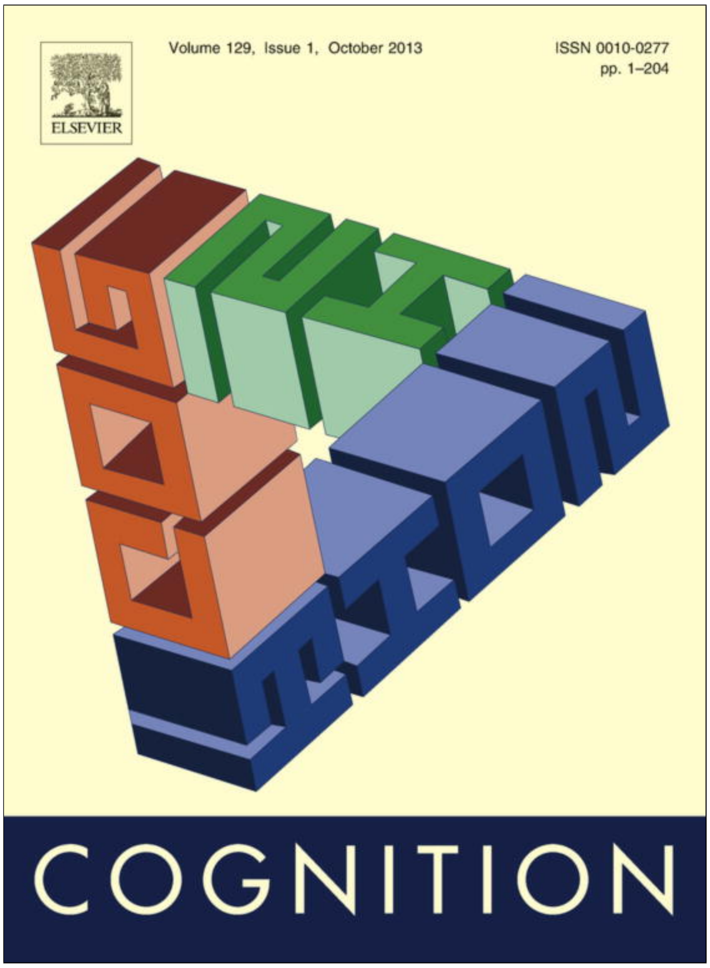
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Global frames of reference organize configural knowledge of paths

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ABSTRACT

Five experiments examined the organization of spatial memory of an irregular path learned by walking with vision. Two hypotheses were tested: (a) that participants would establish a single global frame of reference to organize the spatial memory of the path; or alternatively (b) that participants would establish path-aligned reference directions at each path leg but not establish a global frame of reference. Participants donned a head-mounted display and were asked to navigate through a virtual six-segment path with each turning point indicated by a virtual object. The six legs consisted of two groups of three legs. The legs within groups were aligned (parallel or orthogonal) with each other and between groups were misaligned (45° tilted) with each other. At each leg, participants only perceived the object at the end of this leg. After participants walked the legs 10 times they conducted judgments of relative directions (JRD, e.g. "imagine you are standing at X, facing Y, please point to Z"). The imagined headings in JRD were parallel to the experienced path legs. The paths varied in terms of the salience of the longest leg. Appearance of a room was also manipulated to highlight one group of the legs. The results showed that participants demonstrated significantly lower pointing error for (a) the longest leg when there was no room or (b) the first walking leg when there was no obvious longest leg or the longest leg was misaligned with the room. Pointing error was equivalent for the longest leg and the first walking leg when the longest leg was salient and misaligned with the first walking leg. These results suggested that participants established a single global frame of reference when there was a single salient context cue. However, two oblique reference frames can be established when there are two inconsistent contextual cues.

1. Introduction

In everyday life, people need to walk a variety of paths with multiple segments. For example, over the course of a day, a college student might walk an irregular path from one building to another, returning to the dormitory at the end of the day. A path (e.g., dormitory – building A – building B –...– dormitory) can be defined as a sequence of the landmarks (e.g., buildings) and the traversed legs between any two adjacent landmarks. Landmarks are usually learned by visual perceiving the location and the identity whereas the legs (e.g., distance, turning angle) are primarily learned by path integration (Siegel & White, 1975). A great deal of research has been conducted on the nature of spatial memory learned by walking (or navigation) and how people establish a reference system to organize spatial memory of object arrays. However, what is missing in the literature is a good understanding of how people establish spatial reference frames to organize spatial memory of a path by walking it with vision. This project was conducted to address this issue.

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Spatial knowledge acquired by path integration (or navigation) can be contrasted with spatial knowledge learned by map reading (e.g. Richardson, Montello, & Hegarty, 1999; Shelton & McNamara, 2004; Taylor, Naylor, & Chechile, 1999; Thorndyke & Hayes-Roth, 1982). Spatial knowledge acquired by walking (or navigation) consists primarily (at least initially) of route knowledge whereas spatial knowledge acquired by map reading consists primarily of survey knowledge. Route knowledge has a ground level perspective and is specific to the sequences of segments of the route traveled. Route knowledge supports estimation of the route distance, judgments of the order of the segments, and description the visual appearance of the route. Survey knowledge has a top-down perspective and embodies the information of direction and straight line distance between two places or landmarks. Survey knowledge supports estimation of straight-line distance, and judgments of directions (e.g. McNamara, in press for a review).

Survey knowledge can also be developed by walking (or navigation). Thorndyke and Hayes-Roth (1982) reported that participants who had extensive navigation experience in one specific building developed survey knowledge of the environment that was as good as the survey knowledge acquired by participants who learned the environment by map reading. Taylor et al. (1999) reported that participants who only learned one environment by navigation could develop better survey knowledge if they were explicitly asked to pay attention to the layout of the environment. Ishikawa and Montello (2006) reported that participants developed survey knowledge and route knowledge simultaneously even when participants learned a route by navigation for the first time. Participants could estimate the directions of the places on the route at above chance level after they were passively transported by automobile on this route only once.

The spatial memory literature indicates that spatial memory of objects' locations is organized in terms of a reference frame (e.g., Greenauer & Waller, 2010; Kelly & McNamara, 2010; Mou & McNamara, 2002; Shelton & McNamara, 2001; see McNamara, Sluzenski, & Rump, 2008 for a review). In a typical experiment, participants learned an array of objects in a room from a small number of viewpoints. At each viewpoint participants could see all objects. After learning the array, participants made judgments of relative direction (JRD) using their memories (e.g., "Imagine you are standing at mug, facing phone, please point to ball"). The imagined heading, which was defined by the direction between the first two objects (e.g., from mug to phone), included the headings parallel to the learning viewpoints and several novel headings. A common finding in such experiments is that JRD performance is better for certain key imagined headings than for others; for example, JRD performance is often better for imagined headings parallel to a learning viewpoint than for imagined headings parallel to novel viewpoints (see discussion below for important exceptions to this pattern).

Findings of this kind have been explained in a theoretical framework in which the bearings between objects (e.g., from mug to ball) are represented with respect to a reference direction (Mou, McNamara, Valiquette, & Rump, 2004; Rump & McNamara, 2013). When the imagined heading is aligned with the reference direction, the tested bearing between the first object and the third object (e.g., from mug to ball) in the JRD trial can be directly retrieved from memory, whereas when the imagined heading is misaligned with the reference direction, the tested bearing between the first object and the third object in the JRD trial must be inferred (e.g., Klatzky, 1998). These inferential processes produce costs in error and latency for JRD trials in which the imagined heading is misaligned with a reference direction relative to those trials in which the imagined heading is aligned with a reference direction.

