Intrinsic Frames of Reference in Haptic Spatial Learning[*]

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Abstract: It has been proposed that spatial reference frames with which object locations are specified in memory are intrinsic to a to-be-remembered spatial layout (intrinsic reference theory). Although this theory has been supported by accumulating evidence, it has only been collected from paradigms in which the entire spatial layout was simultaneously visible to observers. The present study was designed to examine the generality of the theory by investigating whether the geometric structure of a spatial layout (bilateral symmetry) influences selection of spatial reference frames when object locations are sequentially learned through haptic exploration. In two experiments, participants learned the spatial layout solely by touch and performed judgments of relative direction among objects using their spatial memories. Results indicated that the geometric structure can provide a spatial cue for establishing reference frames as long as it is accentuated by explicit instructions (Experiment 1) or alignment with an egocentric orientation (Experiment 2). These results are entirely consistent with those from previous studies in which spatial information was encoded through simultaneous viewing of all object locations, suggesting that the intrinsic reference theory is not specific to a type of spatial memory acquired by the particular learning method but instead generalizes to spatial memories learned through a variety of encoding conditions. In particular, the present findings suggest that spatial memories that follow the intrinsic reference theory function equivalently regardless of the modality in which spatial information is encoded.
Keywords: haptics, reference frame, functional equivalence, geometry, modality, spatial memory

1. Introduction

Numerous activities in everyday life require remembering locations of objects in an environment. Because locations can only be defined relative to something else (e.g., Stilwell Hall is east of Chester Building), forming a mental representation of the environment entails establishing coherent frames of spatial reference in memory. Hence, extensive research has been carried out to investigate what types of reference frames are used in spatial memory (e.g., Easton & Sholl, 1995; Greenauer & Waller, 2008; Hintzman, O'Dell, & Arndt, 1981; Kelly, Avraamides, & Loomis, 2007; Marchette & Shelton, 2010; Montello, 1991; Mou & McNamara, 2002; Presson & Hazelrigg, 1984; Rieser, 1989; Sadalla, Burroughs, & Staplin, 1980; Shelton & McNamara, 1997, 2001; Werner & Schmidt, 1999; Yamamoto & Shelton, 2005, 2009a). Traditionally, this research has made a distinction between egocentric reference frames and allocentric reference frames (Klatzky, 1998). Egocentric reference frames specify locations with respect to observers themselves (e.g., a door is 10-ft away to my left). Allocentric reference frames determine locations in reference to environmental features that are external to the observers (e.g., a window is in the middle of the south wall). This dichotomy has been shown to be useful for understanding organization of human spatial memory (for review, see Shelton & Yamamoto, 2009).

The past decade, however, has seen a new development in the classification of spatial reference frames. On the basis of the discovery that spatial structures in the configuration of

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objects (e.g., bilateral symmetry) can be used to specify object locations in memory independently of observers' position and orientation (Mou & McNamara, 2002), McNamara, Mou, and colleagues formulated a theory that spatial reference frames are intrinsic to the object layout that is to be remembered (Mou & McNamara, 2002; Shelton & McNamara, 2001; for review, see McNamara, 2003). According to this theory (referred to as *intrinsic reference theory* hereafter), observers first establish a conceptual "north" of the layout, much like determining the "top" of a figure in form perception (Rock, 1973). This process gives rise to an intrinsic reference frame that consists of a primary north-south axis and secondary east-west axis, with which object locations are defined. A number of spatial cues can influence selection of the conceptual north, including egocentric orientations of observers in an environment (Shelton & McNamara, 1997, 2001), allocentric features of the surroundings (such as a floor mat and room walls; McNamara, Rump, & Werner, 2003; Shelton & McNamara, 2001), geometric structures of the spatial layout (Mou & McNamara, 2002), and the interaction among them (Kelly & McNamara, 2008; Mou, Zhao, & McNamara, 2007; Shelton & McNamara, 2001). For example, in the absence of any salient cues, the first egocentric orientation experienced by observes defines the primary reference axis. On the other hand, if the observers subsequently learn the same environment from another orientation that is reinforced by notable allocentric features (e.g., the new orientation is aligned with room walls), the primary reference axis is re-established based on this new orientation. In this manner, the intrinsic reference theory has proposed a novel framework within which reference frames are characterized as properties of the spatial layout, not of observers or the surroundings. Egocentric and allocentric spatial information provide cues that give life to certain reference frames, all of which are viewed as intrinsic to the spatial layout.

