position with the rectangular room shape). The results showed sensorimotor alignment effects in Experiments 2-3 but not in Experiment 1. These results suggest that updating self-orientation based on self-motion was cancelled by ambiguous orientations indicated by spatial symmetry at the turning position, but not cancelled by ambiguous orientations indicated by the rectangular room shape per se.

Keywords: self-orientation; spatial updating; path integration; piloting; sensorimotor alignment effect

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1. Introduction

In navigation, it is important for animals and humans to update their positions and headings in the environment. In spatial updating, navigators can rely on familiar perceptual cues referred to as piloting (Gallistel, 1990; Gallistel & Matzel, 2013; Loomis et al., 1999) or on self-motion cues, including optic flow, referred to as path integration (Etienne & Jeffery, 2004; Etienne et al., 1998; Loomis et al., 1999).

To examine the pure mechanism of spatial updating using the method of piloting or path integration while locomoting in a room, previous studies intentionally removed the influence of the other method. The role of familiar visual cues (piloting cues) has been studied after participants were disoriented to remove self-motion cues. Consequently, participants regained their orientation using only piloting cues in a room. The findings showed that room geometry/shape is an important cue in reorientation (Cheng, 1986; Cheng & Newcombe, 2005; Hermer & Spelke, 1994, 1996; Ratliff & Newcombe, 2008; Wang & Mou, 2020). In a rectangular room, the room shape can distinguish orientations along the major axis of the room from those along minor axis of the room (e.g., can distinguish north/south from east/west) but cannot distinguish between orientations along the same axis of the room (e.g., cannot distinguish north from south).

Similarly, to examine the pure role of self-motion cues, participants were blindfolded or required to close their eyes after learning objects' locations. Participants judged the relative direction (JRD) of a target location from imagined headings (e.g., imagining standing at object A and facing object B, point to object C). The relationship between the imagined headings and participants' actual heading was manipulated to be aligned or misaligned (e.g., the angular distance was 0º or 180º). In general, the findings showed that JRDs were more accurate when the imagined and actual headings were aligned than when they were misaligned (referred to as sensorimotor alignment effects) (Farrell & Robertson, 1998; Kelly et al., 2007; Klatzky et al., 1998; May, 2004; Mou, Biocca et al., 2004; Rieser 1989; Wang, 2017).

In some studies, participants were explicitly instructed to ignore their body rotation, but the results of whether participants updated their headings were mixed. Farrell and Robertson (1998) still showed sensorimotor alignment effects, indicating that participants could not ignore their body rotation and updated their self-orientation. By contrast, Waller et al. (2002) showed better performance when the imagined headings were aligned with the original learning heading before turning but misaligned with the current actual heading after turning (i.e., reversed sensorimotor alignment effects), indicating that participants could ignore their body rotation and did not show evidence of spatial updating. This discrepancy in the results may be attributed to the items relative to which participants changed their orientation during turning. A 4-point path was used in Waller et al. (2002) whereas a layout of multiple objects was used in Farrell and Robertson (1998). It might be easier to maintain an image of a simple path, compared with an object array, stabilized with their body during body rotation.

Nevertheless, the results from Waller et al. (2002) suggest that people may have an enduring representation of the learning orientation in addition to a transient representation of self-orientation that is updated momentarily from self-motion. With the instructions to ignore body rotation, the participants might have relied on the enduring representation instead of the transient representation, either by not using, or ignoring, an (automatically) updated transient representation or by suppressing updating of the transient representation (Waller et al., 2002, p.1062). The existence of an enduring representation of the learning orientation was further indicated by the findings that participants, while standing in a room different from the learning room, could be instructed to visualize the memorized objects from the original learning orientation and then they could update from this retrieved orientation in their further rotation (Avraamides, Galati, & Papadopoulou, 2013; see also Kelly et al., 2007; May, 2004; Shelton & Marchette, 2010). In addition, Waller et al. (2002) also showed that participants could be instructed to update their self-orientation during turning. Therefore, the findings in the literature indicate that while participants without instructions only used the updated representation of their actual heading to determine their self-orientation, participants with instructions could use either the enduring representation of the learning orientation or the updated representation of their actual heading to determine their self-orientation. As spatial updating may differ with and without instructions, we refer to spatial updating without instructions as *spontaneous spatial updating*, in contrast to the *instructed spatial updating*.

Although the exclusive roles of piloting and self-motion cues are well documented, few studies examined whether piloting cues in a room affect updating self-orientation by self-motion. Kelly et al. (2008) showed that when participants were explicitly asked to keep track of the target location during locomotion, room shape could facilitate their updating of the target location based on self-motion. Participants walked an unpredictable path defined by multiple waypoints and were asked to indicate the path origin after walking in a room with different levels of rotational symmetry (e.g., a rectangular room with two levels, a square room with four levels, or a circular room with infinite levels). Performance was worst in a circular room but equally good in rooms with fewer levels of rotational symmetry. Although a rectangular shape cannot distinguish the orientations along the same axis of the room (e.g., Hermer & Spelke, 1994, 1996), it still can remove the cumulative errors in updating self-orientation by self-motion, provided that the cumulative errors are smaller than 180º. However, as Kelly et al. (2008) examined *instructed spatial updating*, it is still not clear to what extent piloting cues in a room affect updating self-orientation by self-motion in *spontaneous spatial updating*. The current study aimed to tackle this issue.

In particular, after learning an object array in a rectangular room, participants turned their bodies 180° to face the wall originally behind them. We investigated whether the two ambiguous orientations indicated by the rectangular room, after participants turned to face the opposite direction of the same axis of the rectangular room (e.g., turned from facing north to facing south), could *cancel* *spontaneous spatial updating* of self-orientation from self-motion. We refer to '*cancel spontaneous spatial updating'* as the result of using the enduring representation of the learning orientation instead of the updated representation of their actual heading from self-motion whether spatial updating was ignored or suppressed. We proposed and tested three competing hypotheses.

The first hypothesis claims that *spontaneous spatial updating* from self-motion is not affected by ambiguous orientations indicated by a rectangular room shape. It was widely reported that *spontaneous spatial updating* was automatic when only self-motion cues were available (Farrell & Robertson, 1998; Rieser, 1989). Furthermore, when both piloting and self-motion cues are available, some theories stipulate that self-motion may be a fundamental cue in spatial updating. Self-motion can set a universal metric to produce a spatial framework that incorporates visual landmarks (Savelli & Knierim, 2019). When piloting cues are unreliable, self-motion may function as a backup system to detect large shifts of visual landmarks and update self-orientation (Chen et al., 2017; Cheng et al., 2007). Thus, after participants turned to face the opposite direction of the same axis of a rectangular room, ambiguous orientations indicated by the rectangular room shape would not *cancel spontaneous spatial updating* of self-orientation from self-motion. We refer to this hypothesis as *spontaneous-spatial-updating hypothesis.*

The second hypothesis claims that *spontaneous spatial updating* from self-motion is *cancelled* by ambiguous orientations indicated by the rectangular room shape. Although *spontaneous spatial updating* was automatic when only self-motion cues were available (Farrell & Robertson, 1998; Rieser, 1989), it may not be the case when there are piloting cues. Moreover, some theories suggest that piloting cues may be dominant in navigation. Piloting cues can fine-tune, correct and reset path integration (Arthur et al., 2007; Etienne et al., 2004; Jayakumar et al., 2019; Kelly et al., 2008). Studies on cue combination have shown that people weigh piloting cues over self-motion cues in homing when the two cues predict discrepant spatial estimates (Zhang & Mou, 2017; Zhao & Warren, 2015). In addition, studies on across-boundary navigation have shown that when people move between rooms with similar piloting cues, they primarily rely on piloting cues rather than self-motion to update headings (Lei et al., 2020; Marchette et al., 2017; Marchette et al., 2014). Thus, after participants turned to face the opposite direction of the same axis of a rectangular room, ambiguous orientations indicated by the rectangular room shape would *cancel spontaneous spatial updating* of self-orientation from self-motion. We refer to this hypothesis as *cancelled-by-room-shape hypothesis.*

The third hypothesis claims that *spontaneous spatial updating* from self-motion is *cancelled* by ambiguous orientations indicated by spatial symmetry of the turning location instead of the rectangular room shape per se. In addition to the rectangular room shape, other geometric information, including visual distances to individual walls, can also determine spatial symmetry of the turning location. Suppose participants stand at a location that is 1 m to the north wall and 5 m to the south wall and turn from facing north to facing south. Although the rectangular room shape per se cannot distinguish north from south, the change in the perceived distances to the facing walls can disrupt spatial symmetry and distinguish north from south. Because the participants know that their locations are not changed before and after turning, the perceived distance to the facing wall (e.g., 5 m to the facing wall) should be sufficient to indicate which wall they are facing (e.g., the south wall), removing the ambiguity of orientations indicated by the rectangular room shape. By contrast, if the turning location is 3 m to both the north and the south walls, then the perceived distance to the facing wall is similar before and after turning, leading to ambiguity of self-orientation. Ambiguous orientations indicated by the spatial symmetry of the turning location would *cancel spontaneous spatial updating* of self-orientation from self-motion. We refer to this hypothesis as *cancelled-by-spatial-symmetry hypothesis.*

To examine spatial updating, we could ask participants to indicate a target location after walking a path as in Kelly et al. (2008). However, the task of direct pointing in their study is more appropriate to test *instructed spatial updating* rather than *spontaneous spatial updating*. The task of direct pointing usually requires many trials, and, in each trial, participants walk a path and then point to a target location. Thus, even without explicit instructions, participants might know that they need to keep track of the target locations, similar to *instructed spatial updating*. Instead of using the task of direct pointing, the current study tested sensorimotor alignment effects in a JRD task, which is widely used to test *spontaneous spatial updating* (e.g., Kelly et al., 2007; May, 2007; Mou, Biocca et al., 2004; Riecke & McNamara, 2017; Rieser, 1989; Waller et al., 2002). Specifically, after learning an object array, the objects were removed, and the participants maintained their actual perspective or turned 180°. They then conducted JRDs based on the memory of the objects' locations. The imagined perspectives were aligned or misaligned (i.e., same or opposite) with their actual perspectives. Because the JRD task can be accomplished only based on mental perspective-taking and does not require spatial updating relative to the actual space, the sensorimotor alignment effect should be attributed to *spontaneous spatial updating* from self-motion. In contrast, no evidence of the sensorimotor alignment effect would indicate that *spontaneous spatial updating* from self-motion was *cancelled* by piloting cues.

It is important to note that in the literature, there are two ways to examine sensorimotor alignment effects (i.e., to manipulate the distance between actual and imagined perspectives). In the first approach (see Table 1A), participants' actual perspective is fixed (e.g., actually facing south) and their imagined perspectives are manipulated (e.g., imagining facing north or south). In the second approach (see Table 1B), participants' imagined perspective is fixed (e.g., imagining facing south) and their actual perspectives are manipulated (e.g., actually facing north or south).

Table 1

Two ways to manipulate the distance between actual and imagined perspectives in sensorimotor alignment effects.

(A) Fix actual perspectives and manipulate imagined perspectives.

Actual-Imagined (A-I)	Actual perspective	
	North	South
0º	Imagined North	Imagined South
180º	Imagined South	Imagined North

(B) Fix imagined perspectives and manipulate actual perspectives.

Actual-Imagined (A-I)	Imagined perspective	
	North	South
0º	Actual North	Actual South
180º	Actual South	Actual North

Using the first approach, researchers are primarily interested in participants' actual perspective that is different from the learning orientation (e.g., the learning orientation is facing north and participants turn to actually face south for testing). The result of sensorimotor alignment effects (e.g., for actually facing south, better performances for imagining facing south than imagining facing north) suggests that participants update their self-orientation during rotation. This method is typically used for studying how participants update self-orientation relative to a simple path on the floor (e.g., Presson & Hazelrigg, 1984; Waller et al., 2002). However, the result of null or even reversed sensorimotor alignment effects (e.g., for actually facing south, better performances in imagining facing north than imagining facing south) is difficult to interpret when there is a learning orientation effect (e.g., because the learning orientation is north, imagining facing north is easier than imagining facing south, independent of actual perspectives), especially in retrieving memories of an object array instead of a path (e.g., Roskos-Ewoldsen et al., 1998; Shelton & McNamara, 1997, 2001). To separate the sensorimotor alignment effects solely attributed to spatial updating from the learning orientation effect, a neutral imagined perspective is required as a baseline (e.g., imagining facing east) (Avraamides et al., 2013; Kelly et al., 2007). Compared to the baseline imagined perspective, better performances in the imagined perspective aligned with the actual perspective (e.g., imagining facing south is better than imagining facing east) could be used to determine the sensorimotor alignment effects solely attributed to spatial updating. Compared to the baseline imagined perspective, better performances in the imagined perspective same as the learning orientation (e.g., imagining facing north is better than imagining facing east) could be used to determine the learning orientation effect.

