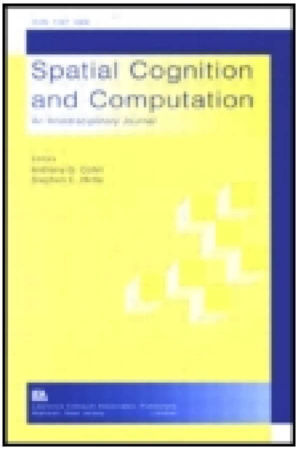

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Xianyun Liu [a b] , Weimin Mou [a c] & Timothy P. McNamara [d]

[a] Institute of Psychology, Chinese Academy of Sciences, Beijing, China
[b] Tianjin Normal University, Tianjin, China
[c] University of Alberta, Edmonton, Alberta, Canada
[d] Vanderbilt University, Nashville, Tennessee, USA

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Xianyun Liu,[1,2] Weimin Mou,[1,3] and Timothy P. McNamara[4]
[1]Institute of Psychology, Chinese Academy of Sciences, Beijing, China
[2]Tianjin Normal University, Tianjin, China
[3]University of Alberta, Edmonton, Alberta, Canada
[4]Vanderbilt University, Nashville, Tennessee, USA

Abstract: Three experiments examined the temporal characteristics in selection of a spatial reference direction. Participants learned a layout of objects presented sequentially in a random order. An array of disks with a symmetric axis different from participants' learning viewpoint was presented before, during, or after learning objects' locations. The results showed that the symmetric axis determined selection of a spatial reference direction when participants perceived the disk array before or during, but not after, learning the objects' locations. These results indicated that participants selected a reference direction prior to seeing objects.

Keywords: spatial reference directions, spatial memory, spatial cognition

1. INTRODUCTION

Memory of objects' locations is critical to our daily lives. Studies of spatial memory have extensively examined selection of spatial reference systems in organizing or reorganizing spatial memories of objects' locations (Shelton & McNamara, 1997, 2001; Greenauer & Waller, 2008, 2010; Mou, Liu, McNamara, 2009; Mou, Xiao, & McNamara, 2009; Waller, Lippa, & Richardson, 2008; Yamamoto & Shelton, 2008). However, the temporal and dynamical characteristics of selecting reference directions are still poorly understood (Kelly & McNamara, 2010). The purpose of the current project was to determine when a reference direction was selected to organize spatial memory.

Locations of objects in the environment can be specified in memory with respect to one or more spatial reference systems (Klatzky, 1998). Investigations of spatial memory have shown that people select a spatial reference system using a variety of cues. These cues include participants' viewing

Correspondence concerning this article should be addressed to Weimin Mou, P217 Biological Sciences Bldg., University of Alberta, Edmonton, Alberta, Canada T6G 2E9. E-mail: wmou@ualberta.ca

directions, external frames surrounding the object array, and intrinsic structure of the object array.

In an early study, Shelton and McNamara (1997) used the orientation dependency in judgments of relative direction (JRD; e.g., imagine you are standing at X, facing Y, please point to Z) to infer the role of learning viewpoints in selecting reference directions. They had participants learn a layout of objects from two learning viewpoints and then complete JRDs in a different room using their memories. The results showed that JRDs were more accurate at the imagined headings parallel to the learning viewpoints than at novel imagined headings. Recently, Waller et al. (2008) showed that spatial reference directions may be determined by the axis between the body and the array of objects and not the orientation of the body.

Yamamoto and Shelton (2008) showed that participants selected an egocentrically aligned reference direction even when they viewed objects sequentially in a random order. Results of these studies indicate that viewing direction can determine spatial reference directions.

There is also evidence indicating that spatial reference directions might be determined by cues independent of the observer (e.g., Greenauer & Waller, 2010; Hintzman, O'Dell, & Arndt, 1981; Marchette & Shelton, 2010; McNamara, Rump, & Werner, 2003; Mou, Liu, & McNamara, 2009; Mou & McNamara, 2002; Mou, Xiao, & McNamara, 2008; Shelton & McNamara, 2001; Werner & Long, 2003; Werner & Schindler, 2004; Werner & Schmidt, 1999).

Shelton and McNamara (2001) reported that participants selected reference directions parallel to the viewing directions that were aligned with the walls of the room or the edge of a mat on which objects were placed, but did not select reference directions parallel to the viewing directions that were misaligned with the room walls and mat edges (when more than one view was learned).

Mou et al. (2008) reported that the reference direction for a briefly viewed array of objects could be primed by the orientation of a rectangular table on which the array of objects was placed, even though the table orientation was misaligned with participants learning viewpoint. McNamara et al. (2003) found that spatial memory of a large-scale environment was organized with respect to the path walked and to a salient landmark in the environment. Finally, Marchette and Shelton (2010) demonstrated that participants even selected a reference direction that was cued by the intrinsic orientations of objects when all the objects were facing the same direction. Collectively, these results indicate that external frames can affect selection of spatial reference directions.