Following the seminal work by Mou and McNamara (2002), a number of studies were conducted to further demonstrate that geometric structures of a spatial layout constitute salient cues for selection of spatial reference frames (e.g., Kelly & McNamara, 2008; Mou et al., 2007; Mou, Fan, McNamara, & Owen, 2008; Mou, Liu, & McNamara, 2009; Mou, McNamara, Valiquette, & Rump, 2004). These studies provided crucial evidence for the intrinsic reference theory by verifying that reference frames can be inherent in the spatial layout itself. Nevertheless, many questions still remain regarding how intrinsic reference frames are used to organize spatial memory. An outstanding issue is that it is yet unclear how universal the role of layout geometry is in establishing reference frames. In the previous studies, an array of objects that had a single axis of bilateral symmetry (such as the one in Figure 1) was typically utilized to help observers memorize object locations by using the symmetry axis (and the axis perpendicular to it as a secondary reference axis). Since this layout was always viewed in its entirety in the previous experiments, the symmetry of the layout would have been apparent to observers, especially when the symmetry axis was aligned with their egocentric view or allocentric features such as room walls (Kelly & McNamara, 2008; Mou et al., 2007). However, in everyday environments, it is quite common that only a fragment of the layout is visible at any given time (e.g., due to blockage of full view by obstacles) and objects must be seen sequentially (Yamamoto & Shelton, 2009b). Thus, compared to the situations examined in the previous studies, under natural conditions it may be more difficult for observers to notice the overall structure of the layout, and consequently, they are more likely to employ reference frames that are based on other cues than the geometry of the layout. In other words, it is possible that the effect of layout geometry may be restricted to (relatively rare) circumstances in which all objects in the layout can be perceived simultaneously. If this were the case, then it would dispute the

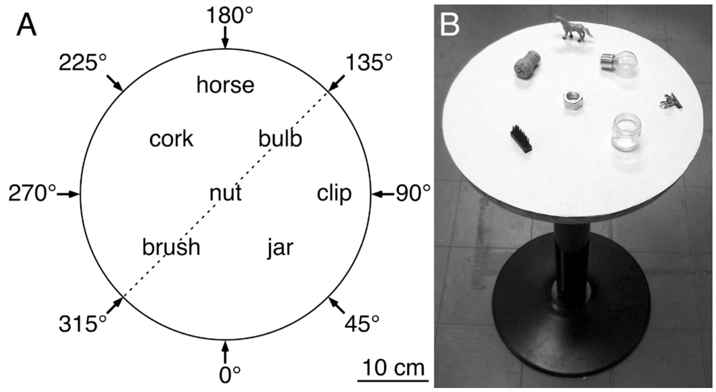

Figure 1. (A) Schematic of the spatial layout used in the present study. Arrows indicate orientations tested in the judgment of relative direction (JRD) task, with 0° corresponding to participants' egocentric orientation during the learning phase in Experiment 1. In Experiment 2, participants learned the layout from 0° and 135° orientations. The axis of bilateral symmetry is marked by the dashed line. (B) Actual layout and its setup. The layout was fixed on a circular board, which was centered on a cylindrical leg and a circular table base.

importance of layout geometry in setting up spatial reference frames, and in turn, the generality of the intrinsic reference theory.

In relation to the issue discussed above, it is worth noting that vision can allow observers to perceive an entire spatial layout at once thanks to its large field of view. It should be pointed out that having a wide field of "view" (or, more generally, spatial bandwidth; Loomis & Lederman, 1986) that can cover the entire spatial layout is not a condition applicable to all modalities. In haptic and proprioceptive spatial learning (i.e., when a spatial layout is learned through touch or blind-walking), object locations must be experienced one by one (or a few at a time when they are close together) due to restrictions inherent to each modality. Therefore, it is also possible that layout geometry plays a role in establishing reference frames only in modalities that have wide-enough spatial bandwidth (i.e., vision and presumably audition). If this were the case, it would limit the scope of the intrinsic reference theory. On the other hand, if layout geometry provided reliable spatial cues for selecting reference frames in other modalities, such a finding would have an important theoretical implication not only because it shows that the intrinsic reference theory is extended to modalities with narrow spatial bandwidth, but also because it suggests that underlying spatial representations function equivalently regardless of the modality in which spatial information is encoded (Loomis & Klatzky, 2008).

Thus, the present study was conducted to examine the generality of the intrinsic reference theory by investigating whether the geometry of a spatial layout influences selection of reference frames when the entire layout cannot be perceived simultaneously through vision. In two experiments, in a manner similar to previous studies (Kelly & McNamara, 2008; Mou & McNamara, 2002; Mou et al., 2007, 2009), participants learned a spatial layout that had a single axis of bilateral symmetry. A critical difference from the previous studies was that participants in the present study were blindfolded throughout the experiments and experienced object locations solely through touch. This prevented them from perceiving all object locations at the same time, making the symmetry axis harder to detect. If the intrinsic reference theory is applicable to conditions in which (visual) perception of the entire layout is precluded, participants' memories for the spatial layout should be organized by the symmetry axis and the axis perpendicular to it.

Such a finding would demonstrate the robustness of the effects of layout geometry on spatial memory organization, providing further support for the intrinsic reference theory.

2. Experiment 1

To begin the investigation, we sought to replicate Mou and McNamara's (2002) original research paradigm with which they first demonstrated the role of layout geometry in establishing reference frames. Modifications were made so that participants encoded a spatial layout through touch instead of vision. Just like Mou and McNamara's experiments, two groups of participants learned seven object locations from the same orientation, which was misaligned with the symmetry axis of the layout. One group of participants was explicitly instructed to use the geometric structure of the layout to memorize where objects were located relative to each other. The other group did not receive any particular instructions. If visual perception of the entire layout is not necessary for layout geometry to exert its effects on selection of spatial reference frames, results similar to those from the Mou and McNamara study should be obtained. That is, participants who received the instruction (*instruction* group) would form memories of the spatial layout in which object locations are specified by the symmetry axis and the axis perpendicular to it. On the other hand, participants who were not given any instructions (*no instruction* group) would define the primary reference axis by using their egocentric orientation (see also Greenauer & Waller, 2008, Experiment 2). In this latter case, it was further predicted that the secondary reference axis (i.e., the axis perpendicular to the egocentric orientation) would have minimal impact on the organization of spatial memory. It has been shown that when a primary reference axis is set up solely on the basis of egocentric orientations, effects of a secondary reference axis are rather small or nonexistent (e.g., Shelton & McNamara, 2001, Experiments 6 and 7).