In the second approach, because the imagined perspective is fixed, the influence from the learning orientation effect is removed when we contrast the performances of the same imagined perspective at two actual perspectives (e.g., in Table 1B, performances in imagining facing south when actually facing south vs. when actually facing north). Thus, the sensorimotor alignment effect reflects the pure influence from spatial updating. If participants update self-orientation when turning from facing north to facing south, then there will be sensorimotor alignment effects (e.g., imagining facing south is easier when actually facing south than when actually facing north); whereas if participants do not update self-orientation when turning from facing north to facing south, then there will be no sensorimotor alignment effects (e.g., imagining facing south is comparable for the two actual perspectives as in both cases participants think they are actually facing north). Importantly, even when participants do not update their self-orientation when turning from facing north to facing south, we should not expect reversed sensorimotor alignment effects (e.g., there is no reason to expect that imagining facing south is easier when actually facing north than when actually facing south because participants think they are actually facing the same direction before and after turning). Since the sensorimotor alignment effects solely attributed to spatial updating are already separated from the learning orientation effect, there is no requirement of a neutral imagined perspective as a baseline to test the sensorimotor alignment effects as well as the learning orientation effect. Mou, McNamara et al. (2004; see also Du et al., 2021; Riecke & McNamara, 2017) used this method and demonstrated both sensorimotor alignment effects and learning orientation effects independently. Mou et al. (2008; see also Mou, Biocca et al., 2004) also used this method and demonstrated only the learning orientation effect but no sensorimotor alignment effects when participants believed that the object array was stabilized relative to their bodies when they turned. The current study primarily used this second approach to examine sensorimotor alignment effects separately from the learning orientation effect.

Note that although the above two approaches are different in examining sensorimotor alignment effects by fixing actual perspectives or fixing imagined perspectives, they share the same four conditions (combination of actual perspectives of facing north or south and imagined perspectives of facing north or south). Consequently, these two approaches are equivalent according to a two-way ANOVA except that they trade main effects and interactions. For example, if the first approach uses the variable A-I (Actual-Imagined, which is the angular distance between actual and imagined perspectives) as the second independent variable in addition to the variable of actual perspective (see Table 1A), then the interaction between actual perspective and A-I is equivalent to the main effect of L-I (Learning-Imagined, which is the angular distance between the learning orientation and imagined perspectives) in the second approach (i.e., the learning orientation effect). If the first approach uses the variable L-I as the second independent variable in addition to the variable of actual perspective, then the interaction between actual perspective and L-I is equivalent to the main effect of A-I in the second approach (i.e., the sensorimotor alignment effect). The current study presented results using the second approach in the main text (using L-I and A-I as independent variables) but included results using the first approach in supplementary materials to show equivalence in the results from the two approaches.

Experiment 1 was designed to differentiate the *spontaneous-spatial-updating* hypothesis from the other two hypotheses. Participants in Experiment 1 turned at the center of a rectangular room so that the perceived distances to the facing walls before and after turning were the same. Such spatial symmetry could not remove the ambiguity of orientations indicated by the rectangular room shape. The *spontaneous-spatial-updating* hypothesis would predict a sensorimotor alignment effect, whereas both *cancelled-by-room-shape* and *cancelled-by-spatial-symmetry* hypotheses would predict a null sensorimotor alignment effect. Experiments 2 and 3 were designed to differentiate the *cancelled-by-room-shape* hypothesis from the *cancelled-by-spatial-symmetry* hypothesis. Participants turned at a location different from the center of the room so that the perceived distances to the facing walls changed before and after turning, leading to spatial asymmetry. Such spatial asymmetry could remove the ambiguity of orientations indicated by the rectangular room shape. Consequently, the *cancelled-by-spatial-symmetry* hypothesis would predict a sensorimotor alignment effect whereas the *cancelled-by-room-shape* hypothesis would predict a null sensorimotor alignment effect.

2. Experiment 1

The purpose of Experiment 1 was to differentiate the *spontaneous-spatial-updating* hypothesis from the other two hypotheses. Participants turned their bodies in the middle of a rectangular room after learning an object array. Participants' self-orientation indicated by the spatial symmetry of the turning location and the rectangular room shape was similar before and after physical turning. They conducted JRDs from both actual perspectives of the original learning orientation and the opposite orientation. If the results showed sensorimotor alignment effects, this would support the *spontaneous-spatial-updating* hypothesis; however, if the results showed null sensorimotor alignment effects, this would support both *cancelled-by-room-shape* and *cancelled-by-spatial-symmetry* hypotheses.

2.1 Method

2.1.1 Participants

Twenty university students (10 female; age: *M*=19.10 years, *SD*=1.52, range=18-23) participated in return for credits in an introductory psychology course. All participants had normal or corrected-to-normal vision. The study was approved by the Ethics Committee of the University of Alberta.

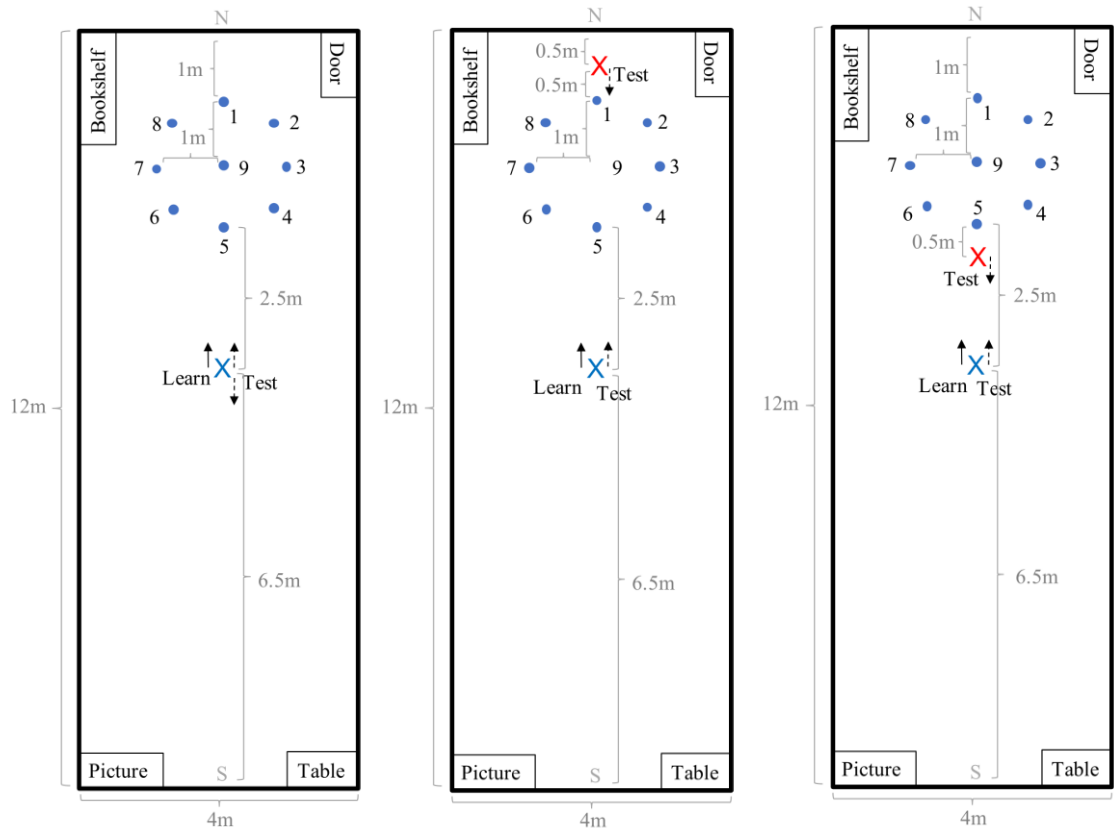
Assuming the partial eta squared (η_p^2) is 0.48 (the observed effect size of the sensorimotor alignment effect in Experiment 1 of Kelly et al., 2007), using 20 participants produced the power value to be 0.98 at the alpha level of .05 to detect a significant main effect of sensorimotor alignment in a 2×2 repeated-measures ANOVA (see the Matlab code for the power analysis at https://doi.org/10.7939/r3-aqm4-3p16, Lei & Mou, 2021).

2.1.2 Materials and Design

The lab experimental room was a square room (4 m by 4 m). The immersive virtual environment was rendered by Vizard software (WorldViz, Inc., Santa Barbara, CA) and presented in a head-mounted display (HMD, Oculus Rift, Oculus VR, LLC., Irvine, CA). The participants' head motions were tracked by an InterSense IS-900 motion tracking system (InterSense, Inc., Massachusetts). The participants physically turned to change their viewing directions, but they used a gamepad controller to translate and the direction of their translation followed their current viewing direction. During learning, the participants replaced objects by controlling a virtual stick associated with a pointing device (an InterSense Wand). During testing, the participants conducted the JRD task using a joystick (Logitech Extreme 3D Pro, Newark, CA).

The virtual room was 4 m by 12 m (Figure 1A), with four walls in the same color and texture. The four corners had distinct room furniture (i.e., a bookshelf, a door, a picture, and a table). North in Figure 1 was arbitrarily defined to indicate the participants' learning orientation. The center of the lab experimental room overlapped with the virtual room at the location that was on the midline of the virtual room and was 8 m from the north wall. During learning, there were nine virtual objects presented on the ground (the dots with numbers in Figure 1A), which formed a circular array (radius=1 m) with one object at the center and the other objects equally distant on the circle. For the learning viewpoint, the learning location was close to the room center (5.5 m from the north wall and 6.5 m from the south wall, indicated by the blue cross in Figure 1A) and the learning direction was facing north (the solid arrow in Figure 1A). During testing, the objects were not presented. There were two actual testing perspectives, facing north and south, although the testing location was at the learning location (the dashed arrows in Figure 1A) (see Figure S2 in supplementary materials for example first-person perspectives in Experiments 1 and 1b). Since the testing location had similar distances to the north and south walls, physical turning at the testing location between the two actual perspectives would lead to similar perceived distances to the walls of the room (i.e., similar distances to the facing walls, which were 5.5 m to the north wall and 6.5 m to the south wall leading to the north-south distance ratio of 0.846, and same distances to the side walls, which were 2 m).

(A) Experiments 1 and 1b **(B) Experiment 2** **(C) Experiment 2b**



(D) Experiment 3

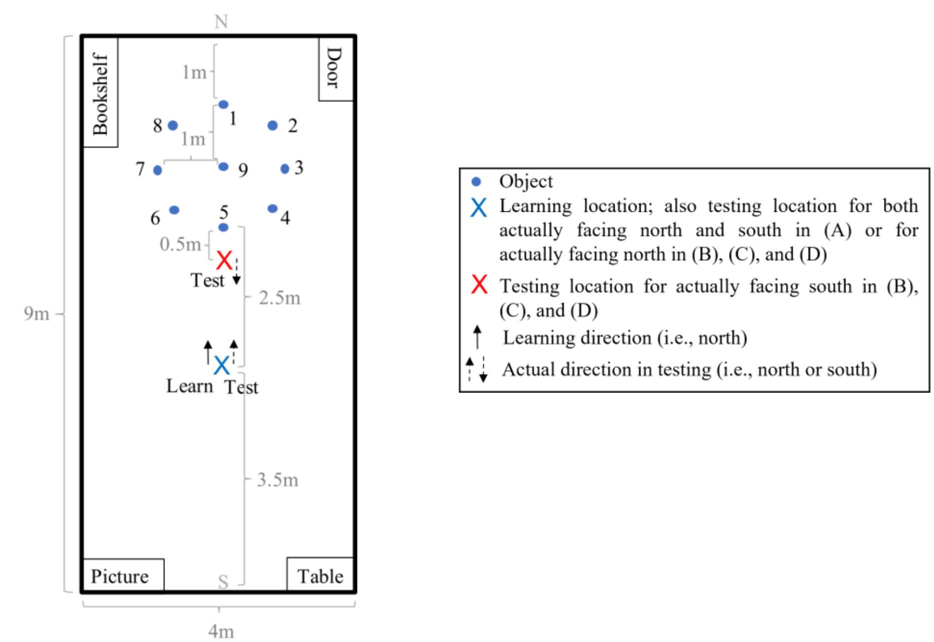


Figure 1. Schematic experimental setup in Experiments 1 and 1b (A), 2 (B), 2b (C), and 3 (D).

In each JRD trial, the participants, while facing an actual perspective, mentally adopted an imagined perspective defined by the remembered objects and pointed to a target object from the imagined perspective (e.g., imagine standing at 6 and facing 8, point to 7, see Figure 1A). Both actual and imagined perspectives included facing north and south. There were two blocks in the JRD task, with each of the two actual perspectives tested in blocks. The order of the two blocks was counterbalanced across the participants. In each block, there were 32 trials in a random order, half of which had imagined perspectives to be facing north and the other half to be facing south (see trials in Table 2). The dependent measures were absolute angular error and response latency in pointing responses.

Table 2

The standing, facing, and target objects used in imagined perspectives of north and south. Numbers refer to Figure 1.