Spatial reference directions can also be determined by intrinsic structure of an array of objects, such as the axis of symmetry (e.g., Mou, Liu, & McNamara, 2009; Greenauer & Waller, 2010). Mou, Liu, and McNamara (2009) showed that participants selected a reference direction that was misaligned with their viewing direction but parallel to the symmetric axis of the layout. Participants learned a layout with a symmetric axis that was misaligned with their viewpoint. As participants were learning the layout, their eye movements were tracked.

After learning, participants were tested using JRD. Pointing performance was better at the imagined heading parallel to the symmetric axis of the layout than at the imagined heading parallel to the viewing direction. Moreover, the directions of eye movements between two fixations on objects corresponded with higher frequency to directions aligned (parallel and orthogonal) with the symmetric axis of the layout than to directions aligned with the viewing direction. These results indicated that the spatial reference directions in encoding and retrieving spatial locations were consistent and determined by the symmetric axis of the array. The influence of a symmetric axis in the selection of a reference direction was confirmed by Greenauer and Waller (2010).

Two recent studies investigated the selection of reference directions when people learned two arrays of objects presented in the immediate environment (Greenauer & Waller, 2010; Kelly & McNamara, 2010). Greenauer and Waller (2010) demonstrated that participants who learned two arrays that were simultaneously presented close to each other selected two misaligned reference directions, one for each array. Participants also established a third reference direction to integrate the two arrays together in memory. Kelly and McNamara (2010) required participants to learn separately in time two arrays of objects that were intermixed spatially; results indicated that participants nevertheless used a single reference direction to represent the objects' locations.

Spatial reference directions can be re-established when participants adopt a new viewpoint that is aligned with salient environmental structures. Valiquette, McNamara, and Labrecque (2007) found that when participants learned the layout of objects from a single view that was misaligned with salient environment structures, they used that view to establish a reference axis, but if they subsequently learned a view that was aligned with salient environment structures, the aligned view was used to establish a new reference axis (see also, Shelton & McNamara, 2001). Kelly and McNamara (2010) also reported that participants re-established a reference direction parallel to the second viewpoint that was aligned with the room's structure even when participants only visualized and pointed to the locations of the objects at the second viewpoint.

In all of these studies, the cues that influenced the selection of the reference direction were presented throughout the period of time during which participants learned the objects' locations. Hence, one cannot determine from these studies the stage at which the dominant cue overrides other cues and selection of a spatial reference direction occurs. Selection of a spatial reference direction might occur prior to encoding locations of objects. Alternatively it might occur during encoding locations of objects.

Theories of spatial memory do not make clear predictions either way. The purpose of this study was to address this issue by investigating whether a cue that has been confirmed to be dominant when it is presented during learning locations of objects can still prime a reference direction even when it is presented prior to learning.

As reviewed here, previous studies showed that a symmetric axis could override participants' learning viewpoint in selection of spatial reference directions (e.g., Mou, Liu, & McNamara, 2009; Greenauer & Waller, 2010). In the current study, an array of disks with an axis of symmetry, which was different from participants' viewpoint, was presented to prime a direction different from participants' viewpoint (Mou et al., 2009). Because the intrinsic structure of the array of objects may also affect the selection of the reference direction, the objects were presented sequentially in a random order (Yamamoto & Shelton, 2008).

JRDs were used to diagnose which cue determined the reference direction in spatial memory. Better JRD performance for the imagined heading parallel to the symmetric axis of the disk array than for the imagined heading parallel to the learning viewpoint will indicate that the disk array overrides participants' learning direction, whereas better JRD performance for the imagined heading parallel to the participants' learning viewpoint than for the imagined heading parallel to the symmetric axis of the disk array will indicate participants' learning direction overrides the disk array.

There are significant procedural differences between the current study and the previous studies (Mou, Liu, & McNamara, 2009; Greenauer & Waller, 2010). In the current study, objects were presented sequentially in a random order and the symmetric axis was presented by an array of disks. In the previous studies, objects were presented simultaneously and the symmetric axis was presented by the object array itself.

We hypothesized that the axis of symmetry of the disk array would be the dominant cue for the selection of a reference direction, in spite of these procedural differences. In Experiment 1, we tested this hypothesis by presenting the array of disks during learning of objects' locations. To preview the results, the axis of symmetry in the array of disks overrode participants' learning viewpoint, confirming that it was the dominant cue despite the procedural changes.