After learning object locations by touch, participants made judgments of relative direction (JRDs) among objects in the layout. For example, a trial was given in the following sentences: "Imagine you are at the jar and facing the bulb. Point to the clip." Participants tried to locate the target object as though they were in the imagined position and orientation defined by the first two objects. In this task, it is postulated that performance would be most efficient when imagined orientations are aligned with reference axes; because object locations are explicitly specified in memory by the reference axes, in these cases the locations of the targets can be readily retrieved. On the other hand, when imagined orientations are misaligned with reference axes, participants need to mentally transform their spatial representations to bring them in alignment with the reference axes in order to find where the targets would be located. Such transformation of spatial information would require additional cognitive processes, producing measurable costs in terms of latency or error during memory access. Therefore, imagined orientations that yield faster or more accurate JRDs are considered to indicate which reference axes are used. According to this rationale, if layout geometry affected the organization of participants' spatial memory in the instruction group, JRDs should be performed better at imagined orientations parallel to the symmetry axis and the axis perpendicular to it. Similarly, in the no instruction group, better performance should be observed only at the imagined orientation that was identical to participants' egocentric orientation.

2.1. Method

2.1.1. Participants

Forty participants (20 men and 20 women, 18–22 years of age) volunteered in Experiment 1. All participants in the present study either fulfilled course requirement or received extra credit in psychology courses by participating in the experiment.

2.1.2. Materials

Participants learned the spatial layout depicted in Figure 1. This was the same layout as that used in previous studies by McNamara, Mou, and colleagues (e.g., Kelly & McNamara, 2008; Mou & McNamara, 2002; Mou et al., 2007, 2008, 2009). In Figure 1A, participants' position and orientation during learning are indicated by the arrow labeled as 0º. The layout was bilaterally symmetrical around the 135°-315° axis. Objects in the layout were common, distinct in shape, similar in size (approximately 3–5 cm in length and width, and 2–4 cm in height), had monosyllabic names, and shared no primary semantic associations. These objects were oriented in different directions so that no orientation of the layout would be particularly accentuated (see Figure 1B). They were firmly fixed onto a circular board (16 in diameter), which was centered on a cylindrical leg and a circular table base. As such, the table did not provide any cues that could have made particular orientations more salient than others.

2.1.3. Design and Procedure

Participants were randomly divided into two groups (with the constraint that each group had 10 men and 10 women), and they received different instructions about how to learn object locations (details shown below). The participants were run individually.

2.1.3.1. Learning Phase

The participants were told that they would learn a spatial layout of seven objects on a tabletop just by touching them for a later memory test. Then they were shown actual objects that would appear in the layout. At this time, only the objects were presented; the participants did not see the table, and the objects were neither put on the tabletop nor arranged in the configuration. Subsequently, the participants wore a blindfold and hearing protectors, and were led into a room and seated in a chair placed at the 0º position. While being taken to the chair, they were guided along a circuitous path and disoriented with respect to the surrounding environment in order to ensure that no allocentric features of the environment were used for learning the spatial layout. They were stationary in the chair except for arm and hand movements to touch objects. They were allowed to use only their dominant hand with a cotton glove on; the glove was used to minimize any effects the texture difference among objects might have on haptic learning of the spatial layout.

Depending on which group participants were assigned to (instruction group or no instruction group), they received particular instructions about how to memorize object locations. They were then given 30 s to freely touch objects. Subsequently, the participants were asked to point to and name the objects without touching them. This study-test sequence was repeated until they pointed correct object locations twice in a row. Accuracy of pointing was visually determined by the experimenter. When this criterion was met, the participants were disoriented again, guided out of the room, and asked to remove the blindfold, hearing protectors, and the glove. The disorientation procedure was included again to make sure that spatial information acquired by touching the objects was the only information available for later retrieval of memory for the spatial layout.

In the instruction group, participants were verbally informed that objects in the layout formed three columns (i.e., bulb-nut-brush, horse-cork, and clip-jar; see Figure 1A). In the beginning of the learning phase, the experimenter moved the participants' hand and had them touch each object in the above order so that they became well aware of the columnar structures in the layout. They were also instructed to learn the object locations on a column-by-column basis. These instructions were modeled after those used in Mou and McNamara's (2002) experiments. In the no instruction group, on the other hand, participants did not receive any particular instructions as to the structure of the layout. They were not informed of the fact that objects in the layout formed three columns, and their hand was moved to object locations in the order that did not correspond to the columns (nut, jar, horse, brush, clip, cork, and bulb). Consequently, these participants were not instructed to learn the object locations on a column-by-column basis. Except these differences, the identical procedure was used for both instruction and no instruction groups.