One of the important findings in the studies of spatial memory of an object array is that not all viewing directions determine a reference frame. For example, Shelton and McNamara (2001, see also Kelly & McNamara, 2010) had participants learn an array of objects from two oblique viewpoints (0° and 135°), one of which was aligned with walls of the experiment room. The superior effect of the learning viewpoint was only observed at the learning viewpoint that was aligned with the external reference frames (e.g., the walls of the room). There was no evidence that the learning viewpoint that was misaligned with the external frames was superior to the novel viewpoints. However, the superior effect of the learning viewpoint misaligned with the external frames was observed if it was the only learning viewpoint. These results indicated that when participants experienced multiple oblique viewpoints, they established reference directions that were aligned with both the learning viewpoints and the external frames. Mou, Zhao, and McNamara (2007) also showed that when participants experienced multiple oblique viewpoints without any salient external frame in a circular room, they established reference directions that were aligned with both the learning viewpoints and the intrinsic feature of the array (e.g., axis of bilateral symmetry). These results indicated that participants had difficulty in establishing two oblique reference directions.

In some special circumstances, participants seem to be able to establish two oblique reference directions. For example, Shelton and McNamara (2001) showed that participants might represent two oblique viewpoints when one of them was aligned with the global external frame (i.e., the walls of the room) and one of them was aligned with the local external frame (i.e., the edges of a mat). Yamamoto and Shelton (2005) also showed that participants established two oblique reference directions. Participants learned an array of objects from two oblique orientations. Participants viewed the locations of the objects at one of learning orientation and walked without vision to the locations of the objects at the other learning orientation. The results showed equivalent performance at both experienced headings. These findings indicated that participants were able to establish two oblique reference directions when each of them was supported by a salient context. It is possible that under such circumstances participants treat the same array as two different arrays from two different viewpoints. Greenauer and Waller (2010) reported that participants established two oblique reference directions when they segmented objects into two different arrays even from a single viewpoint.

Participants learned two arrays of objects, which were spatially proximate. The two arrays of objects were distinguished by category (toy or office supplies) and being placed on two different colored disks (blue or orange). Furthermore, both of the arrays had a perceptually salient axis of bilateral symmetry and the symmetric axes were misaligned with each other. The JRD results showed that participants were able to establish two oblique reference directions, one for each of the two arrays.

A principal aim of the present project was to investigate whether people establish a reference system to organize the configural knowledge of a path learned by walking with vision. The spatial memory literature does not provide a clear answer to this question because few studies have directly investigated it. Meilinger, Riecke, and Bülthoff (2007) investigated this question by having participants learn an immersive virtual environment by repeatedly walking a seven-segment route in which they saw one unique object in each segment. For each test trial, participants were teleported to each of the segments and were presented one of eight views of the segment. Participants were required to point to one of the objects in the other segments. The results showed that participants were more accurate in pointing when the view of the segment was the same as the walking direction; however, participants were not more accurate in pointing when the view of the segment was the same as the first or the longest segment of the route. The first and the longest segment of a route might have been the two best candidates for use as a global reference direction because the first segment is distinctive in terms of egocentric experiences (Shelton & McNamara, 2001) and the longest segment of the route is salient in terms of intrinsic feature of the path (Mou & McNamara, 2002). Meilinger et al. concluded that a local reference direction was established at each segment of the route by the walking direction or the direction of the segment of the route, but a global reference direction was not established to organize the spatial memory of the whole route.

Meilinger et al.'s (2007) study indicated that spatial memory of a path learned by walking with vision might differ from spatial memory of object arrays learned at several static viewpoints or learned by map reading. Spatial memory of a path learned by walking might not have a global reference frame; instead it might have a reference frame at each leg of the path or each experienced viewpoint. Spatial updating processes during walking could account for the finding that spatial memories appear to be orientation independent when participants are tested on headings parallel to familiar legs of the path (e.g., Sholl & Bartels, 2002; Waller, Montello, Richardson, & Hegarty, 2002). For example, when a university student navigates to each landmark (e.g., building A) on a path, he or she may update bearings of all other landmarks relative to the current location (e.g., from building A to building B, from building A to dorm) in terms of the current walking direction (e.g., Wang & Spelke, 2000). If we assume that people can represent these bearings in terms of the local reference direction (walking direction) in long-term memory, then JRD performance may be equally good at all experienced headings parallel to the walking direction in each leg.

Other studies, however, indicated that spatial memory acquired by navigation does have a preferred orientation. McNamara, Rump, and Werner (2003) tested spatial memory after participants physically walked a square route in a park. Eight objects were placed on the route, two on each leg of the route. The results showed that JRD performance at the imagined headings aligned with the legs along the route was better than performance at the imagined headings misaligned with the legs along the route. Recently, evidence has indicated that spatial memory of a familiar environment has a preferred orientation although the learning procedure in these studies was not controlled (e.g. Frankenstein, Mohler, Bulthoff, & Meilinger, 2012; Marchette, Yerramsetti, Burns, & Shelton, 2011). In Frankenstein et al.'s study, participants pointed to familiar target locations in their hometown from various orientations. Participants' performance was most accurate when the orientation was north. Similarly, Marchette et al. reported that students were most accurate in pointing to the buildings of their campus from a perspective that was aligned with salient axes defined by the buildings and paths. These two experiments suggest that spatial memory of a familiar environment, which is presumably learned by navigation, has a global reference direction, although Frankenstein et al. acknowledged that participants may develop the orientation dependent memory of their home town due to map reading in everyday life.

The discrepancy between Meilinger et al.'s (2007) and McNamara et al.'s (2003) findings might be due to the difference in selection of the imagined headings or the way in which imagined headings in the JRD tasks were specified. Meilinger et al. (2007) used eight test headings but test headings were specified by providing participants with views of route segments. Participants might develop a global reference system aligned with the first walking segment or aligned with the longest segment. The absence of superior performance in pointing at the headings parallel to the first or the longest segment of the route might be due to the difficulty in recognizing the novel views of the segment, even though the view was indeed aligned with the global reference system. For example, when participants had a novel view of a specific leg, although the view was indeed aligned with the global reference system, participants might not be aware of this relation because they had never seen the view before. The orientation dependency observed by McNamara et al. (2003) may be due to the selection of the imagined headings at test. They used the imagined headings aligned with the path and the imagined headings misaligned with the path. The aligned imagined headings were all experienced and the misaligned headings were all novel. Orientation dependence was supported by the superior performance at the experienced headings relative to the novel headings. Performance across the experienced headings, which were aligned with each other, did not differ significantly. Their results therefore cannot eliminate the possibility that a local reference direction was established at each walking leg and no global reference direction was established to organize the path memory as Meilinger et al. proposed.

In conclusion, it is still not clear whether spatial memory of multiple-leg path learned by walking with vision is organized with respect to a single (global) reference system or only with respect to multiple local reference directions established at each walking leg. The experiments in this project were designed to tackle this issue. We believe that an experiment designed to investigate this issue should meet two requirements. First, the path should be irregular, which means that some turning angles should be oblique. Otherwise equivalent performance at all experienced headings may be due to the existence of a single global reference system that is aligned with all the experienced legs, as indicated by the sawtooth pattern in the previous studies (e.g. Mou & McNamara, 2002), or due to the existence of multiple local reference systems at each experienced path segment. Second, performance should be assessed only for experienced legs of the path or, if a novel heading that is parallel to the assumed global reference direction is used, participants should be informed that this heading is parallel to the global reference direction. Otherwise the facilitative effect of the single global reference system will be confounded by the superiority of experienced testing perspective to the novel testing perspective. The first aim of this study was to test whether spatial memory of a path learned by walking with vision is organized with respect to a single global reference system. The second aim of this study was to test which cues might determine the reference systems used to organize spatial memory acquired by walking with vision. Previous studies showed that selection of reference directions is the output of an interaction among egocentric, allocentric, and intrinsic cues when people learn an array of objects. The potential cues manipulated in the current study included the longest leg, which corresponds to an intrinsic feature of the path, the external environment, which is an allocentric cue, and the first walking leg, which is a distinctive egocentric cue. Hence, the relative importance of different cues in the current study could be compared to that in previous studies that examined the spatial memory of object arrays.