Imagined perspective	Standing object	Facing object	Target object
North	9	1	2; 3; 4; 6; 7; 8
	5	9	2; 4; 6; 8
	6	8	1; 5; 7
	4	2	1; 3; 5
South	9	5	2; 3; 4; 6; 7; 8
	1	9	2; 4; 6; 8
	2	4	1; 3; 5
	8	6	1; 5; 7

This experiment used a within-subject design (see Table 3) and the conditions were defined in terms of two independent variables following previous studies (Du et al., 2021; Mou, Biocca et al., 2004; Mou, McNamara et al., 2004; Riecke & McNamara, 2017) to separate the sensorimotor alignment effect solely attributed to spatial updating from the learning orientation effect (Table 1B). One independent variable was the angular distance between the actual and imagined perspectives in the JRD task (i.e., Actual-Imagined or A-I) and was manipulated to be 0º or 180º (i.e., the actual and imagined perspectives were aligned or misaligned). The other independent variable was the angular distance between the learning orientation and the imagined perspectives (i.e., Learning-Imagined or L-I), with the values being 0º or 180º. A main effect of A-I would indicate the sensorimotor alignment effect, which was the main focus of the current study. A main effect of L-I would indicate the learning orientation effect.

Table 3

Imagined and actual perspectives in four different conditions in the JRD task. North indicates the learning orientation.

Actual-Imagined (A-I)	Learning-Imagined (L-I)	
	0º	180º
0º	Actual North, Imagined North	Actual South, Imagined South
180º	Actual South, Imagined North	Actual North, Imagined South

2.1.3 Procedure

Before the experiment, the participants signed consent forms, read experimental instructions, and practiced using a joystick to point accurately. Then, the blindfolded participants were led to the center of the real lab experimental room and seated in a swivel chair. They were instructed to keep their eyes closed, remove the blindfold and put on the HMD.

In the virtual environment, participants' initial standing location was 8 m from the north wall (i.e., the center of the lab experimental room) and their initial facing direction was facing the north wall. They were asked to look around the room and recognize the four items of furniture in the room corners. Then a blue platform appeared at the learning location (the blue cross in Figure 1A) and the participants used the gamepad to move onto the platform. They were asked to look around the room for the furniture again from the learning location to ensure they were familiar with the room. After that, the layout of nine objects was presented (Figure 1A). The participants named the objects with the help of an experimenter. Then they had 3 min to learn the locations of the objects. They were required to remain at the learning location but could turn their heads. After 3 min, the objects were removed. A probed object with its name was shown on the HMD, and the participants used a wand to replace the object. The object was presented at both the replaced and the original locations as feedback. There were three blocks to replace the objects. In each block, each object was probed once in a random order. After this, the objects were presented at the original locations and were not removed until the participants reported that they had good memories of the objects' locations.

In the testing phase, the participants conducted the JRD task using a joystick. Each of the two actual perspectives (i.e., actually facing north or south) was tested in blocks. In the north-facing block, the participants while standing at the learning platform were asked to face the north wall ("please face the wall with the bookshelf and the door"). In the south-facing block, the participants while standing at the learning platform were asked to face the south wall. In each JRD trial, the imagined perspective was presented in text at the center of the HMD (e.g., "standing at the lock, facing the candle"). The participants were required to maintain their actual facing direction (i.e., remaining at the testing location and not being allowed to turn their heads) and mentally adopt the imagined perspective. The participants clicked the trigger on the joystick once they had adopted the imagined perspective. The duration between presentation of the instruction for the imagined perspective and the trigger click was recorded as the orientation latency. After the participants clicked the trigger, the instruction establishing the imagined perspective was removed and the target object was presented in text (e.g., "point to the phone"). The participants were required to point with the joystick as fast as possible without sacrificing accuracy. The duration between presentation of the target object and the pointing response was recorded as the response latency. The pointing direction was recorded to calculate the absolute angular error. After the pointing response, the second sentence was removed, and the next trial started in 750 ms.

2.2 Data analysis

The mean orientation latency, mean response latency, and mean absolute angular error were calculated in each condition. 2×2 repeated-measures ANOVAs (A-I [0º, 180º], L-I [0º, 180º]) were conducted in these measures using IBM SPSS 26. For null effects, Bayes factors (BF_{01}) favouring the null effect over the alternative were also calculated in Bayesian Repeated Measures ANOVA using JASP (JASP Team, 2022) to quantify the null effects[1]. We interpreted a BF_{01} larger than 3 as favouring the null, a BF_{01} smaller than 1/3 as favouring the alternative, and a BF_{01} between 1/3 and 3 as favouring neither hypothesis (Rouder et al., 2009). In all experiments of the current study, the results from orientation latency were not significant (see Figure S1 in supplementary materials). The results from response latency and absolute angular error were reported for brevity.

[1] BF_{01} of a null effect is the Bayes factor favouring models excluding the effect over models including the effect from JASP using default priors.

2.3 Results

Response latency and absolute angular error as a function of A-I and L-I were plotted in Figures 2 and 3.

In response latency, the main effect of A-I was not significant, $F(1, 19) = 0.98$, $p = .336$, $\eta_p^2 = .049$, $BF_{01} = 3.015$, indicating a null sensorimotor alignment effect. The main effect of L-I was significant, $F(1, 19) = 51.70$, $p < .001$, $\eta_p^2 = .731$, showing a learning orientation effect. The interaction was not significant, $F(1, 19) = 1.23$, $p = .280$, $\eta_p^2 = .061$, $BF_{01} = 2.018$.

In absolute angular error, the main effect of A-I was not significant, $F(1, 19) = 0.04$, $p = .852$, $\eta_p^2 = .002$, $BF_{01} = 5.668$, demonstrating a null sensorimotor alignment effect. The main effect of L-I was significant, $F(1, 19) = 6.61$, $p = .019$, $\eta_p^2 = .258$, showing a learning orientation effect. The interaction was not significant, $F(1, 19) = 0.08$, $p = .780$, $\eta_p^2 = .004$, $BF_{01} = 4.876$.

These results showed null sensorimotor alignment effects. There was no speed-accuracy trade-off (i.e., no negative correlation between response latency and absolute pointing error in A-I =0 and A-I=180). The response latency and the absolute angular error across participants and A-I conditions (i.e., 20 participants and two A-I conditions leading to 40 pairs of latency and error) were positively correlated, $r(38)=.42$, $p=.007$. The individual data patterns in sensorimotor alignment effects (individual data of response latency and absolute angular error in conditions of A-I=0 and A-I=180) were also plotted in Figures S6 and S7 in supplementary materials.

As mentioned in the Introduction, we designed the experiments following the approach summarized in Table 1B to examine sensorimotor alignment effects solely attributed to spatial updating. For readers' interests, we also tested sensorimotor alignment effects in all experiments using the approach summarized in Table 1A and the results can be found in supplementary materials.

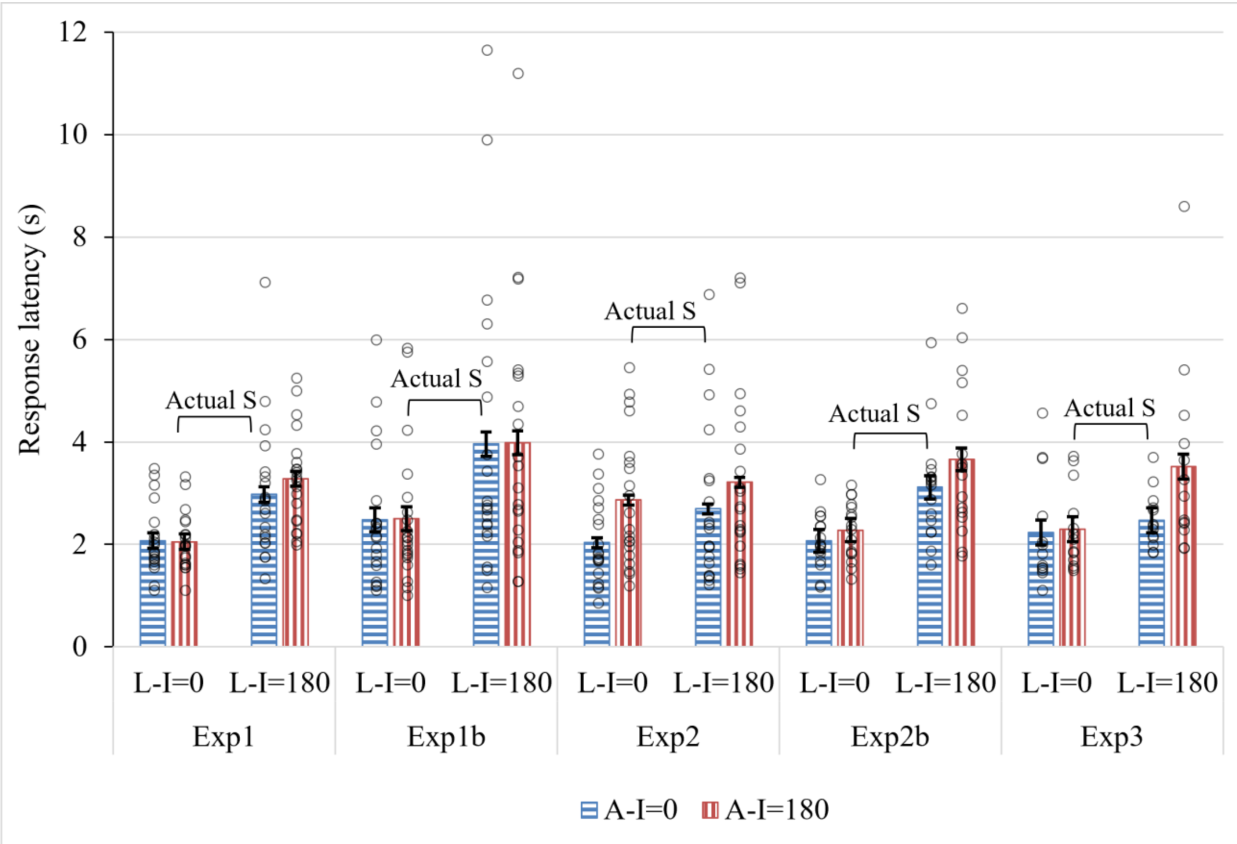


Figure 2. The mean response latency in different conditions in all experiments. Error bars represent ±1 SE (removing the variance from individual differences)[2]. The open dots are individual data points in each condition. Actual S indicates the conditions for the actual perspective of facing south.

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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 and *N* was the number of subjects contributing to the means (Lei & Mou, 2021).

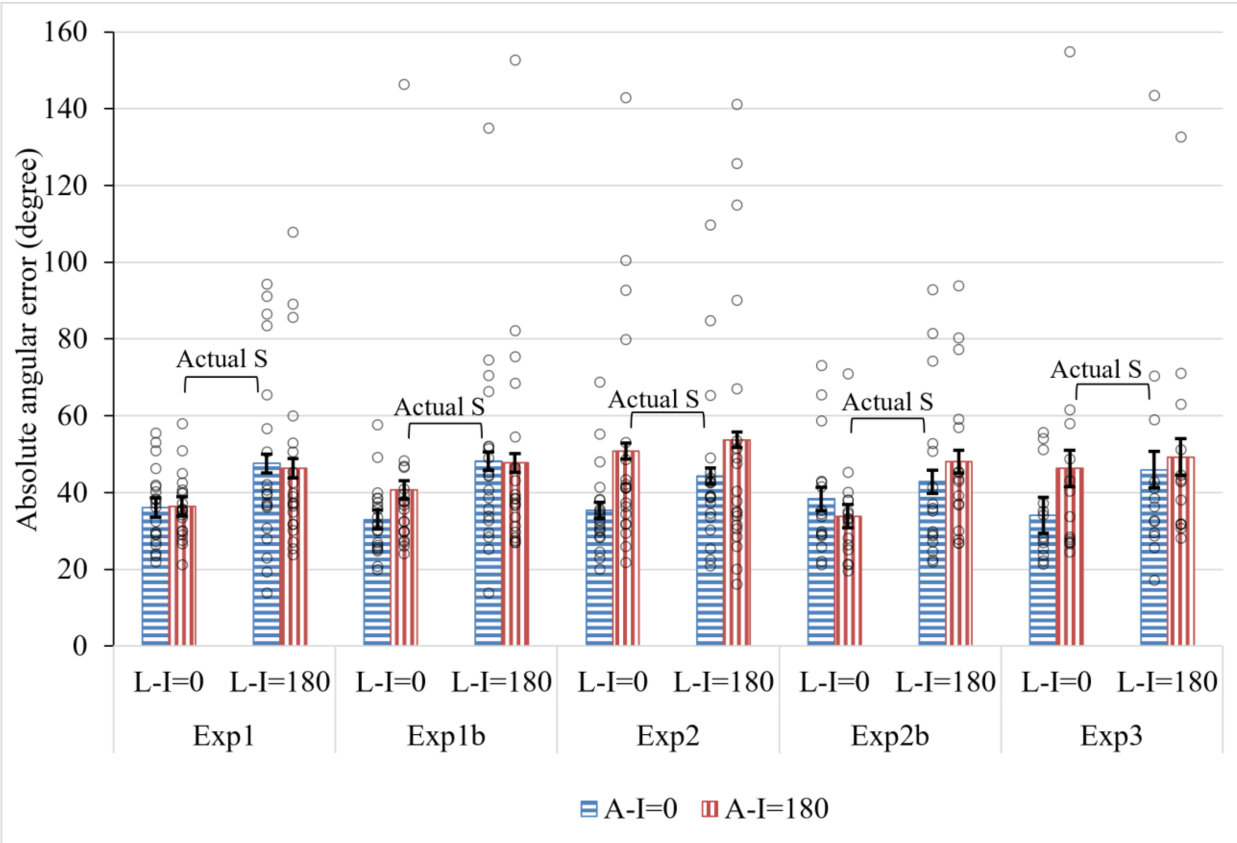

Figure 3. The mean absolute angular error in different conditions in all experiments. Error bars represent ±1 SE (removing the variance from individual differences). The open dots are individual data points in each condition. Actual S indicates the conditions for the actual perspective of facing south.