2.1.3.2. Test Phase

The participants moved to another room and performed the JRD task. The layout yielded 24 object pairs that defined the imagined positions and orientations, from which the participants attempted to locate target objects. There were three instances of each of the eight orientations indicated in Figure 1A. These orientations were labeled counterclockwise from 0° to 315°, with 0° corresponding to the participants' orientation during the learning phase. Target objects were selected such that for each imagined orientation there would be targets located in 45º, 90º, 135º, 225º, 270º, and 315º directions (one in each of these directions), clockwise relative to the imagined orientation. These 48 trials constituted experimental trials. In addition, two more trials were added per each imagined orientation in which targets were in neither orthogonal nor diagonal directions (18º, 27º, 63º, 72º, 288º, 297º, 333º, and 342º). These trials were included to increase the variability of target directions, thereby preventing the participants from noticing that targets were always in one of the six particular directions. Data from these 16 filler trials were not analyzed. Note that not all possible permutations of imagined positions, orientations, and targets were used because specific triads of objects were chosen as described above.

Trials were presented on a computer screen by using custom-written software for the JRD task (Shelton & McNamara, 1997). After receiving instructions about the task and how to use the computer program, the participants performed five practice trials that were composed of buildings on the George Washington University campus. In each trial, sentences giving an imagined position and orientation as well as a target were displayed with a circle and a movable line. The participants positioned the line by using a mouse so that it pointed to the target with respect to the particular imagined heading, which was represented by the 12 o'clock position of the circle (see Figure 3 in Yamamoto & Philbeck, 2013, for an example of the display). The participants then clicked the mouse to record a response. The participants received immediate feedback on their performance after each practice trial, and if incorrect pointing response was made, the experimenter gave another detailed explanation about how to perform the task. When the practice session was successfully completed, an actual test session consisting of 64 trials (including both experimental and filler trials) began. These trials were presented in random order. No feedback was given in the actual test session.

The principal dependent variable was response latency in JRDs. It was defined as time elapsed between the presentation of a JRD stimulus screen and participants' response indicated by the mouse click. The participants were instructed to perform the task as accurately as possible with minimum time required. Accuracy in JRDs was also measured by absolute angular error in pointing (i.e., the absolute angular distance between pointed direction and correct target direction). However, because targets were always in orthogonal or diagonal directions in the experimental trials, it was expected that only response latency would show clear patterns that indicate the use of intrinsic reference frames. It has been shown that pointing responses are biased toward these cardinal directions (Huttenlocher, Hedges, & Duncan, 1991; Montello & Frank, 1996; Sadalla & Montello, 1989; Yamamoto & Okabe, 2002), even if participants are not aware that targets are in these directions. This natural propensity can be more strongly manifested when responses are made by using a pointing dial such as the one simulated on a computer in the present study (Montello, Richardson, Hegarty, & Provenza, 1999). While this could confound the effects of intrinsic reference frames on JRD error, response latency is free from such spatial biases. It should also be noted that in previous studies that employed similar experimental designs, it was generally the case that response latency was more sensitive to the geometric structure of the spatial layout than error (Mou et al., 2007, 2009; see also Waller, Montello, Richardson, & Hegarty, 2002).

2.1.4. Data Analysis

Response latency and absolute angular error were analyzed separately by mixed analyses of variance (ANOVAs) with instruction (instruction or no instruction) as a between-subject factor and imagined orientation (0°-315° with 45° intervals) as a within-subject factor. In these omnibus ANOVAs, a significant interaction between instruction and imagined orientation would generally indicate that instruction and no instruction groups preferred different imagined orientations while performing JRDs. However, given that we sought to find specific patterns of preferred orientations in each group (i.e., the instruction group: geometrically salient 45°, 135°, 225°, and 315° orientations; the no instruction group: the egocentric 0° orientation), more relevant tests of these predictions were given by planned contrasts in which JRD performance at particular orientations was directly compared (e.g., 0°, 90°, 180°, and 270° vs. 45°, 135°, 225°, and 315° in the instruction group).

ANOVAs were also conducted with participants' gender as an additional between-subject factor, but it did not show any main effects or interactions. All *F*-tests were corrected for nonsphericity when appropriate. Generalized eta squared (η_G^2) values are reported as effect size statistics below (Bakeman, 2005; Olejnik & Algina, 2003).

2.2. Results

As expected, absolute angular error was not as responsive to the effects of intrinsic reference frames as response latency (Table 1): Although errors did vary as a function of instruction and imagined orientation (main effect of imagined orientation, $F[7, 266] = 7.226$, $p < .001$, $\eta_G^2 = .082$; interaction between instruction and imagined orientation, $F[7, 266] = 2.687$, $p = .024$, $\eta_G^2 = .032$), both groups showed largely similar patterns. As such, in the interest of brevity, detailed analyses are reported only for response latency data. The correlation coefficient between response latency and absolute angular error was .080, showing no evidence for speed-accuracy tradeoff.