2. Experiment 1

In Experiment 1, participants walked six legs along the path illustrated in Fig. 1A. Participants saw one object at a time and walked the legs in a sequential order. One of the legs (hat–ball) was significantly longer than the others. There were two environmental cue conditions: In the room condition, participants saw a rectangular room with the orientation misaligned with the longest leg as illustrated in Fig. 1B. In the no room condition, participants did not see the room. Participants started the path at one of the six possible starting positions (ball, clock, mug, phone, brush, and hat).

The main purposes of the experiment were to investigate whether participants had a preferred orientation in memory of the path; whether the preferred orientation was determined by the longest leg or the first walking path in the no room condition; and whether the preferred orientation was determined by the room orientation, the longest leg or the first walking in the room condition. Participants experienced the path in immersive virtual reality, as this allowed us to control the sequential appearance of legs and to change the appearance of the room.

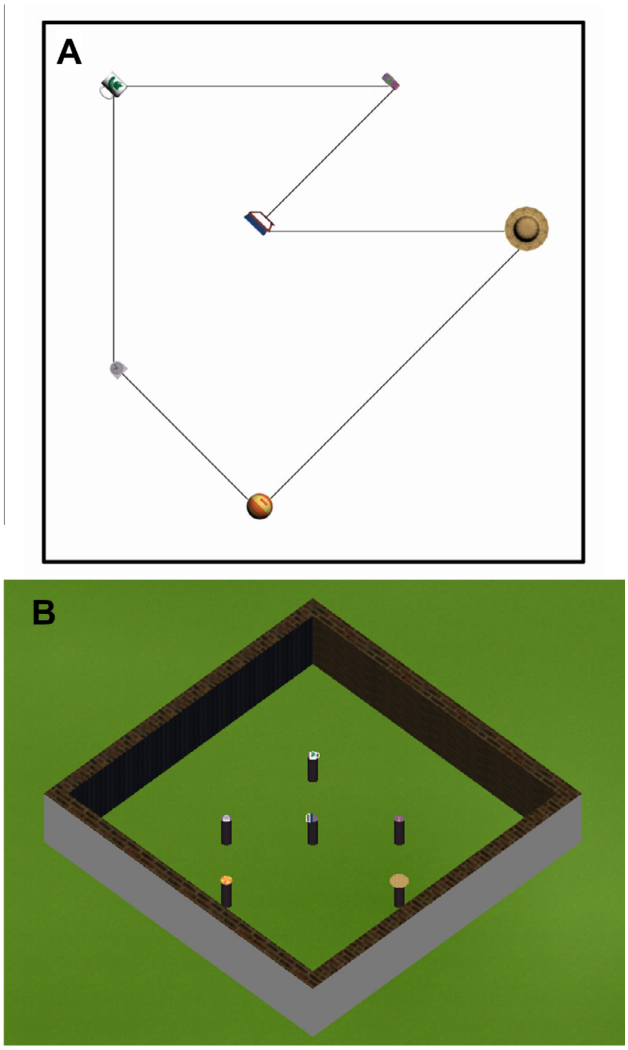

Fig. 1. The path and room used in Experiments 1 and 2. Figure A is the schematic layout of the path. The lines between objects are used to illustrate the legs and were not presented to participants in Experiments. The external square refers to the square room in the room condition in Experiment 1 and in Experiment 2. Figure B is the snapshot of the layout and room (only in the room condition in Experiment 1) from an external levitated viewpoint. In the experiments participants took the ground level view by standing on the green floor, which was registered with the real floor of the lab room.

2.1. Method

2.1.1. Participants

72 university students (36 males, 36 females) participated as partial fulfillment of a requirement for their introductory psychology courses.

2.1.2. Materials and design

The experiment was conducted in a physical room of 4.2 by 4.2 m. A circular curtain with a diameter of 4 m was mounted such that the orientation of the physical room was not visible. The virtual environment was displayed in stereo with an nVisor SX60 head-mounted display (HMD, NVIS, Inc. Virginia). Participants' head motion was tracked with an InterSense IS-900 motion tracking system (InterSense, Inc., Massachusetts).

In the virtual environment, a green floor with an infinite size was always presented. In the room condition, a virtual rectangular room of a width of 4 m and a height of 3 m was also always presented (see Fig. 1B). In the no room condition, only the green floor was always presented and the room was never presented. The path was indicated by the sequential presentation of objects. The path consisted of six legs illustrated by the lines in Fig. 1A. The lines in the figure are included for illustration and were never presented in the virtual environment. Each leg was determined by the two objects at either end. The direction of the path was clockwise. In particular, the six legs were: mug–phone, phone–brush, brush–hat, hat–ball, and ball–clock with lengths of 1.41 m, 1 m, 1.4 m, 2 m, 1 m, and 1.41 m respectively. The angle between two adjacent legs was 45°, 90°, or 135°. Three legs (mug–phone, brush–hat, and clock–mug) were aligned with (parallel or orthogonal to) each other and also aligned with the virtual room in the room condition. The other three legs (phone–brush, hat–ball, and ball–clock) were aligned with each other and misaligned with the virtual room in the room condition. Each object was presented on a pillar with a height of 1.5 m in the virtual environment (Fig. 1B) rather than on the floor so that participants could walk more naturally while looking ahead. The whole path was indicated by sequentially presenting the objects and the corresponding pillar in the clockwise order (e.g., mug, phone, brush, hat, ball, and clock).

Each test trial was constructed from the names of three objects and required participants to use the joystick to point to an object as if standing in a particular position and facing a particular direction along the path. For example, "Imagine you are standing at the ball facing the clock. Point to the mug." The first two objects established the imagined standing location and facing direction (e.g. ball and clock) and the third object was the target (e.g. mug). There were six imagined headings corresponding to the six walking legs. Only the walking direction (e.g. ball–clock) was used and the opposite direction (e.g. clock–ball) was not used as it was still novel. Hence, only experienced headings were used. At each imagined heading, the target objects were the other four objects (e.g., mug, phone, brush, and hat). Hence, 24 test trials (6 imagined headings × 4 targets) were formed.

The primary independent variable was the imagined heading corresponding to each walking leg. The starting object was counter-balanced across participants. The dependent measures were 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, and the response latencies measured as the latencies from the presentation of the target name (the object to point to) to the pointing response.

2.1.3. Procedure

Six participants (3 men and 3 women) were randomly assigned to each of 12 groups defined by the combinations of 6 starting points and 2 room conditions. Before entering the learning room, each participant was brought to a room containing a computer and was instructed to learn how to use the joystick using six practice trials.

2.1.3.1. Learning phase. The participant was blindfolded and led to the learning room. The participant was then led to walk a circuitous path to eliminate his or her orientation in the physical environment before being placed at the designated starting point facing the first leg (e.g., standing at ball, facing clock). The blindfold was removed and the participants donned the head mounted display. The participant first viewed the object (e.g., ball) on a pillar at the starting position. The participant then saw the second object (e.g. clock) on a pillar and was asked to walk to it. The participant learned every leg by viewing each object one at a time in a clockwise order (e.g., ball, clock, mug, phone, brush, and hat) and walking to it. The participant named each of the six objects when walking to it. After walking the path two times in this manner, the participant walked the path relying on his or her memory of the path. The object indicating the next leg was presented to give feedback only when participants finished walking the corresponding leg or started to walk in a wrong direction. The participant walked the path eight times in this manner.

2.1.3.2. Testing phase. After learning the spatial layout, the participant was blindfolded and led to the test room. The test trials were presented aurally via a stereo headset attached to a PC computer. The participant first initiated each trial by pressing a button of the joystick. Trials proceeded as follows: The imagined heading was given aurally (e.g. "Imagine you are standing at ball, facing clock."). 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 item was immediately presented aurally when the participant pulled the trigger (e.g. "Point to mug"). 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. The participant was instructed to point to the target as accurately as possible and as quickly as possible.