In Experiment 2, the array of disks was presented prior to the presentation of objects to test whether selection of the reference direction defined by the axis of symmetry occurs prior to learning objects. If the array of disks still overrides participants' learning viewpoint, it can be concluded that participants select this reference direction prior to learning objects' locations. To preview the results, the axis of symmetry in the array of disks overrode participants' learning viewpoint again. Experiment 3 was conducted to determine whether the JRD pattern in Experiment 2 was caused by factors other than the symmetric axis of the disk array. Experiment 3 was identical to Experiment 2 except that the array of disks was presented after the objects were presented.

We assumed that under these conditions, the learning viewpoint would be the dominant cue to a reference direction and that the brief presentation of the disk array would not be sufficient to cause the reference direction to be redefined. If the disk array could not override participants' viewing direction in Experiment 3, then the finding that the disk array overrode participants' viewing direction in Experiment 2 should be attributed to the disk array presented prior to the presentation of objects.

Previous studies have shown that selection of a reference direction could be determined by both nonegocentric cues (e.g., a table orientation) and participants' viewpoints in virtual environments (e.g., Mou, Xiao, & McNamara, 2008; Li, Mou, & McNamara, 2009). To easily implement the sequential presentation of objects, the layouts and the table were presented through an immersive head mounted display, the location and orientation of which were tracked.

2. EXPERIMENT 1

In Experiment 1, participants learned the locations of seven virtual objects on a circular virtual table (illustrated in Figure 1) from a single viewpoint. An array of circular virtual disks (illustrated by the black circles in Figure 1) was always present during learning and the objects were presented sequentially in a random order. The viewing direction is indicated in Figure 1 by the arrow of 315°; this arrow was not present in the experiment.

The axis of bilateral symmetry (along Glue-Apple-Ball) was 45° counterclockwise from the viewing direction, and is indicated in Figure 1 by the arrow of 0°; this arrow was also not present in the experiment. The main purpose of this experiment was to replicate the finding that the symmetric axis could override participants' viewpoint in selecting a reference direction (e.g., Mou, Liu, & McNamara, 2009; Greenauer & Waller, 2010) in the current experimental setting. Different from the previous studies, in this study, participants learned the locations of the objects sequentially and the reference direction was primed by an array of disks. In addition, participants learned objects in a virtual environment. All of these modifications require a replication of the previous finding.

2.1. Method

2.1.1. Participants. Eight university students (4 men, 4 women) participated in return for monetary compensation.

2.1.2. Material and Design. The virtual environment with a layout of objects on a table was displayed in stereo with light-weight (about 7 oz) glasses-like I-glasses PC/SVGA Pro 3D head-mounted display (HMD, I-O Display Systems, Inc. California). Participants' head motion was tracked with an InterSense IS-900 motion tracking system (InterSense, Inc., Massachusetts). The apparatus was placed in a 6 m × 6 m laboratory with each wall covered by homogeneous black curtains.

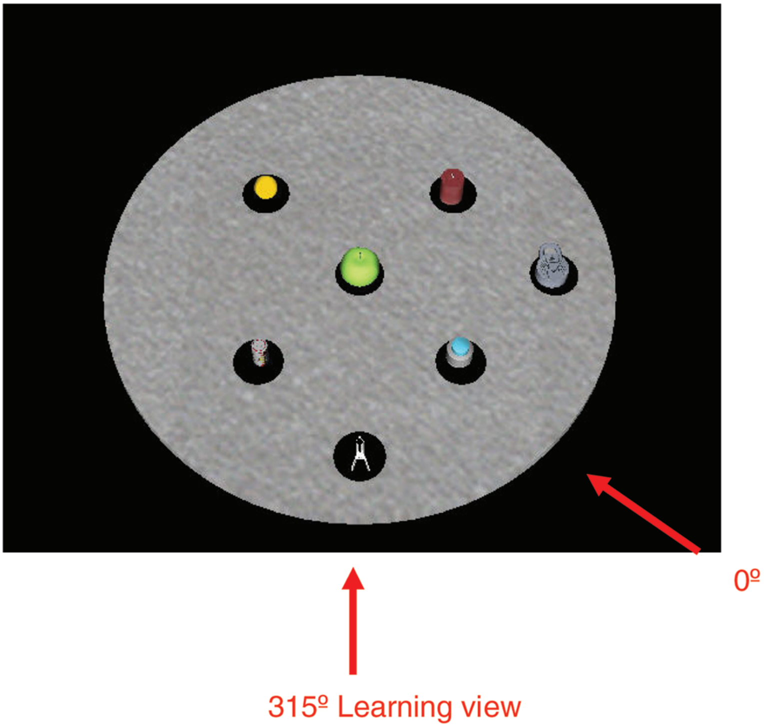

Figure 1. Layout of objects and disks used in Experiments 1, 2, and 3. The disks are the black circles underneath the objects. The objects were presented in a sequence. The disks were presented during, prior to, or after the presentation of the objects in Experiments 1, 2, or 3, respectively (color figure available online).