Table 1. Mean Absolute Angular Error in Judgments of Relative Direction (JRDs) in Experiment 1 as a Function of Instruction and Imagined Orientation

	Imagined orientation							
Group	0°	45°	90°	135°	180°	225°	270°	315°
Instruction	27.87°	28.41°	37.23°	47.63°	47.23°	31.79°	39.00°	29.75°
	(2.83°)	(2.95°)	(3.35°)	(4.67°)	(3.85°)	(3.15°)	(3.44°)	(3.20°)
No instruction	21.89°	35.60°	40.81°	43.43°	42.33°	49.17°	36.12°	38.83°
	(2.43°)	(2.76°)	(3.40°)	(3.87°)	(4.35°)	(4.24°)	(3.58°)	(2.85°)

Note. Standard error of the mean (*SEM*) is shown in parentheses.

Figure 2 depicts mean response latency as a function of instruction and imagined orientation. Although instruction and no instruction groups showed equivalent overall latency (23.81 s and 23.88 s, respectively; $F < 1$), they exhibited very different patterns. In the instruction group, response latency was shorter when imagined orientations were aligned with the axis of bilateral symmetry (135º and 315º) and when they were perpendicular to it (45º and 225º). On the other hand, in the no instruction group, response latency was shortest at the 0º orientation (i.e., egocentric orientation during learning) and it generally increased as imagined orientation deviated from the egocentric orientation. These patterns indicate that participants in the instruction group used the two geometrically salient axes (135º-315º and 45º-225º) to organize their memories for the spatial layout, while those in the no instruction group encoded object locations by using the egocentric orientation.

Statistical analyses supported the above observations. The main effect of imagined orientation was significant, $F(7, 266) = 5.965$, $p < .001$, $\eta_G^2 = .046$, and the interaction between instruction and imagined orientation was marginally significant, $F(7, 266) = 2.134$, $p = .061$, $\eta_G^2 = .017$. More importantly, a planned contrast that compared imagined orientations aligned with the symmetry axis and the axis perpendicular to it (45º, 135º, 225º, and 315º) with other four orientations (0º, 90º, 180º, and 270º) within the instruction group was significant, $F(1, 19) = 14.295$, $p = .001$, $\eta_G^2 = .417$, as was a planned contrast that compared the 0º orientation with other seven orientations within the no instruction group, $F(1, 19) = 25.447$, $p < .001$, $\eta_G^2 = .560$. Finally, a planned contrast that tested the interaction between instruction and the two groups of orientations (0º, 90º, 180º, and 270º vs. 45º, 135º, 225º, and 315º) was also significant, $F(1, 39) = 5.842$, $p = .020$, $\eta_G^2 = .127$, suggesting that the effects of the geometrically salient orientations (45º, 135º, 225º, and 315º) were observable only in the instruction group.

2.3. Discussion

Results from Experiment 1 closely replicated those from the Mou and McNamara (2002) study despite the lack of simultaneous perception of the entire spatial layout through vision. When participants' attention was directed to the geometric structure of the layout by instructions, they formed memories of the layout in which object locations were specified by two reference axes defined by the geometry of the layout (i.e., the symmetry axis and the axis perpendicular to it). On the other hand, when participants were simply told to learn the locations of objects, subsequent memory performance revealed only a single reference axis that was aligned with their egocentric orientation during learning. These findings suggest that layout geometry can play a role in establishing spatial reference frames under a variety of learning conditions including when visual access to the entirety of an environment is completely precluded.

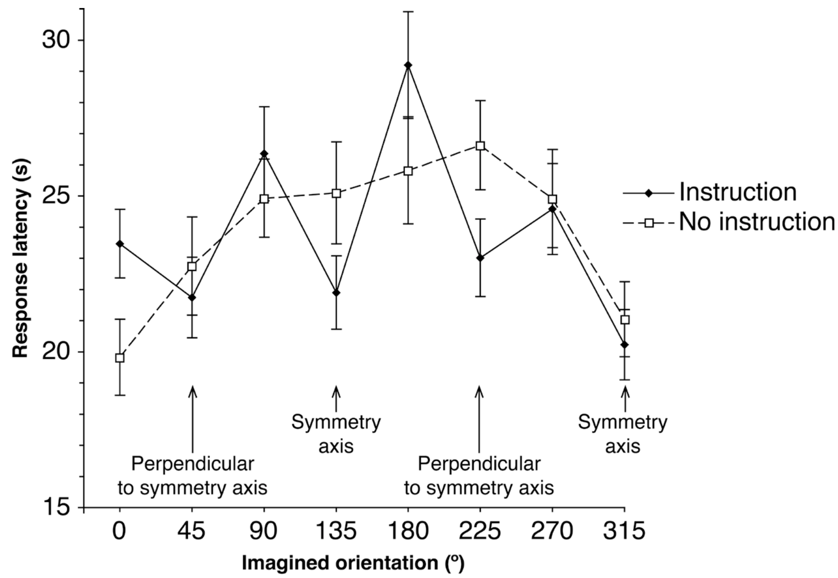

Figure 2. Mean response latency in the JRD task in Experiment 1 as a function of instruction and imagined orientation. Error bars represent ±1 standard error of the mean (*SEM*).