2.2. Results and discussion

In this and all the following experiments, the effects on pointing latency were weaker than on angular error. The effects on pointing latency were not significant in any of the experiments except for Experiment 3. In Experiment 3, the patterns of pointing latency and of angular error were consistent. For the purposes of brevity, the results of pointing latency were not reported. Only the correlations between the pointing latency and angular error across conditions were reported in Table 1 showing that there was no evidence of speed-accuracy trade-offs. In the spatial memory literature, it is very common to see significant effects only in terms of either latency or angular

Table 1
The Pearson's correlation between mean latency and mean angular error across 12 conditions in Experiments 1–4 and 8 conditions in Experiment 5.

Experiment	1	2	3	4	5
r	0.66	0.49	0.55	0.25	0.51

error. The reason for this is not quite clear. We speculate that latency might be more sensitive than error when the spatial configuration is regular because participants can calculate bearings accurately even for more difficult headings but at the cost of longer latency (Mou et al., 2007). Error might be more sensitive than latency when the spatial configuration is irregular or difficult to learn (e.g. in the current study) because participants could not calculate bearings accurately for a more difficult heading even when they take more time. A meta-analysis of the literature might be useful to address this issue (L. Carlson, personal communication, June 1, 2009).

Mean angular error is plotted in Fig. 2 as a function of imagined heading and room. Angular error was analyzed in mixed model ANOVAs with terms for imagined heading and room. Imagined heading was a within-participant factor and room was a between-participant factor. The main effect of imagined heading was significant, $F(5,350) = 3.84$, $p < .01$, $MSE = 448$, $\eta_p^2 = .05$. The main effect of room was significant, $F(1,70) = 18.92$, $p < .001$, $MSE = 1521$, $\eta_p^2 = .21$. The interaction between imagined heading and room was significant, $F(5,350) = 5.24$, $p < .001$, $MSE = 448$, $\eta_p^2 = .07$. The simple effect of imagined heading in the room condition was not significant, $F(5,350) < 1$. The simple effect of imagined heading in the no room condition was significant, $F(5,350) = 8.75$, $p < .001$, $MSE = 448$, $\eta_p^2 = .11$. In particular, angular error at the imagined heading of hat–ball was significantly smaller than at all other imagined headings, $t(350) \geqslant 2.09$, except for ball–clock, $t(350) = .78$.

The superior performance for the legs of hat–ball and ball–clock in the no room condition might have occurred for two reasons. First, spatial memories might have been organized in terms of the longest leg (i.e. hat–ball). Good performance for the leg of ball–clock might have occurred because it immediately followed the longest leg and was also orthogonal to the longest leg. Second, the target pointing directions for the hat–ball and ball–clock legs might have been easier than for other legs, regardless of the organization of spatial memory. For example, people are more accurate pointing to objects to the front than to the back (e.g., Sholl, 1987). However, a post hoc comparison of the pointing directions for the hat–ball and ball–clock legs showed that they should be no more difficult than those for the mug–phone leg (e.g., 27°, 45°, 63°, and 90° for hat–ball; 27°, 45°, 63°, and 90° for ball–clock; 18°, 45°,72°, and 90° for mug–phone), even though pointing performance was better in the first two conditions than in the third. Our tentative conclusion is that in the no room condition, spatial memories were organized in terms of the longest leg.

There was no effect of imagined heading in the room condition, which might indicate that neither the room orientation nor the longest leg was used to organize spatial memory of the path. The misalignment between the room orientation and the longest leg might have made both features less salient. Under such conditions, participants might have used the first leg of the path as a reference direction. To test this hypothesis, each imagined heading was categorized as either the first walking leg or one of the remaining legs. For example, for participants who started at ball, ball–clock was the first walking leg, and all other legs were categorized into the category of the other legs. Mean angular error is plotted in Fig. 3 as a function of imagined heading and room. In the room condition, angular error was significantly smaller at the first walking leg than at the other legs, $t(35) = 3.34$. In the no room condition, angular error was not significantly different between the first walking leg and the other legs, $t(35) = .81$. These results indicated that in the room condition, in which the room orientation was misaligned with the longest path, the spatial memory of the path might be organized in terms of the first walking leg.

3. Experiment 2

Experiment 2 further examined the role of the first walking leg in organization of spatial memory of the path when the longest leg and the room were misaligned as in the room condition in Experiment 1. Only the room condition in Experiment 1 was used. In contrast to Experiment 1, only two starting points (ball, mug) were used (Fig. 1). It was therefore possible to use fewer participants in total but to assign more participants to each starting point,

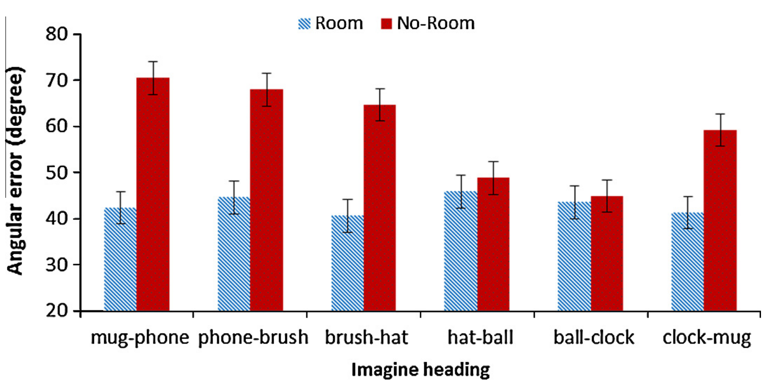

Fig. 2. Mean angular error in JRD as the function of imagined heading (legs) and room condition in Experiment 1 (*Error bars are ±1 standard error of the mean*).

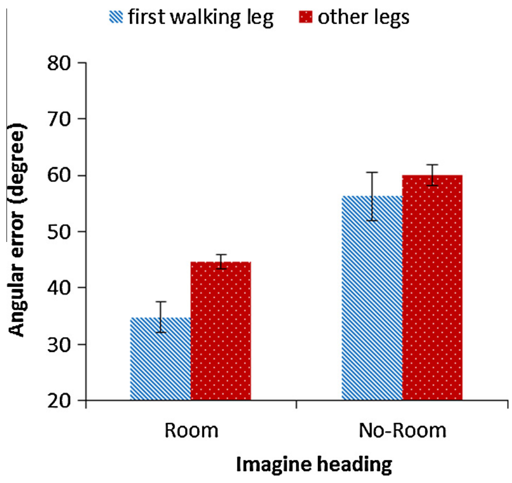

Fig. 3. Mean angular error in JRD as the function of imagined heading (first walking leg vs. others) and room condition in Experiment 1 (*Error bars are ±1 standard error of the mean*).

allowing us to examine the interaction between leg and starting object statistically. This manipulation would be used in all of the following experiments to make the statistical power across the experiments (except for Experiment 1) more comparable. According to the findings of Experiment 1, we expected that neither the longest leg nor the room orientation but the first walking leg would determine the reference system to organize the spatial memory of the path.

3.1. Method

3.1.1. Participants

Forty-eight university students (24 males, 24 females) participated as partial fulfillment of a requirement for their introductory psychology courses.