The virtual layout was presented on a virtual table with height of 69 cm and diameter of 80 cm in the center of the real laboratory room (Figure 1). The layout consisted of a configuration of seven objects and had a symmetric axis. Objects were selected with the restrictions that they be visually distinct, fit within approximately 6 cm on each side, and not share any obvious semantic associations. The distances between Clip and Glue and between Clip and Battery were both 21.2 cm. The distance between Clip and Apple was 30 cm. Participants stood at the viewing position which was 193 cm from the edge of the virtual table, guaranteeing that participants saw the whole table.

The symmetric axis (along Glue-Apple-Ball) was defined as the direction of 0° and the viewing direction (along Clip-Apple) was defined as the direction of 315°. All other allocentric directions between 0° to 315° were determined accordingly. For example, the direction of 45° was along Lock-Apple. The objects' locations were illustrated by circular virtual disks (with a diameter of 7.6 cm) that were always present during learning so that the symmetric axis of the layout could be perceived during the presentation of the sequence of objects in a random order.

Each test trial was constructed from the names of three objects in the layout and required participants to point to an object as if standing in a particular position within the layout; for example, "Imagine you are at the Glue facing the Apple. Point to the Candle." The first two objects established the imagined standing location and facing direction (e.g., Glue and Apple) and the third object was the target (e.g., Candle).

The primary independent variable for JRD was imagined heading. Eight equally spaced headings were used. Headings were defined in the same way as the allocentric direction was defined above, from 0° to 315° in 45° steps beginning with the position labeled 0° in Figure 1. For example, 0° corresponds to all headings oriented in the same direction as the arrow labeled 0° (e.g., at the Glue facing the Apple; at the Lock facing the Candle); and 315° corresponds to all headings oriented in the same direction as the arrow labeled 315° (e.g., at the Clip facing the Apple; at the Battery facing the Ball).

Pointing directions (the direction of the target object relative to the imagined heading) were approximately equivalent across the imagined headings. Participants were given ten blocks of the 48 trials. The order of presenting the trials in each block was randomized. The use of numerous blocks of trials and fewer subjects instead of one block and more subjects was consistent with previous studies (e.g., Mou, Liu, & McNamara, 2009).

The dependent measures in JRDs were the response latencies measured as the latencies from presentation of the name of the target object to the pointing response, and the angular error of the pointing response, measured as the absolute angular difference between the judged pointing direction and the actual direction of the target.

2.2. Procedure

2.2.1. Learning Phase. Before entering the study room, each participant was instructed to learn the locations of the objects for a spatial memory test and trained how to use a joystick to make a judgment of relative direction. Then the participant was blindfolded and led to the viewing position and donned the head-mounted display. Through the head-mounted display, a table with circular disks was presented and the participant was informed that the objects would be presented on the disks. Then the objects were presented sequentially in a random order.

Each object was presented for 4.29 seconds and then disappeared before the presentation of the following object. As a result the participant viewed one complete sequence of objects for 30 seconds. After viewing one object sequence, the participant was asked to name and point to, with eyes closed, the objects in any order the participant preferred. After pointing, the participant viewed the same sequence of objects. After 10 such viewing-pointing sessions, the participant was blindfolded and led by the experimenter to the testing room. The table and disks were always presented when the participant viewed the sequence of presenting objects.

2.2.2. Testing Phase. Seated in a chair, the participant wore a pair of earphones and held a joystick. The test trials were presented via the earphones attached to a PC computer. The participant first initiated each trial by pressing a button of the joystick. Trials proceeded as follows: The imagined standing location and facing object were given aurally (e.g., "Imagine you are standing at the Glue facing the Apple.") as in Mou, Liu, and McNamara (2009).

The participant was instructed to pull the joystick trigger when he or she had a clear mental image of where he or she was standing and what he or she was facing. The target object was immediately presented aurally when the participant pulled the trigger (e.g., "Point to the Candle"). The participant used the joystick to point to where the target would be if he or she occupied the standing location and facing direction as presented. The participant was instructed to hold the joystick exactly in the front of his or her waist and keep the joystick forward when he or she pointed. Pointing accuracy was emphasized ("please point only after you are sure where the target is").