Consistent with Mou and McNamara (2002), in order for layout geometry to influence the organization of spatial memory, participants had to be instructed to use the symmetry axis to memorize object locations. When participants' egocentric orientation and the geometric structure of the layout were pitted against each other in the no instruction group, the egocentric orientation prevailed. This suggests that compared to egocentric orientations during learning, geometric structures of a spatial layout provide relatively weak cues for establishing spatial reference frames. In fact, in the visual modality, it has been shown that layout geometry alone cannot be a strong enough cue to set up spatial reference frames; instead, it needs to be reinforced by other cues such as alignment with an egocentric orientation or allocentric features of a surrounding environment (Greenauer & Waller, 2008; Kelly & McNamara, 2008; Mou et al., 2007; but see also Liu, Mou, & McNamara, 2012; Mou et al., 2009). Given that this has been the case even when visual perception of an entire spatial layout is possible, it is conceivable that haptically encoded geometric structures by themselves have weaker, and perhaps negligible, impact on selection of spatial reference frames. This would undermine the importance of layout geometry because it leaves open the possibility that without the aid of external factors (such as instructions) layout geometry cannot be used to define reference frames in the absence of simultaneous perception of all objects. On the other hand, if layout geometry plays a meaningful role in spatial learning in general, it should be able to exert observable effects on haptic spatial learning without explicit instructions, as long as it is accompanied with other spatial cues inherent in learning conditions such as an egocentric orientation. These ideas were tested in Experiment 2.

3. Experiment 2

In Experiment 2, participants learned the same spatial layout from two orientations, one aligned with the symmetry axis (the position indicated by the arrow labeled as 135º in Figure

1A) and one misaligned (the 0º position used in Experiment 1). The order with which these two orientations were experienced was counterbalanced across participants. No particular instructions about how to memorize object locations were given.

According to the intrinsic reference theory, when a spatial layout is learned multiple times from different egocentric orientations, subsequent memory for the layout is organized by a primary reference axis that is based on the first experienced orientation (Shelton & McNamara, 2001). This is because the reference axis must be established upon the initial encounter with the environment to encode object locations, and observers tend to keep using it while they learn the same object locations from other orientations later. However, an exception to this occurs when non-egocentric spatial cues such as allocentric features of the environment (Kelly & McNamara, 2008; Shelton & McNamara, 2001) or geometric structures of the layout (Mou et al., 2007) make a subsequently experienced egocentric orientation more salient than the first egocentric orientation. In this case, a reference axis is re-established on the basis of the newly experienced egocentric orientation and object locations are specified afresh in memory by using the new reference axis.

If this prediction from the intrinsic reference theory was applicable to the present experiment that lacked simultaneous perception of the entire layout, and in addition, if the geometric structure of the spatial layout was salient enough when it was encoded haptically, then the 135º orientation aligned with the symmetry axis should yield better JRD performance irrespective of the order with which two orientations (0º and 135º) were experienced. That is, participants who learned the 135º orientation first should prefer this orientation (and other geometrically related orientations, viz., 45º, 225º, and 315º) while performing JRDs because the second egocentric orientation (0º) was not reinforced by any other cues. And those who learned the 0º orientation first should re-establish reference axes based on the geometry of the layout (primary 135º-315º axis and secondary 45º-225º axis) when they subsequently touched objects from the 135º orientation, if the geometry had sufficient salience to make the second egocentric orientation (135º) more prominent than the first egocentric orientation (0º). In this manner, enhanced JRDs at geometrically distinguished orientations (primarily 135º and 315º, and secondarily 45º and 225º) independent of the order of learning would constitute evidence that layout geometry encoded through haptic experiences can exert its influence on reference frame selection without the aid of external factors such as instructions.

3.1. Method

3.1.1. Participants

Twenty participants (10 men and 10 women, 18–22 years of age) volunteered in Experiment 2.

3.1.2. Materials, Design, Procedure, and Data Analysis

Experiment 2 was conducted in the same manner as in Experiment 1 with following changes: Participants learned the spatial layout from two different orientations (0º and 135º). Half the participants (5 men and 5 women) experienced the 0º orientation first, while the other half did the 135º orientation first. Unlike Experiment 1, participants' hand was not brought to objects at the beginning of the learning phase. Instead, they were simply told to find all seven objects on the tabletop. After reaching the learning criterion at the first orientation, they stood up from a chair and were guided to the second orientation by taking the shortest path (clockwise or counterclockwise, depending on which orientation was experienced first), and sat in another chair placed at the new position. Participants in both groups did not receive any instructions as to the geometric structure of the layout as well as how object locations should be memorized.

Response latency and absolute angular error were first analyzed by mixed ANOVAs in which order of learning (0º first or 135º first) was a between-subject factor and imagined orientation (0°-315° with 45° intervals) was a within-subject factor. Because it was predicted that geometrically salient orientations (45º, 135º, 225º, and 315º) would be preferred in JRDs irrespective of the order of learning, only the main effect of imagined orientation was expected to be significant in these omnibus ANOVAs. A further test of the prediction was given by planned contrasts in which the geometrically salient orientations were directly compared with other orientations (0º, 90º, 180º, and 270º) within each group of participants.

3.2. Results

As in Experiment 1, absolute angular error was not responsive to the effects of intrinsic reference frames (Table 2): The ANOVA revealed no significant effects and interactions (Fs < 1.345, ps > .250). Thus, detailed analyses are reported only for response latency again. The correlation coefficient between response latency and absolute angular error was .029, showing no evidence for speed-accuracy tradeoff.