3.1.2. Materials, design, and procedure

The materials, design, and procedure were identical to those in Experiment 1 except for the following changes: first, only the room condition was used; second, participants only started at mug or ball. Twenty-four participants (12 men and 12 women) were randomly assigned to each of the two groups of the starting point (mug, ball). We used mug and ball as the starting points because the mug–phone and ball–clock legs were comparable. These legs had similar target directions (27°, 45°, 63°, and 90° for ball–clock; 18°, 45°, 72°, and 90° for mug–phone). Both of them immediately follow an aligned leg and precede a misaligned leg. Furthermore, the mug–phone leg was aligned with the room and the ball–clock leg was aligned with the longest leg such that the role of the room and the longest leg could be examined. Although the ball–clock leg was not the longest leg (i.e. hat–ball), Experiment 1 showed comparable performance for hat–ball and ball–clock in the no room condition, indicating that when the reference direction was determined by the longest leg, similar effects should occur for the longest leg and legs aligned with it. Hat was not used as the starting point because the hat–ball leg immediately followed a misaligned leg and preceded an aligned leg whereas the mug–phone leg immediately followed an aligned leg and preceded a misaligned leg. This difference might confound the reference direction effect. For the same reason, we used mug and ball as the starting points in all following experiments.

3.2. Results and discussion

Mean angular error is plotted in Fig. 4 as a function of imagined heading and starting object. Angular error was analyzed in mixed model ANOVAs with terms for imagined heading and starting object. Imagined heading was a within-participant factor and starting object was a between participant factor. The main effect of imagined heading was nearly significant, $F(5,230) = 2.23$, $p = .052$, $MSE = 446$, $\eta_p^2 = .05$. The main effect of starting object was not significant, $F(1,46) < 1$, $MSE = 1977$. The interaction between imagined heading and starting object was significant, $F(5,230) = 4.03$, $p < .01$, $MSE = 446$, $\eta_p^2 = .08$. The relationship between performance for the mug–phone leg, which was aligned with the room, and the ball–clock leg, which was aligned with the longest leg, reversed in the two groups of participants. For the group starting at the mug, the angular error was significantly smaller for the mug–phone leg than for the ball–clock leg, $t(230) = 2.80$. In contrast, for the group starting at the ball, the angular error was significantly smaller for the

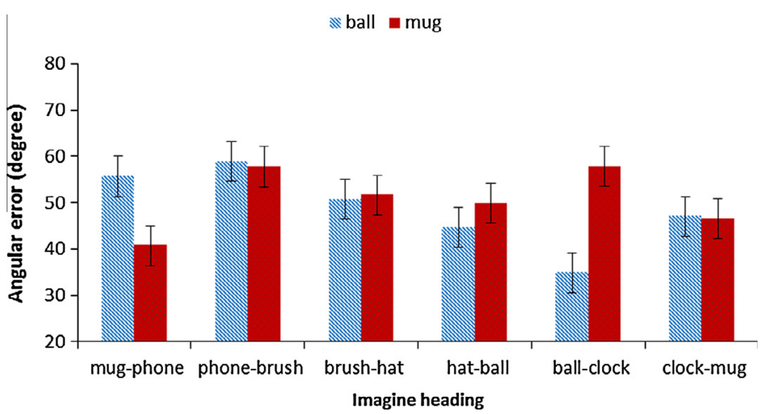

Fig. 4. Mean angular error in JRD as the function of imagined heading and starting object in Experiment 2. (*Error bars are ±1 standard error of the mean*).

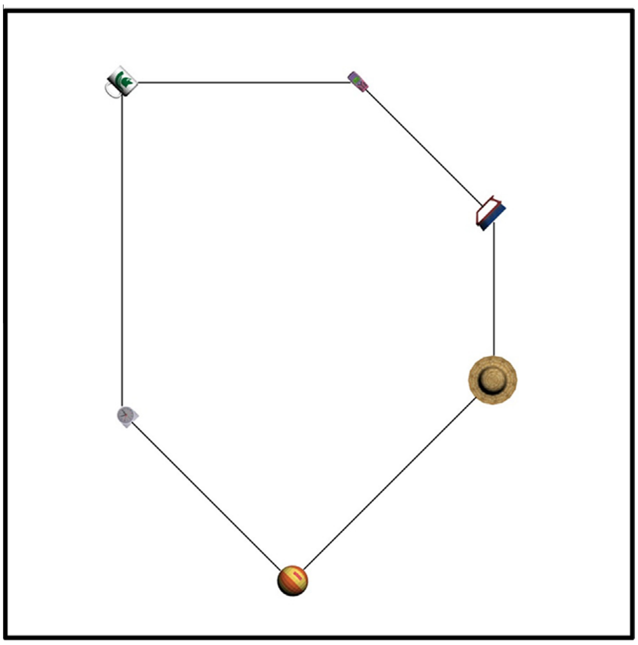

Fig. 5. The path used in Experiment 3. The lines between objects are used to illustrate the legs and were not presented to participants in Experiment. The external square refers to the square room.

ball–clock leg than for the mug–phone leg, $t(230) = 3.40$. The absolute magnitude of the difference in performance between these two legs did not differ between the two groups: 21° vs. 17°, $t(230) = .43$. Consistent with the findings of Experiment 1, the findings of Experiment 2 indicated that when the room was misaligned with the longest leg, the first walking leg might determine the spatial reference system to organize the spatial memory of the path.

4. Experiment 3

Experiment 3 examined the competition between the room and the first walking leg in organization of spatial memory of the path when none of the legs was obviously longer than the others. In a new path (see Fig. 5), the length of hat–ball, which was the longest leg in Experiments 1–2, was shortened to be comparable to that of clock–mug, which was the second longest in Experiments 1–2. In particular, the lengths of mug–phone, phone–brush, brush–hat, hat–ball, and ball–clock were 1.2 m, 0.8 m, 0.7 m, 1.2 m, 1 m, and 1.4 m respectively. We hoped that this change would allow us to examine whether the room or the first walking leg organized the path memory.

4.1. Method

4.1.1. Participants

Forty-Eight university students (24 males, 24 females) participated as partial fulfillment of a requirement for their introductory psychology courses.

4.1.2. Materials, design, and procedure

The materials, design, and procedure were identical to those in Experiment 2 except for the new path replacing the path in Experiment 2.

4.2. Results and discussion

Mean angular error is plotted in Fig. 6 as a function of imagined heading and starting object. Angular error was analyzed in mixed model ANOVAs with terms for imagined heading and starting object. Imagined heading was a within-participant variable and starting object was a between-participant variable. The main effect of imagined heading was nearly significant, $F(5,230) = 1.07$, $p > .05$, $MSE = 539$, $\eta_p^2 = .02$. The main effect of starting object was not significant, $F(1,46) < 1$, $MSE = 1394$. The interaction between imagined heading and starting object was significant, $F(5,230) = 4.78$, $p < .001$, $MSE = 539$, $\eta_p^2 = .09$. The difference between the mug–phone leg and the ball–clock leg reversed in the two groups. For the group starting at the mug, angular error was significantly smaller for the mug–phone leg than for the ball–clock leg, $t(230) = 2.33$. In contrast, for the group starting at the ball, angular error was significantly smaller for the ball–clock leg than for the mug–phone leg, $t(230) = 4.19$. The absolute magnitude of the difference in performance between these two legs did not differ significantly for the two groups: 28° vs. 16°, $t(230) = 1.32$.

The findings of Experiment 3 indicated that the first walking leg rather than the room determined the reference systems that organized the spatial memory of the path.

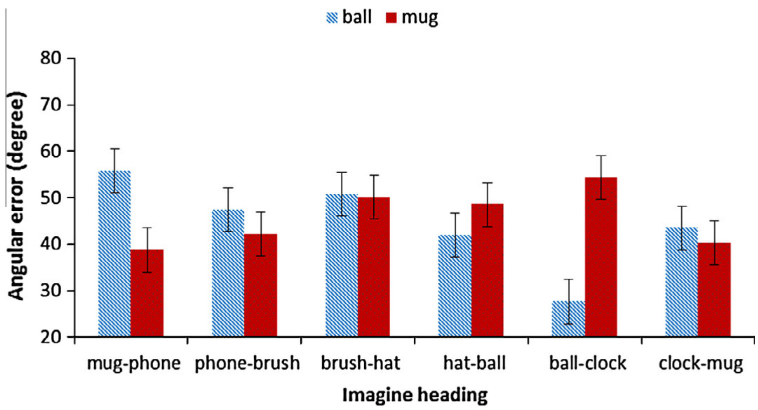

Fig. 6. Mean angular error in JRD as the function of imagined heading and starting object in Experiment 3. (*Error bars are ±1 standard error of the mean*).