2.3. Results and Discussion

Mean pointing latency is plotted in Figure 2 as a function of imagined heading and block. Pointing latency was analyzed in repeated measures analyses of variance (ANOVAs) with terms for imagined heading (0° to 315° in 45° steps) and block. The effect of imagined heading was significant, $F(7, 49) = 6.23$, $p < .001$, $MSE = 4.76$. The effect of block was significant, $F(9, 63) = 8.49$, $p < .001$, $MSE = 3.40$. The interaction between imagined heading and block was not evident, $F(63, 441) = 1.18$, $p > .05$, $MSE = .92$. A planned comparison showed that latency at the heading of 0° was significantly shorter than at the headings of 315°, $t(49) = 2.69$.

As shown in Figure 2, there was a sawtooth pattern which may indicate that participants might use two orthogonal reference directions, one parallel and the other orthogonal with the symmetric axis (e.g., Hintzman et al., 1981). Mean latency across the novel headings of 90°, 180°, and 270°, which were aligned with the symmetric axis of 0°, was significantly shorter than mean latency across the novel headings 45°, 135°, and 225°, which were aligned with the learning view of 315°, $t(49) = 4.98$, which indicated that the sawtooth pattern was reliable.

One may suspect that participants might reorganize their memory during ten blocks of testing trials (Greenauer, Mello, Avraamides, & Waller, 2010) such that the superior performance at the heading of 0° over that at the heading of 315° was caused by the repeated testing. Furthermore, the null

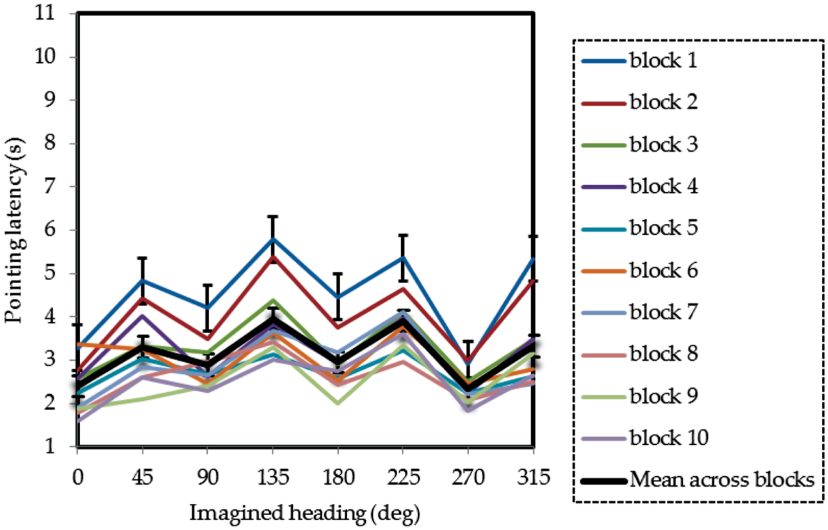

Figure 2. Pointing latency as a function of imagined heading and block in Experiment 1. Error bars of the first block of testing trials and the mean across the blocks are illustrated and correspond to ±1 standard errors (color figure available online).

effect of the interaction between heading and block might be due to the lack of power as the small number of participants was used. In order to ensure that the superior performance at the heading of 0° over that at the heading of 315° was not caused by any effect of repeated testing, the first block of the data was also analyzed.

Pointing latency was analyzed in repeated measures analyses of variance (ANOVAs) with one term for imagined heading (0° to 315° in 45° steps). The effect of imagined heading was significant, $F(7, 49) = 3.79$, $p < .01$, $MSE = 2.21$. A planned comparison showed that latency at the heading of 0° was significantly shorter than at the headings of 315°, $t(49) = 2.76$. Mean latency across the novel headings of 90°, 180°, and 270°, which were aligned with the symmetric axis of 0°, was significantly shorter than mean latency across the novel headings 45°, 135°, and 225°, which were aligned with the learning view of 315°, $t(49) = 3.43$, which indicated that the sawtooth pattern was reliable.

Mean angular error is presented in Table 1 as a function of imagined heading. The effect of imagined heading was not significant, $F(7, 49) = 1.42$, $p > .05$, $MSE = 36.70$. No trade-off was found between pointing latency and error. The Pearson Correlation level between the pointing latency and pointing error was 0.75. In this and the following experiments, there were no trade-offs between latency and angular error; that is, angular error at an imagined heading with shorter latency was not larger than angular error at

Table 1. Mean (and standard deviation) angular error (in degrees) as a function of imagined heading for each experiment

Experiment number	Imagined heading							
	0°	45°	90°	135°	180°	225°	270°	315°
1	16 (5)	21 (4)	23 (9)	23 (9)	21 (12)	22 (11)	17 (6)	19 (5)
2	20 (3)	22 (5)	24 (8)	28 (12)	25 (7)	31 (9)	20 (8)	22 (3)
3	28 (12)	29 (9)	33 (14)	25 (11)	31 (14)	25 (11)	27 (18)	24 (7)

an imagined heading with longer latency. Hence, the results of latency were used to determine the preferred imagined heading.