2.4 Experiment 1b

To ensure that the result of null sensorimotor alignment effects in Experiment 1 was replicable, we conducted the same experiment again in Experiment 1b with another twenty participants (10 female; age: *M*=19.25 years, *SD*=1.25, range=18-23).

In response latency, the main effect of A-I was not significant, $F(1, 19) = 0.02$, $p = .891$, $\eta_p^2 = .001$, $BF_{01} = 5.044$, indicating a null sensorimotor alignment effect. The main effect of L-I was significant, $F(1, 19) = 23.43$, $p < .001$, $\eta_p^2 = .552$, showing a learning orientation effect. The interaction was not significant, $F(1, 19) < 0.01$, $p = .986$, $\eta_p^2 < .001$, $BF_{01} = 4.289$.

In absolute angular error, the main effect of A-I was not significant, $F(1, 19) = 0.32$, $p = .581$, $\eta_p^2 = .016$, $BF_{01} = 3.794$, demonstrating a null sensorimotor alignment effect. The main effect of L-I was significant, $F(1, 19) = 6.74$, $p = .018$, $\eta_p^2 = .262$, showing a learning orientation effect. The interaction was not significant, $F(1, 19) = 2.87$, $p = .107$, $\eta_p^2 = .131$, $BF_{01} = 3.336$.

These results replicated the null sensorimotor alignment effects in Experiment 1. There was no speed-accuracy trade-off. The response latency and the absolute angular error were not significantly correlated, $r(38)=-.24$, $p=.140$.

2.5 Discussion

Experiments 1 and 1b demonstrated null sensorimotor alignment effects, supporting the *cancelled-by-room-shape* and *cancelled-by-spatial-symmetry* hypotheses over the *spontaneous-spatial-updating* hypothesis. The spatial symmetry of the turning location and the rectangular room shape both indicate similar self-orientation before and after physical turning. Thus, it is not clear whether *spontaneous spatial updating* was *cancelled* by the spatial symmetry of the turning location or the rectangular room shape. Experiments 2-3 further examined the boundary conditions in which *spontaneous spatial updating* was *cancelled*, differentiating the *cancelled-by-room-shape* hypothesis from the *cancelled-by-spatial-symmetry* hypothesis.

3. Experiment 2

Experiment 2 was designed to investigate whether the rectangular room shape but spatial asymmetry of the turning location could still *cancel spontaneous spatial updating*. Participants turned their bodies in locations other than the middle of the room. As distances to the facing walls changed before and after turning bodies, it introduced spatial asymmetry of the turning position.

If a sensorimotor alignment effect appeared, then it would suggest that *spontaneous spatial updating* was *cancelled* by the spatial symmetry of the turning location in Experiment 1, supporting the *cancelled-by-spatial-symmetry* hypothesis. If a null sensorimotor alignment effect still appeared as in Experiments 1 and 1b, then it would suggest that *spontaneous spatial updating* was *cancelled* by the rectangular room shape alone, supporting the *cancelled-by-room-shape* hypothesis.

3.1 Method

3.1.1 Participants

Twenty university students (10 female; age: *M*=20.80 years, *SD*=3.79, range=18-30) with normal or corrected-to-normal vision participated in return for credits in an introductory psychology course.

3.1.2 Materials, Design and Procedure

The materials, design and procedure were the same as in Experiment 1, except for the following changes. In Experiment 2, for the actual perspective of facing south, the testing location was changed to be 0.5 m from the north wall (the red cross in Figure 1B). Since this testing location was much more distant from the south wall than the north wall (0.5 m to the north wall and 11.5 m to the south wall leading to the north-south distance ratio of 0.043), this manipulation ensured that participants perceived a different distance to the facing wall after physical turning 180° at this testing location (see Figure S3 in supplementary materials for example first-person perspectives in Experiment 2).

During testing, in the block of actually facing north, the participants were on the blue platform (the learning platform, the blue cross in Figure 1B) and faced north. In the block of actually facing south, the participants were on the red platform (the red cross in Figure 1B) and faced south. The red platform disappeared after the participants positioned themselves on it, whereas the blue platform was presented throughout the testing phase. Between the two blocks, the participants used a gamepad to move onto the platforms but physically turned to face north or south.

3.3 Results

2×2 repeated-measures ANOVAs (A-I [0º, 180º], L-I [0º, 180º]) were conducted in response latency and absolute angular error.

In response latency (Figure 2), the main effect of A-I was significant, $F(1, 19) = 15.37$, $p = .001$, $\eta_p^2 = .447$, indicating a sensorimotor alignment effect. The main effect of L-I was also significant, $F(1, 19) = 6.78$, $p = .017$, $\eta_p^2 = .263$, showing a learning orientation effect. The interaction was not significant, $F(1, 19) = 2.54$, $p = .128$, $\eta_p^2 = .118$, $BF_{01} = 0.615$.

In absolute angular error (Figure 3), the main effect of A-I was significant, $F(1, 19) = 4.61$, $p = .045$, $\eta_p^2 = .195$, demonstrating a sensorimotor alignment effect. The main effect of L-I was not significant, $F(1, 19) = 1.54$, $p = .229$, $\eta_p^2 = .075$, $BF_{01} = 2.376$. The interaction was not significant, $F(1, 19) = 2.08$, $p = .166$, $\eta_p^2 = .099$, $BF_{01} = 2.334$.

These results demonstrated the sensorimotor alignment effects. There was no speed-accuracy trade-off. The response latency and the absolute angular error were positively correlated, $r(38)=.40$, $p=.012$.

3.4 Discussion

Experiment 2 showed sensorimotor alignment effects in the JRD task, which differed from the findings in Experiments 1 and 1b but replicated the previous findings that people update self-orientation relative to objects within the same room based on self-motion (e.g., Rieser, 1989). This finding suggests that *spontaneous spatial updating* was *cancelled* in Experiments 1 and 1b by the spatial symmetry of the turning location rather than the rectangular room shape alone, supporting the *cancelled-by-spatial-symmetry* hypothesis over the *cancelled-by-room-shape* hypothesis.

However, the different results in Experiments 1 and 2 might not be due to spatial symmetry/asymmetry at the turning location. Rather, it might be due to the fact that the object array, although removed during testing, was always in front of the participants for both actual perspectives in Experiment 2 but was on their back for the actual perspective of facing south in Experiment 1. Experiment 2b addressed this issue.

3.5. Experiment 2b

Experiment 2b tested the speculation that the null sensorimotor alignment effects in Experiment 1 were because the hidden object array would be behind the participants for the actual perspective of facing south. In Experiment 2b, the hidden object array was still behind the participants when they were actually facing south; yet the perceived distances to the facing walls were different before and after physical turning (i.e., spatial asymmetry). If a sensorimotor alignment effect appeared, then it would disapprove the above speculation and further support the *cancelled-by-spatial-symmetry* hypothesis.

3.5.1 Method

3.5.1.1 Participants. Sixteen university students (8 female; age: *M*=19.94 years, *SD*=3.55, range=18-32) [3] with normal or corrected-to-normal vision participated for credits in an introductory psychology course.

3.5.1.2 Materials, Design, and Procedure. The materials, design and procedure were similar as Experiment 2, except that the testing location for the actual perspective of facing south was moved to be 3.5 m from the north wall (the red cross in Figure 1C), so that the hidden object

[3] Half participants (4 female) had the testing order of actually facing north first, and the other half (4 female) had the testing order of actually facing south first.

array would be behind the participants when they were facing south. Since this testing location was much more distant to the south wall than the north wall (3.5 m to the north wall and 8.5 m to the south wall leading to the north-south distance ratio of 0.412), physical turning of 180° at this testing location would lead to different perceived distances to the facing walls across turning (see Figure S4 in supplementary materials for example first-person perspectives in Experiment 2b).

3.5.2 Results

2×2 repeated-measures ANOVAs (A-I [0º, 180º], L-I [0º, 180º]) were conducted in response latency and absolute angular error.

In response latency (Figure 2), the main effect of A-I was significant, $F(1, 15) = 4.91$, $p = .043$, $\eta_p^2 = .247$, indicating a sensorimotor alignment effect. The main effect of L-I was significant, $F(1, 15) = 32.77$, $p < .001$, $\eta_p^2 = .686$, showing a learning orientation effect. The interaction was not significant, $F(1, 15) = 0.55$, $p = .468$, $\eta_p^2 = .036$, $BF_{01} = 1.122$.

In absolute angular error (Figure 3), the main effect of A-I was not significant, $F(1, 15) = 0.02$, $p = .879$, $\eta_p^2 = .002$, $BF_{01} = 2.987$, indicating a null sensorimotor alignment effect. The main effect of L-I was significant, $F(1, 15) = 8.45$, $p = .011$, $\eta_p^2 = .360$, showing a learning orientation effect. The interaction was not significant, $F(1, 15) = 2.67$, $p = .123$, $\eta_p^2 = .151$, $BF_{01} = 1.320$.

These results showed the sensorimotor alignment effect (in response latency). There was no speed-accuracy trade-off. The response latency and the absolute angular error were not significantly correlated, $r(30)=-.14$, $p=.436$.

3.5.3 Discussion

Experiment 2b demonstrated a sensorimotor alignment effect, which is inconsistent with the possibility that the null sensorimotor alignment effects in Experiment 1 occurred because the hidden object array would be behind the participants for the actual perspective of facing south. This further supports the *cancelled-by-spatial-symmetry* hypothesis.

However, the perceived distances to the facing walls were similar at the two actual testing perspectives in Experiments 1 and 1b (i.e., 5.5 m to the north wall for the actual testing perspective of facing north and 6.5 m to the south wall for the actual testing perspective of facing south, see Figure 1A). In contrast, the perceived distances to the facing walls at the two actual testing perspectives significantly changed in Experiments 2 and 2b (i.e., 5.5 m to the north wall for the actual testing perspective of facing north and 11.5 m or 8.5 m to the south wall for the actual testing perspective of facing south for Experiments 2 or 2b, see Figures 1B and 1C). This discrepancy, rather than the spatial symmetry/asymmetry at the turning location (indicated by the change in the perceived distances to the facing walls before and after turning), could have caused the different results in Experiments 1 and 2. Experiment 3 tested this possibility.

4. Experiment 3

The purpose of Experiment 3 was to test the possibility that the different results in Experiments 1 and 2 were caused by the similar or significantly changed perceived distances to the facing walls at the two actual testing perspectives. In Experiment 3, the distances to the facing walls were the same at the two actual testing perspectives (i.e., 5.5 m to the north wall for the actual testing perspective of facing north and 5.5 m to the south wall for the actual testing perspective of facing south, see Figure 1D). However, the perceived distance to the facing wall changed before and after turning at the testing locations (i.e., 3.5 m before turning and 5.5 m after turning), leading to spatial asymmetry of the turning locations. The occurrence of sensorimotor alignment effects would be inconsistent with the preceding possibility and further support the *cancelled-by-spatial-symmetry* hypothesis.

4.1 Method

4.1.1 Participants

Thirteen university students (5 female; age: *M*=18.69 years, *SD*=1.11, range=18-21)[4] with normal or corrected-to-normal vision participated in return for credits in an introductory psychology course. Assuming η_p^2 is 0.447 (the observed effect size of the sensorimotor alignment effect for response latency in Experiment 2), using 13 participants produced the power value to be 0.82 at the alpha level of .05 to detect a significant main effect of sensorimotor alignment in a 2×2 repeated-measures ANOVA.

4.1.2 Materials, Design, and Procedure

The materials, design and procedure were similar to those of Experiment 2, except for the following changes. To make the actual perspectives of facing north and south have the same distances to the facing walls, the virtual south wall was moved to be closer to the north wall (i.e., the room length decreased to 9 m, see Figure 1D) and the testing location for the actual perspective of facing south was moved to be 3.5 m from the north wall. Consequently, the actual testing perspectives of facing north and south were equally distant to the facing walls (i.e., 5.5 m). Meanwhile, physical turning at each testing location would lead to different distances to the facing walls before and after turning at the testing location (e.g., in Figure 1D, the red cross was 3.5 m to the north wall and 5.5 m to the south wall leading to the north-south distance ratio of 0.636) (see Figure S5 in supplementary materials for example first-person perspectives in Experiment 3).

4.2 Results

[4] Less than twenty participants were collected due to the interruption by Covid-19. Among these thirteen participants, six (2 female) had the testing order of actually facing north first, and the other participants (3 female) had the testing order of actually facing south first.

2×2 repeated-measures ANOVAs (A-I [0º, 180º], L-I [0º, 180º]) were conducted in response latency and absolute angular error.

In response latency (Figure 2), the main effect of A-I was significant, $F(1, 12) = 11.29$, $p = .006$, $\eta_p^2 = .485$, indicating a sensorimotor alignment effect. The main effect of L-I was also significant, $F(1, 12) = 13.65$, $p = .003$, $\eta_p^2 = .532$, showing a learning orientation effect. The interaction was not significant, $F(1, 12) = 4.11$, $p = .065$, $\eta_p^2 = .255$, $BF_{01} = 0.129$[5].