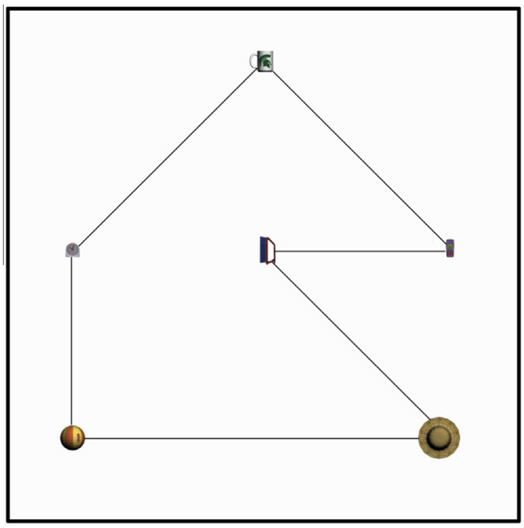

Fig. 7. The path used in Experiment 4. The lines between objects are used to illustrate the legs and were not presented to participants in Experiment. The external square refers to the square room.

Furthermore, there was no evidence that the room facilitated the leg aligned with it. The superior performance for the mug–phone leg relative to the ball–clock leg in the group starting at the mug was actually smaller in magnitude than the superior performance for the ball–clock leg relative to the mug–phone leg in the group starting at the ball.

5. Experiment 4

Experiment 4 examined the competition between the longest leg and the first walking leg in organization of spatial memory of the path. The path in Experiments 1–2 was used. In order to make the longest leg (i.e., hat–ball) salient, the room orientation was aligned with it (see Fig. 7). According to the findings of the no-room condition in Experiment 1, we expected that the longest leg would organize the spatial memory of the path. We used mug and ball as the starting points as in Experiment 2 because the mug–phone and ball–clock legs were comparable in terms of the target directions and the category of the leg preceding and following them. Unlike Experiment 2, the ball–clock leg was aligned with the room and also with the longest leg (i.e. hat–ball). Hence, when mug was the starting point, the comparison between mug–phone, which was aligned with the first leg, and ball–clock, which was aligned with the longest leg, could test the competition between the longest leg and the first walking leg in organization of spatial memory of the path.

5.1. Method

5.1.1. Participants

Forty-Eight university students (24 males, 24 females) participated as partial fulfillment of a requirement for their introductory psychology courses.

5.1.2. Materials, design, and procedure

The materials, design, and procedure were identical to those in Experiment 2 except that the virtual room was aligned with the longest leg (i.e. hat–ball).

5.2. Results and discussion

Mean angular error is plotted in Fig. 8 as a function of imagined heading and starting object. Angular error was analyzed in mixed model ANOVAs with terms for imagined heading and starting object. Imagined heading was a within-participant variable and starting object was a between-participant variable. The main effect of imagined heading was significant, $F(5,230) = 8.81$, $p < .001$, $MSE = 400$, $\eta_p^2 = .16$. The main effect of starting object was also significant, $F(1,46) = 6.53$, $MSE = 1282$, $\eta_p^2 = .12$. The interaction between imagined heading and starting object was significant, $F(5,230) = 2.35$, $p < .05$, $MSE = 400$, $\eta_p^2 = .05$. The difference between the mug–phone leg and the ball–clock leg differed in the two groups defined by the starting object. For the group starting at the mug, the angular error did not differ between the mug–phone leg and the ball–clock leg, $t(230) = 1.06$. As shown in Experiment 1 (no room condition), the longest leg had similar and the largest effects on the imagined headings of hat–ball and ball–clock (see Fig. 2). Hence, we expected that the angular error should not differ between the mug–phone leg (the first leg) and the hat–ball leg (the longest leg) either, which is confirmed by the result, $t(230) = .87$. In contrast, for the

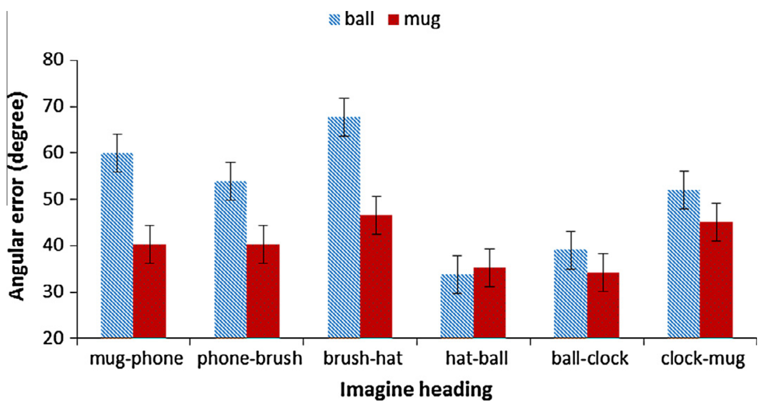

Fig. 8. Mean angular error in JRD as the function of imagined heading and starting object in Experiment 4. (*Error bars are ±1 standard error of the mean*).

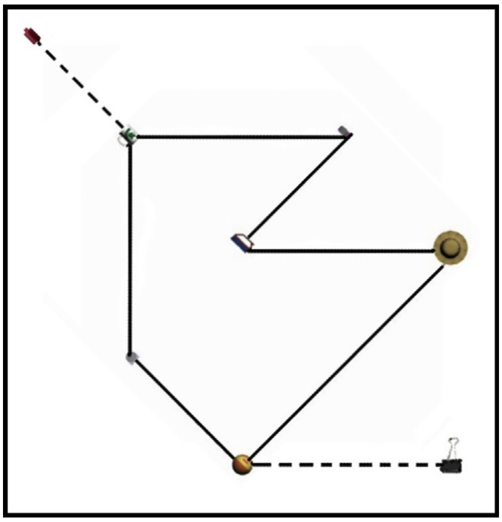

Fig. 9. The path used in Experiment 5. The solid line between objects indicates the walking path. The dashed line indicates the viewing direction. These lines are used to illustrate the legs and were not presented to participants in the experiment. The external square refers to the square room.

group starting at the ball, the angular error was significantly smaller at the ball–clock leg than at the mug–phone leg, $t(230) = 3.60$.

These results indicated that both the longest leg and the first walking leg contributed to the selection of the reference system for spatial memory of the path, at least when the longest leg and the first walking leg differed (i.e. in the group starting at mug).

6. Experiment 5

In the previous experiments, a preferred leg was observed in JRD supporting a single global reference direction. These experiments, however, cannot determine whether there is one local reference direction parallel to each walking leg as proposed by Meilinger et al. (2007). Meilinger et al. used a novel heading, which was not parallel to the walking direction but parallel to the hypothesized global heading, and a familiar heading, which was parallel to the walking direction, at each leg so that the local frame of reference could be determined by the superior performance for the familiar heading relative to the novel heading. In the Introduction, we argued that the superior performance at the familiar heading relative to the novel heading in Meilinger et al.'s experiments might have occurred because participants did not realize the novel heading was parallel to the hypothesized global heading. The purpose of Experiment 5 was to demonstrate that a novel heading could be better than the familiar heading when the novel heading was consistent with the global reference direction but the familiar heading was not consistent with the global reference direction.[1]

We added two objects, candle and clamp, near the path used in Experiments 1–2 (see Fig. 9). The direction of ball–clamp was aligned with the mug–phone leg and the direction of mug–candle was aligned with the ball–clock leg. Therefore, the heading of ball–clamp was parallel to the global reference direction (mug–phone) for the group who started at the mug and the heading of mug–candle was parallel to the global reference direction (ball–clock) for participants who started at the ball. Participants saw the candle when they walked the leg of mug–phone and saw the clamp when they walked the leg of ball–clock but never directly walked towards clamp or candle. We refer to these headings of ball–clamp and mug–candle as *non-local headings.* These headings are not parallel to the assumed local reference direction but also are not novel because participants did see candle and clamp. We refer to the headings of ball–clock and mug–phone as *local-headings* because they are parallel to possible local reference directions.