Mean response latency is plotted in Figure 3 as a function of order of learning and imagined orientation. As illustrated by the figure, response latency showed a similar pattern irrespective of whether the 0º orientation or the 135º orientation was learned first. In both groups, the orientations aligned with the symmetry axis (135º and 315º) and the axis perpendicular to it (45º and 225º) generally yielded faster JRD responses. By contrast, although the 0º orientation was experienced during the learning phase, JRD performance was not facilitated when imagined orientations were parallel to this orientation. This was the case even when the 0º orientation was learned first. When it was learned second, it actually produced the longest latency. Together, these results indicate that in participants' memories object locations were specified by an intrinsic reference frame defined by the geometric structure of the layout. This occurred independently of the order with which the two orientations were learned.

The above observations were supported statistically. The main effect of imagined orientation was significant, $F(7, 126) = 2.853$, $p = .044$, $\eta_G^2 = .071$. On the other hand, neither the main effect of order of learning nor the interaction between imagined orientation and order was significant, Fs < 1. A planned contrast that compared the two groups of orientations (45º, 135º, 225º, and 315º vs. 0º, 90º, 180º, and 270º) within the 135º-first group was significant, $F(1, 9) = 11.411$, $p = .008$, $\eta_G^2 = .559$. Although the same contrast within the 0º-first group did not reach significance, $F(1, 9) = 3.104$, $p = .112$, $\eta_G^2 = .256$, it was because the effect of the

Table 2. Mean Absolute Angular Error in JRDs in Experiment 2 as a Function of Order of Learning and Imagined Orientation

	Imagined Orientation							
Group	0°	45°	90°	135°	180°	225°	270°	315°
0° first	39.92°	38.48°	35.28°	36.02°	34.75°	38.65°	39.20°	42.02°
	(5.61°)	(4.36°)	(4.05°)	(3.68°)	(4.14°)	(4.14°)	(4.73°)	(4.98°)
135° first	42.02°	23.25°	32.55°	31.85°	33.73°	24.45°	41.50°	26.03°
	(5.44°)	(3.89°)	(3.87°)	(5.72°)	(3.96°)	(4.16°)	(5.43°)	(4.21°)

Note. *SEM* is shown in parentheses.

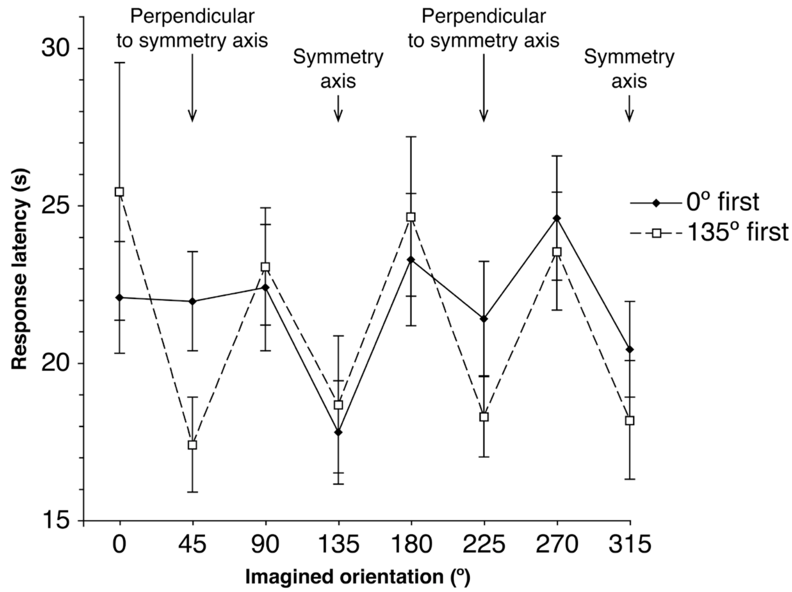

Figure 3. Mean response latency in the JRD task in Experiment 2 as a function of order of learning and imagined orientation. Error bars represent ±1 *SEM*.

secondary axis (45º-225º) was not as pronounced as that in the 135º-first group. There was a clear preference for the primary axis (135º-315º) in the 0º-first group, as shown by a contrast in which 135º and 315º orientations were compared with all other orientations, $F(1, 9) = 5.412$, $p = .045$, $\eta_G^2 = .376$. These statistical results indicate that geometrically salient orientations, especially those along the symmetry axis (135º-315º), yielded faster JRDs regardless of which orientation (0º or 135º) was learned first.

3.3. Discussion

Results from this experiment clearly showed that object locations were specified in memory by reference axes based on the geometric structure of the learned spatial layout. Importantly, this pattern was observed when the 0º orientation was experienced first. This suggests that participants in this group initially set up a reference axis according to their egocentric orientation at 0º, and upon experiencing the second orientation (135º), they replaced the previously established reference axis with a new one that was aligned with the symmetry axis (135º-315º). This replacement of reference axes indicates that the second learned orientation was more salient than the first learned orientation. Given that neither allocentric features of the environment nor external factors such as instructions were existent in the present experiment, this increased salience of the second learned orientation should be attributed to the geometry of the layout. As such, the present experiment demonstrated that layout geometry can influence selection of reference frames by itself even when it is encoded haptically in the absence of visual perception of the entire layout.