The results confirmed that the symmetric axis of the disk array could override participants' viewpoint as a cue to the reference direction, in spite of the sequential presentation of objects and the other procedural differences between this study and previous ones (e.g., Mou, Liu, & McNamara, 2009; Greenauer & Waller, 2010).

3. EXPERIMENT 2

In Experiment 2, participants viewed the circular disks for five seconds just before the objects were presented sequentially in a random order. The main purpose of this experiment was to investigate whether the disk array would override participants' viewpoint in selection of a reference direction before participants learned the object-location relations.

3.1. Method

3.1.1. Participants. Eight university students (4 men, 4 women) participated in return for monetary compensation.

3.1.2. Materials, Design, and Procedure. The materials, design, and procedure were similar to those used in Experiment 1 except that the array of circular disks was presented once, for a duration of 5 seconds, prior to the first presentation of the objects. Participants therefore did not see the array of disks at any time while they were learning the locations of the objects.

3.2. Results and Discussion

Mean pointing latency is plotted in Figure 3 as a function of imagined heading and block. The effect of imagined heading was significant, $F(7, 49) = 13.85$, $p < .001$, $MSE = 4.60$. The effect of block was significant, $F(9, 63) =$

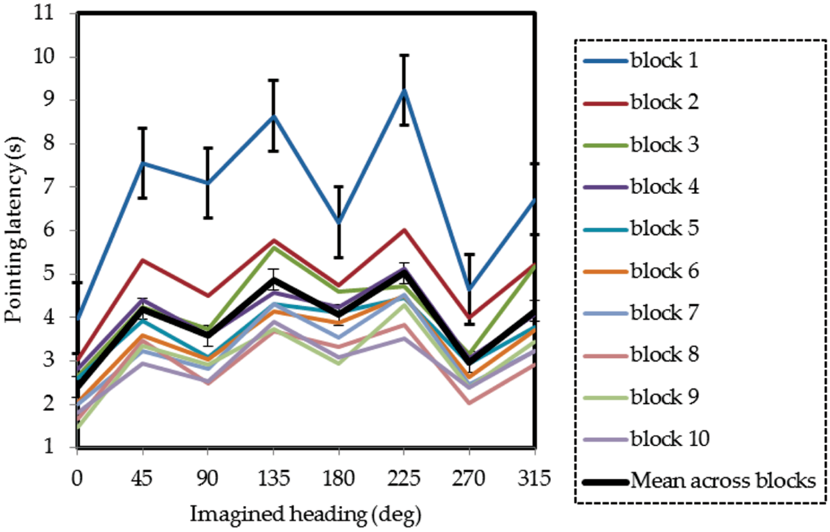

Figure 3. Pointing latency as a function of imagined heading and block in Experiment 2. Error bars of the first block of testing trials and the mean across the blocks are illustrated and correspond to ±1 standard errors (color figure available online).

13.35, $p < .001$, $MSE = 6.62$. The interaction between heading and block was also significant, $F(63, 441) = 1.39$, $p < .05$, $MSE = 1.02$. A planned comparison showed that latency at the heading of 0° was significantly shorter than that at the headings of 315°, $t(49) = 5.14$. Mean latency across the novel headings of 90°, 180°, and 270°, which were aligned with the symmetric axis of 0°, was significantly shorter than mean latency across the novel headings 45°, 135°, and 225°, which were aligned with the learning view of 315°, $t(49) = 5.92$, indicating a sawtooth pattern.

To remove any effect of repeated testing on memory reorganization, only the first block of the data was analyzed. The effect of imagined heading was significant, $F(7, 49) = 5.0$, $p < .001$, $MSE = 5.24$. A planned comparison showed that latency at the heading of 0° was significantly shorter than that at the headings of 315°, $t(49) = 2.39$. Mean latency across the novel headings of 90°, 180°, and 270°, which were aligned with the symmetric axis of 0°, was significantly shorter than mean latency across the novel headings 45°, 135°, and 225°, which were aligned with the learning view of 315°, $t(49) = 3.78$, indicating a sawtooth pattern.

Mean angular error is presented in Table 1 as a function of imagined heading. The effect of imagined heading was significant, $F(7, 49) = 2.89$, $p < .05$, $MSE = 40.81$. Accuracy at the heading of 0° was not significantly different from that at the headings of 315°, $t(49) = .91$. No trade-off was found between pointing latency and error. The Pearson Correlation level between the pointing latency and pointing error was 0.87.