If there is a local reference direction parallel to each walking leg instead of a single global reference direction, we would expect superior performance for the local heading relative to the non-local heading (e.g. smaller error for the heading of mug–phone than for the heading of mug–candle), regardless of whether the non-local heading is parallel to the global reference direction. If there is a single global reference direction, we would expect superior performance for the local heading relative to the non-local heading when the non-local heading is not parallel to the global reference direction (e.g. smaller error for the heading of mug–phone than for the heading of mug–candle when the starting object is mug) but superior performance for the non-local heading relative to the local heading when the non-local heading is parallel to the global reference direction (e.g. smaller error for heading of mug–candle than for heading of mug–phone when the starting object is ball).

6.1. Method

6.1.1. Participants

Forty-eight university students (24 males, 24 females) participated as partial fulfillment of a requirement for their introductory psychology courses.

6.1.2. Material and design

The materials, design and procedure were identical to those in Experiment 2 except for the following changes:

(1) A clamp and a candle were added and the distances between ball and clamp and between mug and candle were 1.41 m and 1 m respectively. Participants who started at the ball were asked to turn to face towards candle and remember its position when arriving at mug. Participants were also instructed that the direction from mug to candle was the same as that from ball to clock. When reaching the ball from the hat, participants were asked to face towards clamp and to remember its location. They were also told that the direction from ball to clamp was parallel to the leg of mug–phone. Participants were informed of these relations the first three times that they walked the path. At the second and third walking of the path, participants were also told of

[1] We are grateful to an anonymous reviewer for suggesting this experiment to us.

these parallel relations when they stopped at the ball and faced the clock, and when they stopped at the mug and faced the phone. Starting at the fourth learning trial, participants were required to point to the clamp and the candle when they stopped at the ball and mug respectively, and then objects were presented as feedback. The learning procedure was the same for the participants who started at the mug.

(2) Participants walked the path three times rather than two times with the next object being presented as there were more objects to learn. Then participants walked the path relying on their memory of the path seven times instead of eight times.

(3) We were interested in the difference between local headings and non-local headings when non-local headings were parallel to the global reference direction and when non-local headings were not parallel to the global reference direction. Therefore, only four imagined headings were used: ball–clock, ball–clamp, mug–phone and mug–candle. The legs of ball–clock and mug–phone were parallel to the hypothesized local reference direction (local headings), because participants physically walked these legs, and the legs of ball–clamp and mug–candle were not consistent with the local reference direction (i.e. non-local headings). When the imagined headings were ball–clock and mug–phone, participants pointed to the other 4 objects on the path as in the previous experiments. When the imagined headings were ball–clamp and mug–candle, participants pointed to the other five objects on the path.

6.2. Results and discussion

Mean angular error is plotted in Fig. 10 as a function of imagined heading and starting object. Angular error was analyzed in mixed model ANOVAs with terms for imagined heading and starting object. Imagined heading was a within-participant variable and starting object was a between-participant variable. Only the interaction between imagined heading and starting object was significant, $F(3,138) = 3.45$, $p < .05$, $MSE = 541.36$, $\eta_p^2 = .07$.

The difference in performance between the non-local and the local headings (non-local heading minus local heading) when the non-local heading was consistent with the global reference direction (global consistent) and when they were not consistent (global inconsistent) is plotted in Fig. 11. The global consistent condition includes the difference between mug–candle and mug–phone when ball is the starting point and the difference between ball–clamp and ball–clock when mug is the starting point. The global inconsistent condition includes the difference between mug–candle and mug–phone when mug is the starting

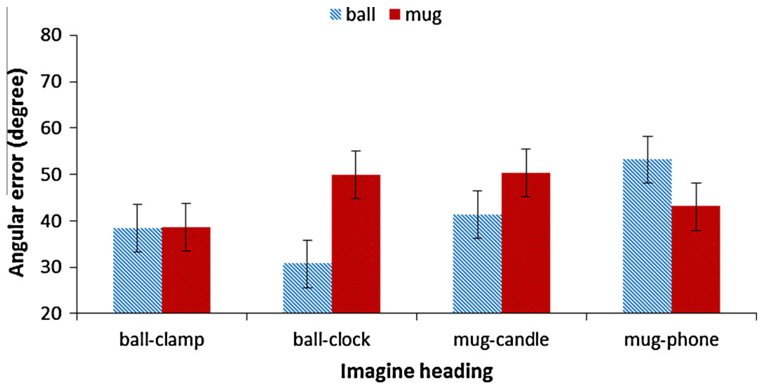

Fig. 10. Mean angular error in JRD as the function of imagined heading (legs) and starting object in Experiment 5 (*Error bars are ±standard error of the mean*).

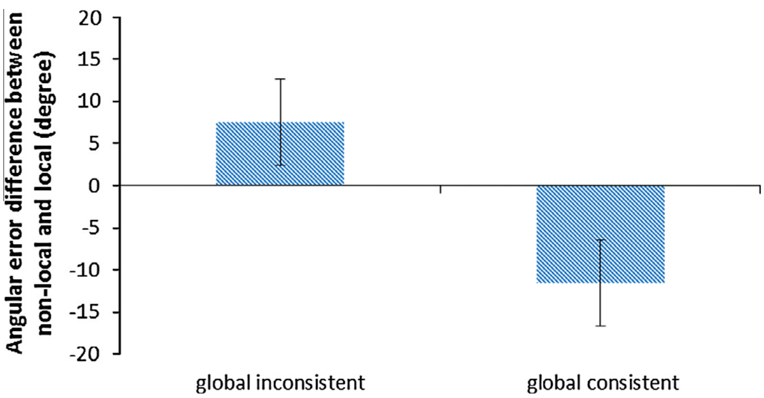

Fig. 11. Angular error difference between non-local and local headings (non-local minus local) when the non-local heading was consistent with the global reference direction (i.e. the first walking leg) and when the non-local heading was not consistent with the global reference direction in Experiment 5. Positive difference indicates a larger error at the non-local heading whereas negative difference indicates a smaller error at the non-local heading (*Error bars are ±standard error*).

point and the difference between ball–clamp and ball–clock when ball is the starting point. In the global consistent condition, the signed difference in angular error between the non-local heading and the local heading (−12°) was significantly smaller than 0, $t(138) = 2.27$. In the global inconsistent condition, the signed difference in angular error between the non-local heading and the local heading (7°) was greater than 0, although not significantly, $t(138) = 1.47$. The interaction between the heading (non-local heading vs. the local heading) and global consistency was significant, $t(138) = 2.64$. These results clearly indicated that the difference between the non-local and local headings was modulated by the consistency between the non-local heading and the global reference direction, showing that participants did not establish one local reference direction at each walking leg.

7. General discussion

Substantial spatial knowledge is acquired in everyday life by walking paths using vision. The nature of route knowledge and the development of survey knowledge from route knowledge have been investigated extensively (e.g. Ishikawa & Montello, 2006; Richardson et al., 1999; Shelton & McNamara, 2004; Taylor et al., 1999; Thorndyke & Hayes-Roth, 1982). An important aspect of route knowledge that has not received a great deal of attention is the nature of the spatial reference systems that are used to organize memory acquired by walking a path. In this project, we asked whether memory of a path is organized in terms of a global reference frame or in terms of multiple local reference frames that are determined at each walking leg (and without a global reference frame; Meilinger et al., 2007).