In absolute angular error (Figure 3), none of the main effects or interaction were significant (Fs ≤ 2.00, ps $\geq .183$, $\eta_p^2 \leq .143$, $BF_{01} \geq 2.643$).

These results demonstrated the sensorimotor alignment effect (in response latency). There was no speed-accuracy trade-off. The response latency and the absolute angular error were positively correlated, $r(24)=.52$, $p=.006$.

4.3 Discussion

Experiment 3 showed a sensorimotor alignment effect, which is inconsistent with the possibility that the null sensorimotor alignment effects in Experiment 1 were due to the similar perceived distances to the facing walls at the two actual testing perspectives. This further supports the *cancelled-by-spatial-symmetry* hypothesis.

5. General Discussion

The current study demonstrated that *spontaneous spatial updating* of self-orientation based on self-motion was *cancelled* by ambiguous orientations indicated by spatial symmetry of the turning location but not *cancelled* by ambiguous orientations indicated by the rectangular room

[5] Since the interaction effect was close to significance and BF_{01} favoured the alternative, pairwise comparisons were conducted within the two L-I conditions. For L-I=180, responses were significantly faster in A-I=0 condition than A-I=180 condition ($t(12)=2.65$, $p=0.02$), indicating a sensorimotor alignment effect. However, for L-I=0, there was no difference between A-I=0 and A-I=180 conditions ($t(12)=0.52$, $p=0.61$), suggesting no sensorimotor alignment effect. This is consistent with some previous studies showing a smaller sensorimotor alignment effect for the imagined heading of the learning orientation (e.g., Du et al., 2021; Mou, McNamara et al., 2004).

shape. These findings support the *cancelled-by-spatial-symmetry* hypothesis over the *spontaneous-spatial-updating* and the *cancelled-by-room-shape* hypotheses.

Previous studies have thoroughly examined the exclusive roles of piloting cues and self-motion in updating self-orientation within a room by using the paradigms of reorientation and spatial updating (e.g., Cheng & Newcombe, 2005; Rieser, 1989). In reorientation, a rectangular room shape produces two ambiguous orientations along the same axis of the room (e.g., Hermer & Spelke, 1996). The literature of spatial updating indicates that *spontaneous spatial updating* occurs when people locomote without vision (Farrell & Robertson, 1998; Rieser 1989). They spontaneously update the transient representation of their actual orientation based on self-motion. By contrast, in *instructed spatial updating*, participants could use the enduring representation of the learning orientation as their self-orientation, such that spatial updating of self-orientation from self-motion was *cancelled* (e.g., Waller et al., 2002). Kelly et al. (2008) conducted a pioneering study to bridge the gap between reorientation and spatial updating. Their study showed that when participants were instructed to keep track of a location during walking, the room shape could facilitate updating of the target location based on self-motion.

Nevertheless, the questions remain whether piloting cues affect *spontaneous spatial updating* from self-motion and which piloting cues do so. The *spontaneous-spatial-updating* hypothesis claims that *spontaneous spatial updating* from self-motion is not affected by two ambiguous orientations indicated by a rectangular room shape. This hypothesis is consistent with some theories stipulating that path integration based on self-motion may be fundamental to updating self-orientation (e.g., Savelli & Knierim, 2019), and therefore resistant to the influence of piloting cues. In contrast, both the *cancelled-by-room-shape* and the *cancelled-by-spatial-symmetry* hypotheses claim that *spontaneous spatial updating* from self-motion is affected by ambiguous orientations indicated by piloting cues in a rectangular room. These two hypotheses are consistent with the theories suggesting that piloting cues may be predominant and may affect path integration (e.g., Spiers et al., 2015; Zhao & Warren, 2015). Moreover, the *cancelled-by-room-shape* and the *cancelled-by-spatial-symmetry* hypotheses claim that different piloting cues affect *spontaneous spatial updating* from self-motion. While the *cancelled-by-room-shape* hypothesis conceives of the room shape alone, the *cancelled-by-spatial-symmetry* hypothesis conceives of the spatial symmetry of the turning location (determined by the room shape and other geometric cues including the perceived distances to the facing walls before and after turning). The findings in the current study clearly favor the *cancelled-by-spatial-symmetry* hypothesis.

Sensorimotor alignment effects were consistently reported by studies examining *spontaneous spatial updating*, indicating that spatial updating from self-motion was automatic when only self-motion cues were available (Farrell & Robertson, 1998; Rieser 1989). Therefore, it is surprising to show null sensorimotor alignment effects when both piloting and self-motion cues were available during locomotion (Experiment 1), indicating that participants did not maintain the representation of self-orientation updated from self-motion while conducting JRDs. Previous studies showed that conflicting piloting cues overrode self-motion (Zhao & Warren, 2015). However, the current study never rotated or displaced the room to create two conflicting cues. To the best of our knowledge, the current study provides, for the first time, *spontaneous spatial updating* relative to an object array based on self-motion was *cancelled* by piloting cues when there were self-motion and piloting cues without any conflict manipulation.

The current finding of the strong influence of piloting cues on spatial updating in a room is consistent with previous findings on spatial representations across structurally similar spaces. When path integration is disrupted during across-boundary navigation, similar environmental geometry between rooms can elicit re-anchoring in the remote room (Riecke & McNamara, 2017). When path integration functions during across-boundary navigation, structural similarity between local spaces may dominate in updating headings and locations and in developing spatial representations (e.g., Marchette et al., 2014). The current study shows the strong influence from piloting cues on self-orientation even when navigation does not cross boundaries, extending the findings in across-boundary navigation to within-boundary navigation. This extension is significant as it has been well accepted that spatial updating in a room is effortless and self-orientation is primarily based on self-motion than piloting cues (e.g., May & Klatzky, 2000; Rieser, 1989).

The finding that *spontaneous spatial updating* was *cancelled* by ambiguous orientations indicated by piloting cues seems similar to the finding of rotational errors in reorientation based on room shape (e.g., Hermer & Spelke, 1994, 1996; Ratliff & Newcombe, 2008). However, as participants in the current study knew that their location was the same before and after turning, the change in perceived distances to the facing walls should remove the ambiguity of orientations indicated by the room shape. Therefore, spatial symmetry of the turning location rather than the room shape per se produced ambiguous orientations, a key theoretical insight differentiating the *cancelled-by-spatial-symmetry* hypothesis from the *cancelled-by-room-shape* hypothesis.

The findings of the current study favored the *cancelled-by-spatial-symmetry* hypothesis over the *cancelled-by-room-shape* hypothesis. *Spontaneous spatial updating* was *cancelled* only when there was spatial symmetry of the turning location indicated by similar perceived distances to the facing walls before and after turning 180° (Experiment 1). Although the distances to the facing walls before and after turning 180° were not exactly the same (5.5 m vs 6.5 m), this distance difference may not be obvious to detect from different perspectives after body rotation. When the distances to the facing walls changed more substantially before and after turning (0.5 m vs 11.5 m, 3.5 m vs. 8.5 m, and 3.5 m vs. 5.5 m in Experiments 2, 2b, and 3 respectively), which disrupted spatial symmetry, *spontaneous spatial updating* occurred (i.e., was not *cancelled)*. Spatial asymmetry removed the ambiguity of orientations indicated by the rectangular room shape alone. In a rectangular room, participants' self-location could be defined by the perceived distances to different walls (e.g., the *red* testing location in Figure 1D was 3.5 m to the north wall and 5.5 m to the south wall) (O'Keefe & Burgess, 1996). If participants knew their location (e.g., still standing at the *red* testing location after turning as they turned in place), then the perceived distance to the facing wall (e.g., 5.5 m to the facing wall) should be sufficient to indicate which wall they were facing (e.g., the south wall). Besides, the finding that *spontaneous spatial updating* was *cancelled* only when there was spatial symmetry of the turning location implies that the rotational errors in the reorientation paradigm could also disappear if participants would be spun in place in one side, rather than the middle, of a rectangular room.

The finding that *spontaneous spatial updating* was *cancelled* only when there was spatial symmetry of the turning location can also partially explain the discrepancy between the findings of Kelly et al. (2008) and the current study. Kelly et al. (2008) showed that when both piloting and self-motion cues were available during locomotion, angular room geometry helped participants to track a target waypoint while walking an unpredictable path defined by multiple waypoints. As participants in their study walked and turned, rather than standing in the middle of the room, their distances to the facing walls changed after turns, similar to Experiments 2-3 of the current study. Thus, the results of spatial updating should be expected in their study as indicated by the results in Experiments 2-3 of the current study. The other important procedural difference between Kelly et al. (2008) and the current study is that their study asked participants to keep track of a target location whereas the current study did not. In addition, the JRD task in the current study required participants to point from imagined perspectives rather than from their actual position or heading. While Kelly et al. (2008) examined the representation of self-orientation in *instructed spatial updating*, the current study examined the representation of self-orientation in *spontaneous spatial updating*. The finding that spatial updating from self-motion was *cancelled* by spatial symmetry of the turning location should be specific to the *spontaneous spatial updating* examined in the current study but not to the *instructed spatial updating* examined in Kelly et al. (2008). In the *instructed spatial updating*, the instructions to attend to spatial updating may strengthen the transient representation of self-orientation updated from self-motion and make it immune to the influence of ambiguous orientations indicated by spatial symmetry. In contrast, in the *spontaneous spatial updating*, the transient representation of self-orientation updated from self-motion is prone to the influence of ambiguous orientations indicated by spatial symmetry.

Previous studies on spatial updating have demonstrated that people have both transient representations from spatial updating and enduring representations from the learning orientation (Avraamides et al., 2013; Avraamides & Kelly, 2008; Kelly et al., 2007; Shelton & Marchette, 2010; Waller et al., 2002). During physical turning at the testing location, participants in Experiment 1 of the current study might have updated transient representations of the object array from self-motion and meanwhile maintained enduring representations from the learning viewpoint. Due to spatial symmetry of the turning location, both orientations before and after turning were similar to the learning viewpoint. This might have triggered the use of the enduring representations from the learning viewpoint rather than the updated representations when participants physically turned from facing north to facing south, so *spontaneous spatial updating* from self-motion was *cancelled* by ambiguous orientations indicated by spatial symmetry of the turning location. It is also plausible that participants might have imagined the object array stabilized relative to their bodies such that the egocentric relations to the object array never changed during locomotion, thus they might not have any transient representation of self-orientation updated from self-motion. We doubt this possibility as previous studies showed that it was much more difficult to instruct participants to imagine an object array stabilized relative to their bodies (Mou et al., 2008) than to imagine a simple path stabilized relative to their bodies (Waller et al., 2002). We acknowledge that the current study cannot distinguish these two possibilities.

The current study manipulated spatial symmetry/asymmetry at the turning location (spatial symmetry in Experiments 1 and 1b vs. spatial asymmetry in Experiments 2, 2b and 3). In addition, the current study also manipulated whether the hidden object array was behind the participants for the actual testing perspective of facing south (to participants' back in Experiments 1, 1b, 2b, and 3 vs. to participants' front in Experiment 2). Furthermore, the current study also manipulated whether the distances to the facing walls at the two actual testing perspectives were similar (similar in Experiments 1, 1b, and 3 vs. significantly changed in Experiments 2 and 2b). The results of null sensorimotor alignment effects in Experiments 1and 1b and the results of sensorimotor alignment effects in Experiments 2, 2b, and 3 indicate that the disappearance and appearance of sensorimotor alignment effects were attributed to spatial symmetry/asymmetry at the turning location but not the other two variables.

Across all the experiments of the current study, the encoding conditions of the object array were the same (i.e., the object array, the distance from the learning location to the facing wall, the furniture by the facing wall, and the learning procedures). Previous studies have indicated that people may employ different strategies to encode spatial information using egocentric or allocentric reference frames and they may spontaneously shift from using one strategy to another when there are no changes in the environment (e.g., Iglói et al., 2009). We acknowledge that even though the encoding process was constant across experiments in the current study, participants might still have used different strategies to encode spatial information, and this could be a source of variability in experimental results. Nevertheless, the likelihood that the encoding strategies in Experiments 1 and 1b would be consistently different from those in the other experiments should be very low. However, participants in Experiments 1 and 1b did not move but those in Experiments 2, 2b, and 3 moved between the two testing locations. Consequently, the two actual testing perspectives in Experiments 1 and 1b were at the same location, which was also the learning location, whereas the two actual testing perspectives in Experiments 2, 2b, and 3 were at two different locations and could be different from the learning location. Although participants in all experiments moved from the starting location to the learning location at the beginning of the experiments, participants in Experiments 2, 2b, and 3 had more experiences of translation with the presence of piloting cues. During translation between the two testing locations, piloting cues provided decisive self-location (distances to the facing wall decreased), consistent with the self-location from self-motion, and participants should have updated their self-location in the transient representation. Thus, more experiences of translation (i.e., coupling of self-motion and piloting cues) might have strengthened the transient representation updated from self-motion (Rieser, 1999). Future studies should differentiate the roles of spatial symmetry/asymmetry and translation experiences in *spontaneous spatial updating*.