The results showed that the symmetric axis of the disk array overrode participants' viewpoint in selection of a reference direction even when the disk array was presented before participants learned the object-location relations.

4. EXPERIMENT 3

In Experiment 3, the layout's geometric structure was displayed for 5 s after participants finished the sequential learning of objects' locations. The main purpose of this experiment was to examine whether any extraneous factors other than the presentation of the array of disks prior to the presentation of objects caused the results in Experiment 2. For example, one may argue that the JRD trials with the imagined heading parallel to the symmetric axis might be easier *a priori* than those with the imagined heading parallel to the learning viewpoint regardless of the experimental manipulations.

If the results of Experiment 3 showed a different JRD pattern, in particular that the imagined heading parallel to the symmetric axis of the array of disks was not superior to the imagined heading parallel to participants' learning viewpoint, then we could be more confident that presentation of the array of disks prior to the presentation of objects caused the selection of a reference direction parallel to the symmetric axis of the array of disks in Experiment 2.

4.1. Method

4.1.1. Participants. Eight university students (4 men, 4 women) participated in return for monetary compensation.

4.1.2. Materials, Design, and Procedure. The materials, design, and procedure were similar to those used in Experiment 2 except that the disks were displayed five seconds after participants learned the objects sequences for 10 times.

4.2. Results and Discussion

Mean pointing latency is plotted in Figure 4 as a function of imagined heading and block. Pointing latency was analyzed in repeated measures analyses of variance (ANOVAs) with terms for imagined heading (0° to 315° in 45° steps) and block. The overall effect of imagined heading was significant, $F(7, 49) = 2.20$, $p < .05$, $MSE = 5.11$. The block effect was significant, $F(9, 63) = 19.85$, $p < .01$, $MSE = 4.67$. The interaction between heading and block was not evident, $F(63, 441) = 1.21$, $p > .05$, $MSE = 1.44$. Latency at the heading of 315° was not significantly shorter than that at the headings of 0°, $t(49) = .96$.

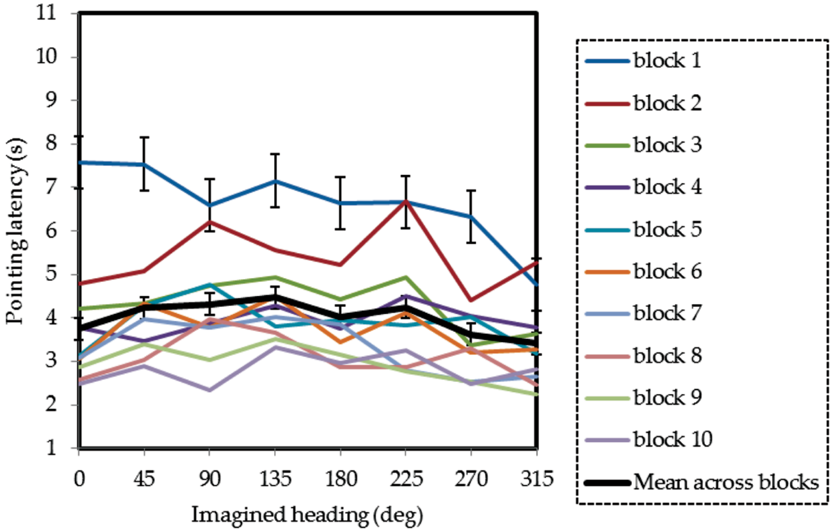

Figure 4. Pointing latency as a function of imagined heading and block in Experiment 3. Error bars of the first block of testing trials and the mean across the blocks are illustrated and correspond to ±1 standard errors (color figure available online).

The first block of the data was also analyzed. Pointing latency was analyzed in repeated measures analyses of variance (ANOVAs) with one term for imagined heading (0° to 315° in 45° steps). The overall effect of imagined heading was marginally significant, $F(7, 49) = 2.17$, $p > .05$, $MSE = 2.92$. Latency at the heading of 315° was significantly shorter than that at the headings of 0°, $t(49) = 3.28$.

Mean angular error is presented in Table 1 as a function of imagined heading. The effect of imagined heading was significant, $F(7, 49) = 1.62$, $p > .05$, $MSE = 51.01$. No trade-off was found between pointing latency and error. The Pearson Correlation level between the pointing latency and pointing error was 0.29.

The results showed that the symmetric axis of the array of disks did not override the learning viewpoint, at least in the first of block of the test, providing evidence that the presentation of the array of disks prior to the presentation of objects in Experiment 2 caused the superior effect at the imagined heading parallel to the symmetric axis of the disk array.