In the first four experiments, participants walked a six-leg path ten times and then completed JRD. There were two important controls in these experiments: (a) half of the turning angles were oblique; and (b) only the experienced imagined headings were tested in JRD. These two controls ensured that the experiments in this study could distinguish between these two hypotheses. Experiment 5 directly tested whether there is a local reference direction at each walking leg.

There were four important findings: First, when there was no environmental reference frame (i.e., room), the preferred heading in JRD was parallel to the longest leg of the path (Experiment 1); second, when the longest leg was misaligned with the room, the preferred heading in JRD was parallel to the first walking leg of the path (Experiments 1 and 2); third, when there was no obvious longest leg in the path, the preferred heading in JRD was parallel to the first walking leg of the path but not parallel to the room (Experiment 3); fourth, when the longest leg was aligned with the room, the longest leg and the first walking leg determined two oblique reference frames, at least when the longest leg and the first walking leg differed (Experiment 4). These findings lend additional support to the hypothesis that spatial memory of a path learned by walking with vision has a single global reference frame. All findings except for finding 4 indicated that participants established a single global reference frame when organizing spatial memory of the path. Only finding 4 might indicate that participants established oblique reference frames, one determined by the first walking leg and the other determined by the longest leg of the path.

The conclusion that spatial memory of a path learned by walking with vision has a single global reference system was similar to the conclusion in McNamara et al. (2003). However, there is one critical difference in experimental manipulation between these two studies. In McNamara et al., participants walked a square path and four of the eight imagined headings were experienced. This design cannot distinguish between the use of a single global reference frame and multiple local reference frames aligned with individual walking legs. Both hypotheses can account for the finding that experienced legs will be superior to novel legs and that performance for all experienced legs may be the same. According to the hypothesis of multiple local reference frames, all experienced legs are represented and should be easier to process in JRD. According to the hypothesis of a global reference frame, the reference frame might be determined by one of the legs and all experienced legs would be facilitated because they are all aligned with the reference frame. In the current study, participants walked an irregular path and all of the six imagined headings were experienced. With this design, the two hypotheses lead to two different predictions. The hypothesis of a single global reference frame predicts that some imagined headings will be better than others whereas the hypothesis of multiple local reference frames predicts that all imagined headings will be equivalent.

Although Meilinger et al. (2007) used an irregular path, as in the current study, they did not find any facilitation at the imagined heading parallel to the first walking leg or the longest leg of the path. In contrast, the current study found facilitation at the first walking leg (Experiments 1–3) or the longest leg of the path (Experiments 1 and 4). The discrepancy between these two findings might be due to the way heading information was provided to participants. Meilinger et al. (2007) presented views of each leg to indicate participants' testing headings. Participants might not know the exact direction of the testing heading relative to the reference direction (e.g., the first walking leg) using such a method when the views were novel. In contrast, in the first four experiments of the current study, all of the imagined headings were experienced. This conjecture was supported by the results of Experiment 5 of the current study. In this experiment, participants learned two directions that were oblique to the walking directions but they were informed that these new directions were parallel to or not parallel to the global reference direction. The results showed that these new directions were superior to the testing heading parallel to the walking leg when these new directions were parallel to the global reference direction. This finding is not consistent with the hypothesis of multiple local reference directions.

The findings of this study also indicated that organization of spatial memory of a path learned by walking with vision is similar to organization of spatial memory of an array of objects learned at static viewpoints. One of the important findings on spatial memory of an array of objects is that not all experienced viewpoints establish a reference direction (e.g., Kelly & McNamara, 2010; Mou et al., 2007; Shelton & McNamara, 2001). When participants learned a layout of object from two oblique viewpoints and only one of the viewpoints was aligned with other salient cues (e.g., environmental frame, intrinsic features), the aligned viewpoint established a reference frame and the other did not. In some special conditions, two oblique viewpoints can both determine an individual reference frame (e.g., Shelton & McNamara, 2001; Yamamoto & Shelton, 2005). The necessary conditions for such an effect might be that both oblique viewpoints are aligned with salient cues (e.g., one is aligned with the edges of a mat and the other is aligned with the walls of a room). The findings of the current study followed a very similar pattern. When the longest leg was not obvious (Experiment 3) or was not consistent with the room orientation (Experiments 1–2), only one reference frame was established by the first walking leg although all legs were experienced for ten times. When the longest leg was salient and differed from the first walking leg (Experiment 4), two reference frames seemed to be established, one consistent with the first walking leg and the other consistent with the longest leg. These similarities may occur because the path is relatively short, compact, and of a size comparable to the object array learned at static viewpoints.

In spite of these similarities, there are also some important differences in organization of spatial memories of a path learned by walking with vision and of an object array learned at static viewpoints. When participants learned an array of objects from two oblique viewpoints in a rectangular room, the experienced viewpoint that was aligned with the room orientation established a reference direction to organize the spatial memory of the array of objects (e.g., Shelton & McNamara, 2001). However, there was no evidence indicating that the room orientation determined the reference direction in the current study. In Experiment 3, participants walked a path without an obvious longest leg, starting at the mug or at the ball (Fig. 5). For the group starting at the ball, the first walking leg was misaligned with the room orientation, whereas for the group starting at the mug, the first walking leg was aligned with the room orientation. The results showed that the preferred orientation was determined by the first walking leg rather than the room orientation, regardless of whether or not the first walking leg was aligned with the room. Furthermore, the results did not indicate any facilitation from the room orientation for the leg (mug–phone) that was aligned with the room. The cause of the minimal effect of the room in selection of the reference frame in the current study is not clear. We speculate that it might be due to the learning modality. Participants learned the path by walking legs sequentially. The first walking leg and the longest leg are more salient than the leg aligned with the room due to the sequential nature of walking the path. In the studies of spatial memory of object arrays (e.g., Shelton & McNamara, 2001), participants viewed the whole structure of the array together with the room orientation from each viewpoint. The room orientation as an external frame might influence the perception of the structure of the object array as a whole. Functions of a boundary (i.e. a room) in selection of spatial reference system, goal localization, orientation, or reorientation have been well documented (Cheng, 1986; Doeller & Burgess, 2008; Kelly, McNamara, Bodenheimer, Carr, & Rieser, 2008; Shelton & McNamara, 2001). The minimal effect of the room in selection of the reference frame for spatial memory learned by walking indicates that boundaries might not affect the knowledge acquired by locomotion per se, which deserves further investigation.

The findings of this study indicated that people establish a global reference system to represent the spatial configuration of the whole path. However, it is still possible that people may also develop a local reference system at each segment to represent the spatial relations between the adjacent legs rather than all legs. These local and global reference systems are analog to the micro and macro reference systems proposed by Greenauer and Waller (2010) and might form hierarchical spatial representations of the path (McNamara et al., 2008; Meilinger & Vosgerau, 2010; Poucet, 1993). Participants might develop the configural knowledge of the path in terms of the global reference system through path integration mechanisms (e.g., Wehner, Michel, & Antonsen, 1996). Participants walked to different positions by calculating the bearing of the current position with respect to the reference point (e.g., the first object at the longest leg) in terms of the reference direction (e.g., the longest leg). For example, in Fig. 1, when participants reached clock, they might have updated the bearing between clock and hat, which was the first object at the longest leg, with respect to the direction of hat–ball using path integration. In this study, we only tested participants' knowledge of the path after 10 times walking of the path. It would be interesting to see when participants establish the global reference direction by testing the orientation dependence of the path knowledge after each walking of the path (e.g. Ishikawa & Montello, 2006).

In conclusion, this study indicated that spatial memory of a path learned by walking with vision was organized with respect to a single global reference system that was determined either by the first walking leg or by the longest leg of the path. When the first walking leg and the longest leg were not aligned, two oblique reference directions seem to have been established, one aligned with the first walking leg and the other aligned with the longest leg.

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