Experiment 1 showed null sensorimotor alignment effects when the room looked similar before and after physical turning. This result seems to conflict with the results in Kelly et al. (2007). Their Experiment 1 showed sensorimotor alignment effects when participants physically turned in the learning room and the room looked the same before and after turning. One experimental difference that might lead to the different results was whether participants turned inside the object array (Experiment 1 in Kelly et al.) or outside (the current Experiment 1). Updating headings relative to an object array by physical turning might be more automatic and less prone to interference from ambiguous self-orientations indicated by spatial symmetry of the turning location when participants turn inside rather than outside the object array. The other important difference was the room shape: octagon in Kelly et al. but rectangular in the current study. The visual structure of an octagon might be less informative to orientation thus might have less interference with spatial updating from self-motion.

Note that the virtual room in the current study had distinct furniture in room corners. In addition, participants were explicitly asked to turn and face a wall with specific features for an actual perspective during testing. Thus, participants should have known which wall they were actually facing. However, the null sensorimotor alignment effects in Experiment 1 indicate that the room features did not help to update headings relative to the object array especially when the room looked similar before and after physical turning. The participants might have prioritized room geometry over features when updating headings relative to the object array. This is consistent with some findings in reorientation showing a stronger influence of geometry over features in a room (Ratliff & Newcombe, 2008; Wang & Mou, 2020). More salient or stable features might be more effective than the furniture in room corners in confronting the influence from spatial symmetry of the turning location and updating headings relative to the object array.

The current study demonstrated that spatial symmetry based on visual cues could cancel spatial updating based on path integration. In general, this behavioral finding is consistent with the findings of no updating of neural representations based on path integration in a visually ambiguous environment[6]. Studies on rats have shown that hippocampal place cells exhibit repeated firing fields when rats forage across visually similar compartments that are parallel (i.e., facing the same global direction), indicating that updating by self-motion may be reset at specific, ambiguous locations in an environment such that place cell firing patterns are similar across different compartments (Spiers et al. 2015). More related to heading updating in the current study, studies have discovered head direction cells with multiple directional tunings within a compartment when rats forage and see similar views in the environment. Some cells showed bi-directional tunings in a two-fold environment and four-directional tuning in a four-fold environment (Jacob et al., 2017; Zhang et al., 2020). The current study also indicated that spatial updating based on path integration occurred when extra information (e.g., the distances to the walls before and after turning) removed the spatial symmetry based on visual cues. Similarly, when extra cues remove visual ambiguity, neural representations can be updated by path integration. Place fields do not repeat when compartments are radial (i.e., facing different global directions) (Grieves et al., 2016) unless head direction cell system is lesioned (Harland et al., 2017). Thus, directional information provided by head direction cells are critical for place cells to differentiate visually similar spaces facing different directions. Hence, evidence from place and head direction cells may provide neural bases of the current findings.

In the current study, sensorimotor alignment effects in Experiments 2, 2b, and 3 were consistently shown in response latency but not shown in absolute pointing error in Experiments 2b and 3. Previous studies have shown that alignment effects can be evident only in latency (e.g., Avraamides & Kelly, 2005; Brockmole & Wang, 2003; Farrell & Robertson, 1998; Marchette et al., 2014; May, 2007, Experiment 2; Mou et al., 2008; Mou et al., 2007), only in error (e.g., Riecke

[6] We are grateful to one anonymous reviewer for directing us to the neural bases of the current findings.

& McNamara, 2017, Experiment 2; Shelton & Marchette, 2010; Shelton & McNamara, 2001), or in both latency and error (e.g., Kelly et al., 2007; Liu & Xiao, 2018; May 2004; May, 2007, Experiment 1; Mou, McNamara et al., 2004; Riecke & McNamara, 2017, Experiment 1; Rieser, 1989; Shelton & McNamara, 1997; Waller et al., 2002). To our knowledge, there are no systematic investigations of why alignment effects might be revealed in latency or error or both. We did not have any theoretical reason to expect sensorimotor alignment effects to occur in response latency but not in pointing error in the current study. Mou et al. (2007, see also Sholl & Bartels, 2002) conjectured that well-developed spatial representations may more likely lead to alignment effects in latency, while underdeveloped spatial representations may more likely lead to alignment effects in error. In the current study, spatial representations should be of high fidelity since the object array was well learned (i.e., participants viewed the array for three minutes and then replaced each object to the remembered location followed by the feedback of its correct location for three times). Thus, response latency, rather than pointing error, might be more sensitive to the sensorimotor alignment effects.

Overall, the current study demonstrated that when participants had both piloting and self-motion cues in a room, physical turning that produced ambiguous orientations based on spatial symmetry of the turning location did not lead to updating of headings relative to an object array in a room, indicating that *spontaneous spatial updating* from self-motion in a room was *cancelled*. Furthermore, *spontaneous spatial updating* occurred (was not *cancelled)* when participants could use different distances to the walls (e.g., the facing wall) to remove ambiguity of orientations indicated by the rectangular room shape across physical turning. These results suggest that spatial symmetry/asymmetry of the turning position can modulate spontaneous updating of self-orientation relative to an object array by self-motion in a room.

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Supplementary Materials

1. Results from Orientation Latency

Orientation latency as a function of A-I and L-I was plotted for all experiments in Figure S1.

In Experiment 1, none of the main effects or interaction were significant (Fs $\leq$ 2.50, ps $\geq$ .130, $\eta_p^2 \leq$ .116, $BF_{01} \geq$ 2.265).

In Experiment 1b, the main effect of A-I was not significant, $F(1, 19) = 1.02$, $p = .324$, $\eta_p^2 = .051$, $BF_{01} = 0.735$, indicating a null sensorimotor alignment effect. The main effect of L-I was not significant, $F(1, 19) = 3.96$, $p = .061$, $\eta_p^2 = .173$, $BF_{01} = 0.576$. The interaction was significant, $F(1, 19) = 5.26$, $p = .033$, $\eta_p^2 = .217$. Pairwise comparisons showed that for L-I = 0º, orientation latencies were significantly faster when A-I = 0º than A-I = 180º, $t(19) = 2.83$, p=.011; whereas for L-I = 180º, there was no difference between A-I = 0º and A-I = 180º, $t(19) = 1.53$, p=.143.

In Experiment 2, none of the main effects or interaction were significant (Fs $\leq$ 1.61, ps $\geq$ .220, $\eta_p^2 \leq$ .078, $BF_{01} \geq$ 3.079).

In Experiment 2b, none of the main effects or interaction were significant (Fs $\leq$ 0.34, ps $\geq$ .568, $\eta_p^2 \leq$ .022, $BF_{01} \geq$ 4.744).

In Experiment 3, none of the main effects or interaction were significant (Fs $\leq$ 4.22, ps $\geq$ .062, $\eta_p^2 \leq$ .260, $BF_{01} \geq$ 3.198).

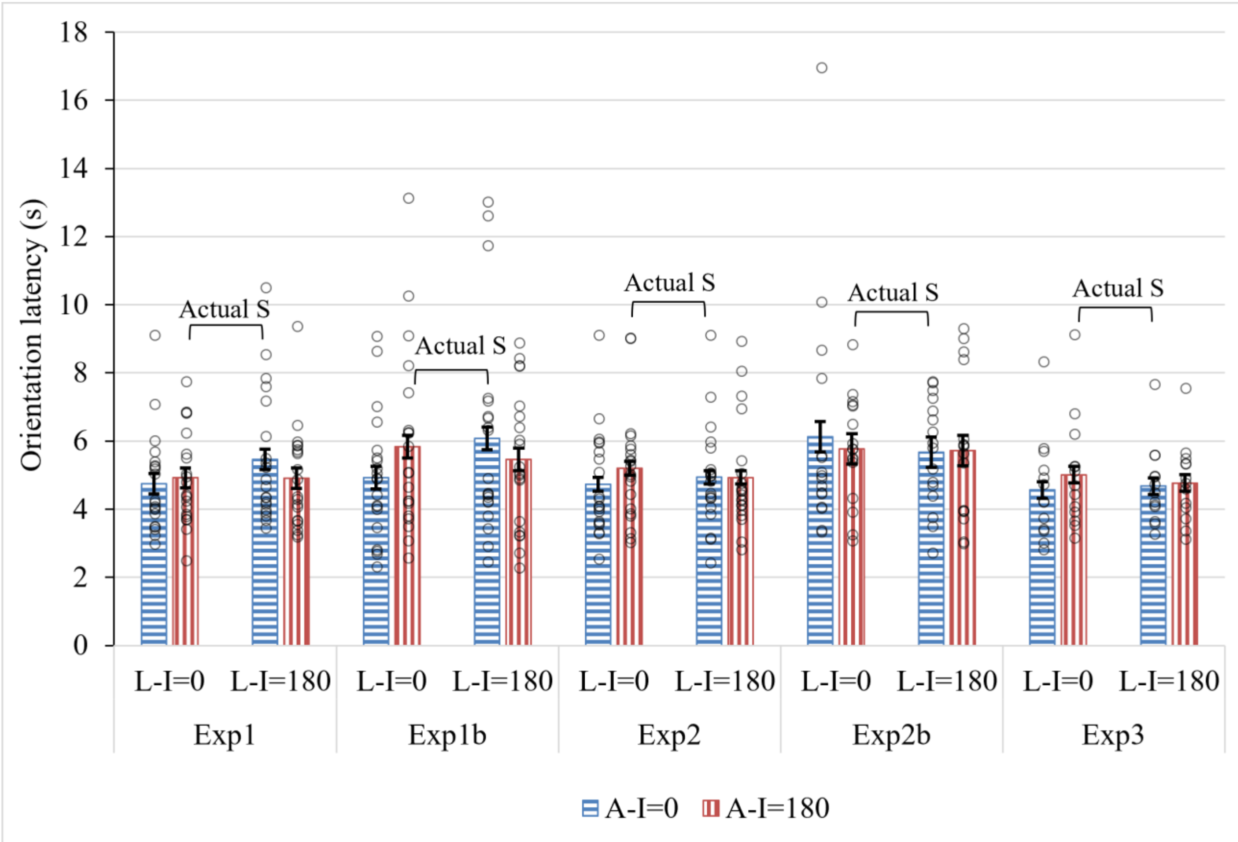
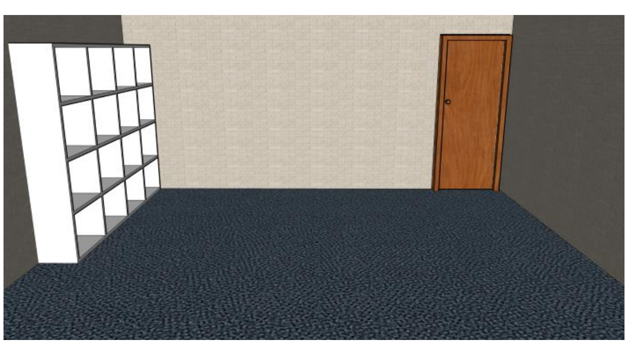


Figure S1. The mean orientation latency for different conditions in all experiments. Error bars represent ±1 SE (removing the variance from individual differences). The open dots are individual data points in each condition. Actual S indicates the conditions for the actual perspective of facing south.

2. Example First-person Perspectives in the Virtual Environment

(A) **(B)**



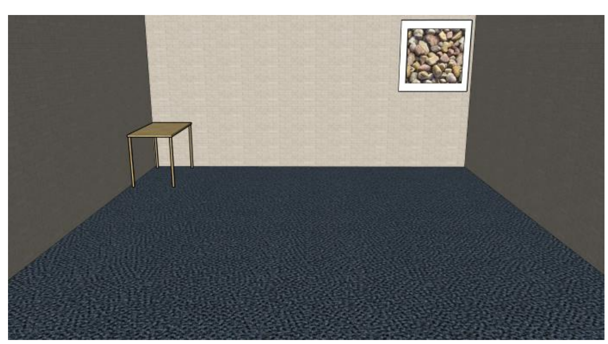


Figure S2. *Example first-person perspectives in the virtual environment in Experiments 1 and 1b. (A) The learning perspective, which is also the actual testing perspective of facing north (i.e., standing at the blue cross in Figure 1A and facing north). (B) The actual testing perspective of facing south (i.e., standing at the blue cross in Figure 1A and facing south).*

(A) **(B)**

Figure S3. *Example first-person perspectives in the virtual environment in Experiment 2. When participants stood at the testing location for the actual perspective of facing south (i.e., the red cross in Figure 1B), the view of facing north is shown in (A), and the view of facing south is shown in (B).*

Note: The learning perspective in Experiment 2 is the same as Figure S2A. When participants stood at the testing location for the actual perspective of facing north (i.e., the blue cross in Figure 1B), the view of facing north is the same as Figure S2A, and the view of facing south is the same as Figure S2B.