5. GENERAL DISCUSSION

The temporal characteristics of organizing and reorganizing spatial memory are poorly understood. This study examined whether selection of reference directions could occur prior to or during learning of the locations of objects by placing cues to different spatial reference directions in conflict. A symmetric axis was presented during, prior to, or after the presentation of objects in Experiments 1, 2, or 3 respectively. The results showed that the symmetric axis overrode the participants' learning viewpoint in Experiments 1, 2, but not Experiment 3.

The finding that a symmetric axis overrode the participants' learning viewpoint was not novel. Previous studies showed that an axis of symmetry could determine a nonegocentric reference direction in memory of the layout (e.g., Greenauer & Waller, 2010; Mou, Liu, & McNamara, 2009). One new finding in the current study is that an axis of symmetry of an array of disks could override participants' viewing direction in determining a nonegocentric reference direction when objects were presented sequentially in a random order and in a virtual environment (Experiment 1). A more important new finding in the current study was that the axis of symmetry of an array of disks could override participants' viewing direction in determining a nonegocentric reference direction when the array of disks was briefly presented prior to the presentation of objects (Experiment 2).

This finding for the first time clearly indicated that selection of a spatial reference direction might occur prior to learning where objects were located. Experiment 3 showed that this finding was probably not caused by other confounding factors. In Experiment 3 participants saw the array of disks after the presentation of the objects. As in Experiment 2, the presentation of the symmetric axis lasted for 5 seconds in Experiment 3. The only difference between Experiments 2 and 3 is the presentation order of the symmetric axis and learning sequence. The result showed that the axis of symmetry did not determine the spatial reference direction when it was presented after participants learned the objects' locations.

The current study showed that participants could select a reference direction determined by a nonegocentric cue prior to encoding objects' locations. We speculate that selection of a reference direction determined by participants' learning viewpoint should also occur prior to encoding objects' locations. An object's location must be specified with respect to a reference system in memory. Without a reference system, location cannot be defined. Hence people might need to select a reference direction first whether using egocentric or nonegocentric cues, and then encode locations of objects sequentially, as indicated by the eye movement pattern reported by Mou, Liu, and McNamara (2009). Of course, it would be challenging to test directly whether selection of a reference direction determined by participants' learning viewpoint occurs prior to or during encoding objects' locations because the learning viewpoint cannot be removed during learning.

In addition to the key finding that participants could select a reference direction prior to learning objects, other findings in the current study also have meaningful implications for the temporal characteristics of organizing or reorganizing spatial memory.

The findings of Experiment 2 imply that once a reference direction is established, the visual presentation of the reference direction is not necessary to organize spatial memory of objects' locations. It is possible that participants were able to maintain the reference direction in the absence of the disk array because they represented their learning viewpoint with respect to the reference direction and their learning viewpoint did not change even though the symmetric axis was removed. Participants might have visualized the whole array of locations while objects were assigned to locations. Future studies are warranted to test whether this finding would generalize to situations in which participants move after the brief presentation of the array of disks.

Experiment 2 also showed that a 5 second presentation of the symmetric axis was enough to establish a reference direction. This suggests that selection of a reference direction might be a relatively quick process. Several interesting questions follow from this conjecture: What is the minimum time needed to establish a reference direction? Does this time differ for egocentrically aligned and nonegocentrically aligned directions and is it variable across different layouts of objects? Additional experimental study is needed to answer these questions.

Experiment 3 showed that presentation of the symmetric axis after learning sequence does not override the viewpoint aligned reference direction at least at the first block of test. However we should not conclude from this result that people cannot reorganize spatial memory using a new reference direction given appropriate experiences. Indeed, previous studies have shown that people can change reference directions when they experience a more salient direction (e.g., Kelly & McNamara, 2010; Shelton & McNamara, 2001; Valiquette, McNamara, & Labrecque, 2007).

The results of Experiment 3 might have occurred because participants did not have a strong motivation or incentive to recode their spatial knowledge on the basis of information that was only displayed very briefly. In previous experiments, participants learned or visualized the locations of the objects at the second viewpoint for a substantial amount of time. Future studies are needed to examine the roles of the duration of presentation of a new cue and the motivations for reselecting a spatial reference direction.

The current study used a virtual environment because it made implementing the experiments much easier. We believe that the current findings will generalize to real environments because symmetric axes have been shown to override participants' learning viewpoint in both real and virtual environments (e.g., Mou, Liu, & McNamara, 2009; Greenauer & Waller, 2010).

Although the results of the present experiments raise many questions about the dynamic and temporal characteristics of organizing and reorganizing spatial representations, they also answer the question raised in the Introduction. A symmetric axis dominated participants' learning viewpoint in determining the spatial reference direction in memory when participants briefly viewed the symmetric axis prior to seeing objects. This finding indicated that people can select a reference direction prior to encoding of objects' locations.

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