(A) **(B)**

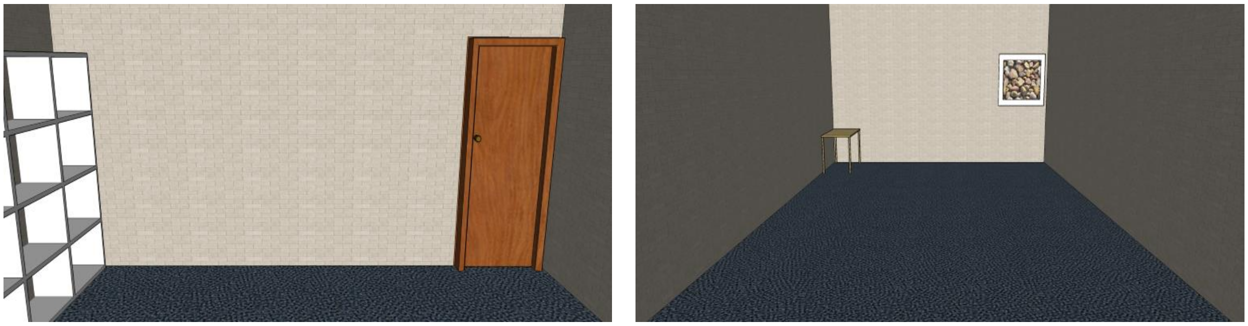
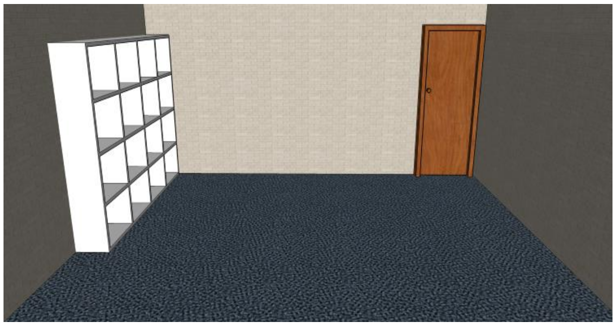
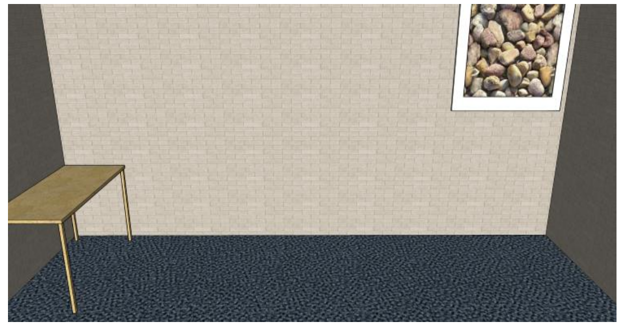


Figure S4. *Example first-person perspectives in the virtual environment in Experiment 2b. When participants stood at the testing location for the actual perspective of facing south (i.e., the red cross in Figure 1C), the view of facing north is shown in (A), and the view of facing south is shown in (B).*

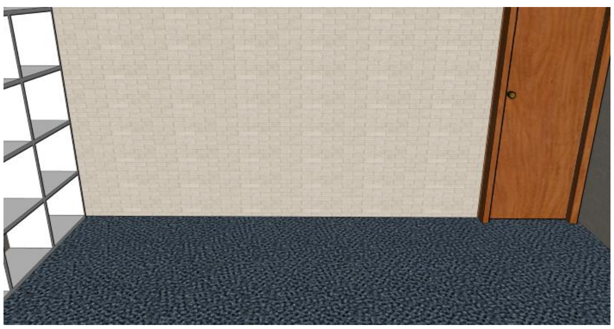
Note: The learning perspective in Experiment 2b is the same as Figure S2A. When participants stood at the testing location for the actual perspective of facing north (i.e., the blue cross in Figure 1C), the view of facing north is the same as Figure S2A, and the view of facing south is the same as Figure S2B.

(A) **(B)**





(C) **(D)**



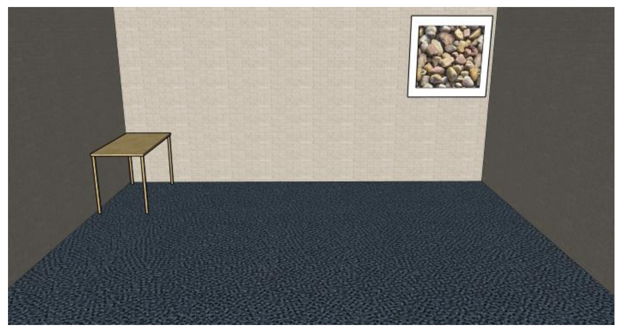


Figure S5. Example first-person perspectives in the virtual environment in Experiment 3. The learning perspective in Experiment 3 is shown in (A). When participants stood at the testing location for the actual perspective of facing north (i.e., the blue cross in Figure 1D), the view of facing north is shown in (A), and the view of facing south is shown in (B). When participants stood at the testing location for the actual perspective of facing south (i.e., the red cross in Figure 1D), the view of facing north is shown in (C), and the view of facing south is shown in (D).

3. Results Using the First Approach in Introduction to Test Sensorimotor Alignment Effects

As mentioned in the Introduction, we designed the experiments following the second approach (Table 1B) to examine sensorimotor alignment effects solely attributed to spatial updating. Specifically, for the imagined perspective of north, the actual perspective of north was compared with the actual perspective of south (i.e., A-I=0, L-I=0 vs. A-I=180, L-I=0, see the left two bars out of the four bars in each experiment in Figures 2 and 3); whereas for the imagined perspective of south, the actual perspective of south was compared with the actual perspective of north (i.e., A-I=0, L-I=180 vs. A-I=180, L-I=180, see the right two bars in each experiment in Figures 2 and 3); and the main effect of A-I indicated sensorimotor alignment effects.

In addition to using the second approach mentioned in the Introduction (Table 1B), for readers' interests, we also tested sensorimotor alignment effects in all experiments using the first approach (Table 1A), although our experimental design did not follow the first approach to include any neutral imagined perspective as a baseline to dissociate sensorimotor alignment effects and learning orientation effects. Specifically, for the actual perspective of north, the imagined perspective of north was compared with the imagined perspective of south (i.e., A-I=0, L-I=0 vs. A-I=180, L-I=180, see the outer two bars in each experiment in Figures 2 and 3); whereas for the actual perspective of south, the imagined perspective of north was compared with the imagined perspective of south (i.e., A-I=180, L-I=0 vs. A-I=0, L-I=180, see the inner two bars in each experiment labeled as 'Actual S' in Figures 2 and 3); the interaction between the variables of actual perspectives (actually facing north vs. actually facing south) and imagined perspectives (imagined facing north vs. imagined facing south) indicated the sensorimotor alignment effects shown in the second approach.

To use the first approach to examine sensorimotor alignment effects, in the measures of response latency, absolute angular error, and orientation latency, we conducted 2×2 repeated-measures ANOVAs (Actual [north, south], Imagined [north, south]). For simple effects (i.e., for Actual north, Imagined north vs. Imagined south; for Actual south, Imagined south vs. Imagined north), pairwise comparisons were conducted to see if performances were faster or more accurate when actual and imagined perspectives were aligned than misaligned. The interaction effects would indicate sensorimotor alignment effects, which were the same results as the main effects of A-I presented in the main text. The main effects of Imagined [north, south] would indicate the learning orientation effects, which were the same results as the main effects of L-I presented in the main text.

3.1 Experiment 1

3.1.1 Response Latency

The main effect of Imagined was significant, $F(1, 19) = 51.70$, $p < .001$, $\eta_p^2 = .731$, indicating a learning orientation effect. The main effect of Actual was not significant, $F(1, 19) = 1.23$, $p = .280$, $\eta_p^2 = .061$. The interaction was not significant, $F(1, 19) = 0.98$, $p = .336$, $\eta_p^2 = .049$, indicating a null sensorimotor alignment effect.

In terms of simple effects, for Actual north, imagined facing north was significantly faster than imagined facing south, $t(19) = 6.76$, $p < .001$, Cohen's $d = 2.139$, showing a sensorimotor alignment effect (A-I=0, L-I=0 vs. A-I=180, L-I=180, see the outer two bars for Experiment 1 in Figures 2 and 3). For Actual south, imagined facing north was significantly faster than imagined facing south, $t(19) = 3.97$, $p < .001$, Cohen's $d = 1.257$, showing a reversed sensorimotor alignment effect (A-I=180, L-I=0 vs. A-I=0, L-I=180, see the inner two bars labeled as 'Actual S' for Experiment 1 in Figures 2 and 3).

3.1.2 Absolute Angular Error

The main effect of Imagined was significant, $F(1, 19) = 6.61$, $p = .019$, $\eta_p^2 = .258$, indicating a learning orientation effect. The main effect of Actual was not significant, $F(1, 19) = 0.08$, $p = .780$, $\eta_p^2 = .004$. The interaction was not significant, $F(1, 19) = 0.04$, $p = .852$, $\eta_p^2 = .002$, showing a null sensorimotor alignment effect.

In terms of simple effects, for Actual north, imagined facing north and imagined facing south were not significantly different, $t(19) = 1.91$, $p = .071$, Cohen's $d = 0.606$, showing a null sensorimotor alignment effect (A-I=0, L-I=0 vs. A-I=180, L-I=180, see the outer two bars for Experiment 1 in Figures 2 and 3). For Actual south, imagined facing north had significantly smaller errors than imagined facing south, $t(19) = 2.63$, $p = .016$, Cohen's $d = 0.832$, showing a reversed sensorimotor alignment effect (A-I=180, L-I=0 vs. A-I=0, L-I=180, see the inner two bars labeled as 'Actual S' for Experiment 1 in Figures 2 and 3).

3.1.3 Orientation Latency

None of the main effects or interaction were significant (Fs ≤ 2.50, ps $\geq .130$, $\eta_p^2 \leq .116$).

In terms of simple effects, for either Actual north or Actual south, imagined facing north and imagined facing south were not significantly different, ts$(19) \leq 1.47$, ps $\geq .157$, Cohen's ds $\leq$ 0.466, showing null sensorimotor alignment effects (see Figure S1).

3.2 Experiment 1b

3.2.1 Response Latency

The main effect of Imagined was significant, $F(1, 19) = 23.43$, $p < .001$, $\eta_p^2 = .552$, indicating a learning orientation effect. The main effect of Actual was not significant, $F(1, 19) <$ 0.01, $p = .986$, $\eta_p^2 < .001$. The interaction was not significant, $F(1, 19) = 0.02$, $p = .891$, $\eta_p^2 = .001$, showing a null sensorimotor alignment effect.

In terms of simple effects, for Actual north, imagined facing north was significantly faster than imagined facing south, $t(19) = 4.64$, $p < .001$, Cohen's $d = 1.467$, showing a sensorimotor alignment effect (A-I=0, L-I=0 vs. A-I=180, L-I=180, see the outer two bars for Experiment 1b in Figures 2 and 3). For Actual south, imagined facing north was significantly faster than imagined facing south, $t(19) = 3.97$, $p < .001$, Cohen's $d = 1.256$, showing a reversed sensorimotor alignment effect (A-I=180, L-I=0 vs. A-I=0, L-I=180, see the inner two bars labeled as ‘Actual S’ for Experiment 1b in Figures 2 and 3).

3.2.2 Absolute Angular Error

The main effect of Imagined was significant, $F(1, 19) = 6.74$, $p = .018$, $\eta_p^2 = .262$, indicating a learning orientation effect. The main effect of Actual was not significant, $F(1, 19) = 2.87$, $p = .107$, $\eta_p^2 = .131$. The interaction was not significant, $F(1, 19) = 0.32$, $p = .581$, $\eta_p^2 = .016$, indicating a null sensorimotor alignment effect.

In terms of simple effects, for Actual north, imagined facing north was significantly more accurate than imagined facing south, $t(19) = 2.20$, $p = .040$, Cohen’s $d = 0.697$, showing a sensorimotor alignment effect (A-I=0, L-I=0 vs. A-I=180, L-I=180, see the outer two bars for Experiment 1b in Figures 2 and 3). For Actual south, imagined facing north and imagined facing south were not significantly different, $t(19) = 0.868$, $p = .396$, Cohen’s $d = 0.274$, showing a null sensorimotor alignment effect (A-I=180, L-I=0 vs. A-I=0, L-I=180, see the inner two bars labeled as ‘Actual S’ for Experiment 1b in Figures 2 and 3).

3.2.3 Orientation Latency

The main effect of Imagined was not significant, $F(1, 19) = 3.96$, $p = .061$, $\eta_p^2 = .173$, indicating no learning orientation effect. The main effect of Actual was significant, $F(1, 19) = 5.26$, $p = .033$, $\eta_p^2 = .217$. The interaction was not significant, $F(1, 19) = 1.02$, $p = .324$, $\eta_p^2 = .051$, suggesting a null sensorimotor alignment effect.

In terms of simple effects, for Actual north, imagined facing north was significantly faster than imagined facing south, $t(19) = 3.07$, $p = .006$, Cohen’s $d = 0.972$, showing a sensorimotor alignment effect (A-I=0, L-I=0 vs. A-I=180, L-I=180, see the outer two bars for Experiment 1b in Figure S1). For Actual south, imagined facing north and imagined facing south were not significantly different, $t(19) = 0.791$, $p = .439$, Cohen's $d = 0.250$, showing a null sensorimotor alignment effect (A-I=180, L-I=0 vs. A-I=0, L-I=180, see the inner two bars labeled as 'Actual S' for Experiment 1b in Figure S1).

3.3 Experiment 2

3.3.1 Response Latency

The main effect of Imagined was significant, $F(1, 19) = 6.78$, $p = .017$, $\eta_p^2 = .263$, indicating a learning orientation effect. The main effect of Actual was not significant, $F(1, 19) = 2.54$, $p = .128$, $\eta_p^2 = .118$. The interaction was significant, $F(1, 19) = 15.37$, $p = .001$, $\eta_p^2 = .447$, indicating a sensorimotor alignment effect.

In terms of simple effects, for Actual north, imagined facing north was significantly faster than imagined facing south, $t(19) = 4.95$, $p < .001$, Cohen's $d = 1.566$, showing a sensorimotor alignment effect (A-I=0, L-I=0 vs. A-I=180, L-I=180, see the outer two bars for Experiment 2 in Figures 2 and 3). For Actual south, imagined facing north and imagined facing south were not significantly different, $t(19) = 0.62$, $p = .542$, Cohen's $d = 0.196$, showing a null sensorimotor alignment effect (A-I=180, L-I=0 vs. A-I=0, L-I=180, see the inner two bars labeled as 'Actual S' for Experiment 2 in Figures 2 and 3).

3.3.2 Absolute Angular Error

The main effect of Imagined was significant, $F(1, 19) = 1.54$, $p = .229$, $\eta_p^2 = .075$, indicating a learning orientation effect. The main effect of Actual was not significant, $F(1, 19) = 2.08$, $p = .166$, $\eta_p^2 = .099$. The interaction was significant, $F(1, 19) = 4.61$, $p = .045$, $\eta_p^2 = .195$, showing a sensorimotor alignment effect.

In terms of simple effects, for Actual north, imagined facing north was significantly more accurate than imagined facing south, $t(19) = 2.50$, $p = .022$, Cohen's $d = 0.789$, showing a sensorimotor alignment effect (A-I=0, L-I=0 vs. A-I=180, L-I=180, see the outer two bars for Experiment 2 in Figures 2 and 3). For Actual south, imagined facing north and imagined facing south were not significantly different, $t(19) = 0.859$, $p = .401$, Cohen's $d = 0.272$, showing a null sensorimotor alignment effect (A-I=180, L-I=0 vs. A-I=0, L-I=180, see the inner two bars labeled as 'Actual S' for Experiment 2 in Figures 2 and 3).

3.3.3 Orientation Latency

None of the main effects or interaction were significant (Fs ≤ 1.61, ps $\geq .220$, $\eta_p^2 \leq .078$).

In terms of simple effects, for either Actual north or Actual south, imagined facing north and imagined facing south were not significantly different, ts$(19) \leq 0.945$, ps $\geq .257$, Cohen's ds ≤ 0.299, showing null sensorimotor alignment effects (see Figure S1).

3.4 Experiment 2b

3.4.1 Response Latency

The main effect of Imagined was significant, $F(1, 19) = 32.77$, $p < .001$, $\eta_p^2 = .686$, indicating a learning orientation effect. The main effect of Actual was not significant, $F(1, 19) = 0.553$, $p = .468$, $\eta_p^2 = .036$. The interaction was significant, $F(1, 19) = 4.91$, $p = .043$, $\eta_p^2 = .247$, showing a sensorimotor alignment effect.

In terms of simple effects, for Actual north, imagined facing north was significantly faster than imagined facing south, $t(19) = 5.56$, $p < .001$, Cohen's $d = 1.965$, showing a sensorimotor alignment effect (A-I=0, L-I=0 vs. A-I=180, L-I=180, see the outer two bars for Experiment 2b in Figures 2 and 3). For Actual south, imagined facing north was significantly faster than imagined facing south, $t(19) = 3.27$, $p = .005$, Cohen's $d = 1.155$, showing a reversed sensorimotor alignment effect (A-I=180, L-I=0 vs. A-I=0, L-I=180, see the inner two bars labeled as 'Actual S' for Experiment 2b in Figures 2 and 3).

3.4.2 Absolute Angular Error

The main effect of Imagined was significant, $F(1, 19) = 8.45$, $p = .011$, $\eta_p^2 = .360$, indicating a learning orientation effect. The main effect of Actual was not significant, $F(1, 19) = 2.67$, $p = .123$, $\eta_p^2 = .151$. The interaction was not significant, $F(1, 19) = 0.02$, $p = .879$, $\eta_p^2 = .002$, showing a null sensorimotor alignment effect.

In terms of simple effects, for Actual north, imagined facing north was significantly more accurate than imagined facing south, $t(19) = 3.82$, $p = .002$, Cohen's $d = 1.350$, showing a sensorimotor alignment effect (A-I=0, L-I=0 vs. A-I=180, L-I=180, see the outer two bars for Experiment 2b in Figures 2 and 3). For Actual south, imagined facing north and imagined facing south were not significantly different, $t(19) = 1.76$, $p = .099$, Cohen's $d = 0.622$, showing a null sensorimotor alignment effect (A-I=180, L-I=0 vs. A-I=0, L-I=180, see the inner two bars labeled as 'Actual S' for Experiment 2b in Figures 2 and 3).

3.4.3 Orientation Latency

None of the main effects or interaction were significant (Fs ≤ 0.34, ps $\geq .568$, $\eta_p^2 \leq .022$).

In terms of simple effects, for either Actual north or Actual south, imagined facing north and imagined facing south were not significantly different, ts$(19) \leq 0.52$, ps $\geq .611$, Cohen's ds ≤ 0.184, showing null sensorimotor alignment effects (see Figure S1).

3.5 Experiment 3

3.5.1 Response Latency

The main effect of Imagined was significant, $F(1, 19) = 13.65$, $p = .003$, $\eta_p^2 = .532$, indicating a learning orientation effect. The main effect of Actual was not significant, $F(1, 19) = 4.11$, $p = .065$, $\eta_p^2 = .255$. The interaction was significant, $F(1, 19) = 11.29$, $p = .006$, $\eta_p^2 = .485$, indicating a sensorimotor alignment effect.

In terms of simple effects, for Actual north, imagined facing north was significantly faster than imagined facing south, $t(19) = 3.84$, $p = .002$, Cohen's $d = 1.504$, showing a sensorimotor alignment effect (A-I=0, L-I=0 vs. A-I=180, L-I=180, see the outer two bars for Experiment 3 in Figures 2 and 3). For Actual south, imagined facing north was not significantly different from imagined facing south, $t(19) = 1.20$, $p = .252$, Cohen's $d = 0.472$, showing a null sensorimotor alignment effect (A-I=180, L-I=0 vs. A-I=0, L-I=180, see the inner two bars labeled as 'Actual S' for Experiment 3 in Figures 2 and 3).

3.5.2 Absolute Angular Error

None of the main effects or interaction were significant (Fs ≤ 2.00, ps $\geq .183$, $\eta_p^2 \leq .143$).

In terms of simple effects, for Actual north, imagined facing north was not significantly different from imagined facing south, $t(19) = 1.97$, $p = .072$, Cohen's $d = 0.773$, showing a null sensorimotor alignment effect (A-I=0, L-I=0 vs. A-I=180, L-I=180, see the outer two bars for Experiment 3 in Figures 2 and 3). For Actual south, imagined facing north and imagined facing south were not significantly different, $t(19) = 0.02$, $p = .982$, Cohen's $d = 0.009$, showing a null sensorimotor alignment effect (A-I=180, L-I=0 vs. A-I=0, L-I=180, see the inner two bars labeled as 'Actual S' for Experiment 3 in Figures 2 and 3).

3.5.3 Orientation Latency

None of the main effects or interaction were significant (Fs ≤ 4.22, ps $\geq .062$, $\eta_p^2 \leq .260$).

In terms of simple effects, for either Actual north or Actual south, imagined facing north and imagined facing south were not significantly different, ts$(19) \leq 0.75$, ps $\geq .468$, Cohen's ds ≤ 0.294, showing null sensorimotor alignment effects (see Figure S1).

4. Individual Data Patterns in Sensorimotor Alignment Effects

To show the individual data patterns for the sensorimotor alignment effects, individual data of response latency and absolute pointing error in each A-I condition (0º, 180º) were plotted in Figures S6 and S7 for all experiments.

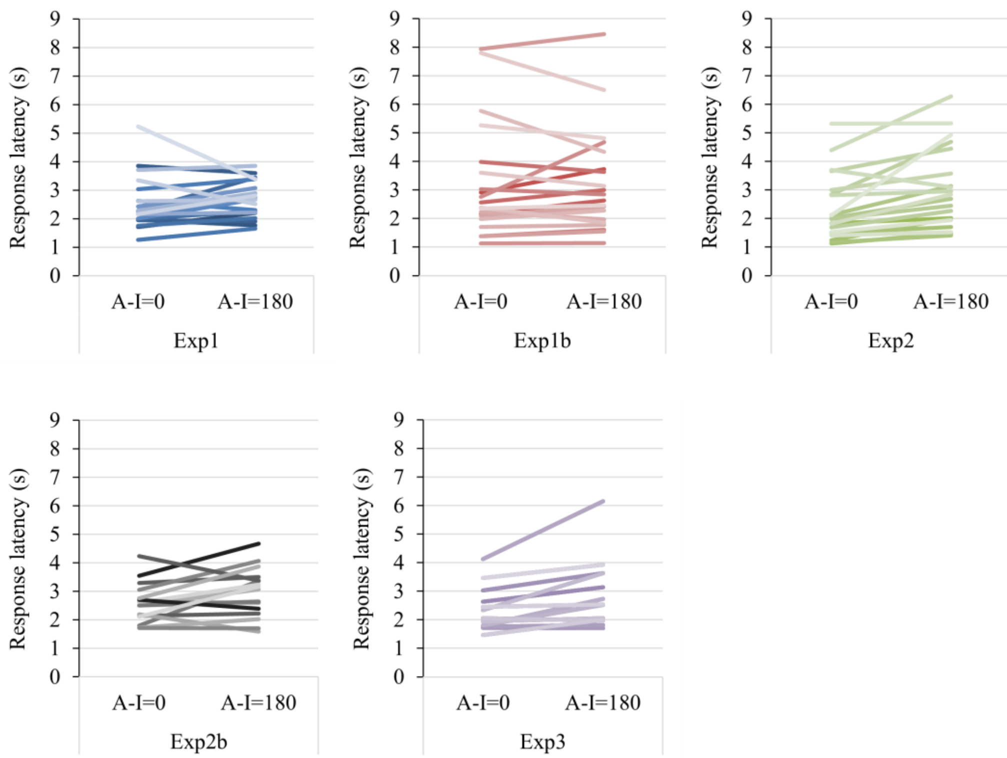


Figure S6. Individual data of response latency in the A-I=0 and A-I=180 conditions in all experiments. Each line represents one participant.

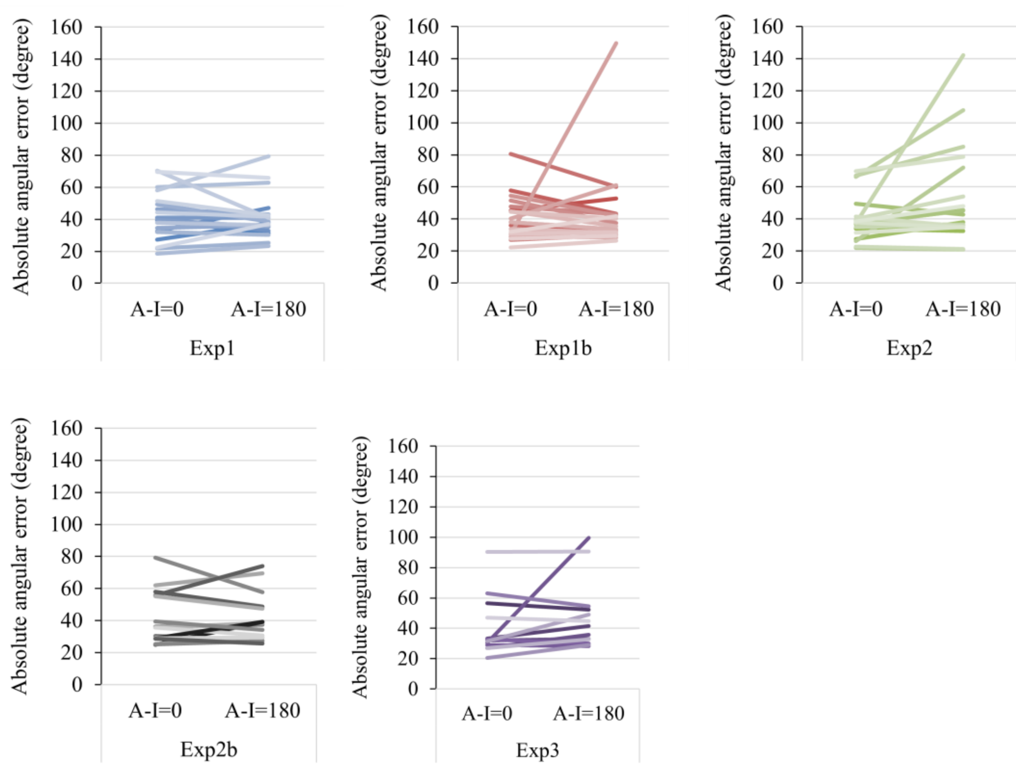


Figure S7. Individual data of absolute angular error in the A-I=0 and A-I=180 conditions in all experiments. Each line represents one participant.