Although the two groups of participants produced similar patterns of response latency, the effects of the geometry of the layout were stronger in participants who experienced the 135º orientation first. This was presumably due to the fact that participants in this group essentially learned the layout twice by using the geometric axes (once from the 135º orientation and then from the 0º orientation): Because the 0º orientation was not made salient by other spatial cues, these participants likely kept using the same reference axes established at the 135º orientation while touching objects from the 0º orientation. On the other hand, participants who experienced the 0º orientation first started encoding object locations according to the geometric axes only after moving to the 135º orientation. As a consequence, compared to the other group of participants, the layout geometry made smaller impact on the pattern of response latency.

4. General Discussion

The present study was conducted to investigate whether the intrinsic reference theory proposed by McNamara, Mou, and colleagues (Mou & McNamara, 2002; Shelton & McNamara, 2001) can be applied to learning conditions in which the entirety of a to-be-learned spatial layout is not perceived immediately. In particular, experiments were focused on examining how the geometric structure of the spatial layout plays a role in establishing spatial reference frames when it was encoded solely through haptic experiences. Experiment 1 replicated Mou and McNamara's procedure with the exception that objects were touched instead of viewed. Results showed that participants used two geometric axes of the spatial layout (the symmetry axis and the axis perpendicular to it) to specify object locations when they were instructed to pay attention to the geometry of the layout. On the other hand, when participants were not given any particular instructions, their egocentric orientation during learning defined a single dominant reference axis. In Experiment 2, participants haptically learned the same spatial layout from two orientations, one aligned with the symmetry axis and one misaligned with it, without any instructions. All participants memorized object locations according to the geometric structure of the layout regardless of which orientation was experienced first, indicating that the layout geometry itself had sufficient salience to exert observable influence on selection of spatial reference frames in the absence of visual perception of the whole spatial layout. Together, these findings suggest that layout geometry provides an important cue for setting up spatial reference frames even when encoding of the entire spatial layout is gradually carried out over time in a nonvisual modality, successfully extending the intrinsic reference theory beyond conditions in which all object locations are viewed simultaneously.

It is worth noting that results from the present study strikingly resemble those from previous studies in which comparable procedures were carried out in vision. Experiment 1 was a replication of Mou and McNamara's (2002) study, and nearly identical findings were made despite the difference in modalities (vision or touch) used for encoding object locations. Participants in Experiment 2 learned the spatial layout in a similar manner to those in Mou et al. (2007) and Shelton and McNamara (2001) studies, and showed patterns of response latency that closely coincided with predictions based on data from these two studies. Thus, the present study gave an important demonstration (first time in the literature, to our knowledge) that the function of layout geometry in spatial learning is equivalent between visual and nonvisual modalities. This helps establish a link between two major theories of spatial representation: the intrinsic reference theory and the functional equivalence theory, which posits that mental representations of space function equivalently regardless of the modality through which spatial information is encoded (Loomis & Klatzky, 2008). The present findings suggest that the intrinsic reference theory provides a comprehensive scheme for understanding an aspect of mental spatial representations that is independent of learning modalities. This derives a specific prediction that spatial representations that follow the intrinsic reference theory should also exhibit functional equivalence. Testing this prediction would promise to significantly advance our understanding of human spatial memory, given that early evidence supporting this prediction has already been obtained (e.g., Giudice, Betty, & Loomis, 2011; Kelly & Avraamides, 2011; Kelly, Avraamides, & Giudice, 2011; Yamamoto & Shelton, 2009a).

Although the present study successfully broadened the scope of the intrinsic reference theory to a nonvisual modality and encoding conditions in which the entirety of a spatial layout is not perceived simultaneously, it is worth noting that most of the issues regarding the effect of layout geometry have been examined only with bilateral symmetry. Thus, it has yet to be seen whether other kinds of layout geometry can also influence selection of spatial reference frames. It is important to demonstrate that geometric structures other than bilateral symmetry can be used to set up reference axes, given that conception of the idea of intrinsic reference frames was based on the observation that objects in everyday environments tend to make up certain geometric patterns, not necessarily bilateral symmetry (Mou & McNamara, 2002). For instance, Mou, McNamara, and colleagues frequently used chairs in a classroom as an example; they often form rows and columns, which could presumably define reference axes even if the configuration of the chairs is not bilaterally symmetrical (e.g., Mou, McNamara, et al., 2004). The theory will be even more strengthened by showing that a variety of geometric structures can function in a similar manner to bilateral symmetry.

Another unique aspect of the present study was that participants' preference for particular orientations during spatial memory retrieval was thoroughly examined following haptic encoding of a spatial layout. Previous studies that utilized similar paradigms of haptic spatial learning typically contrasted a learned orientation only with one particular novel orientation (e.g., Newell, Woods, Mernagh, & Bülthoff, 2005). Although this methodology was effective for demonstrating general enhancement of memory retrieval at the learned orientation, it could not unequivocally show that the learned orientation yielded the best (or among the best) memory performance because it did not rule out the possibility that there were other orientations that were even more preferred than the learned orientation. As a consequence, results from previous studies did not clearly indicate which reference axis (or axes) was used to specify object locations in memory when they were encoded through touch. On the other hand, the no instruction group in Experiment 1 provided more detailed data from a condition in which haptic exploration of a spatial layout was mostly unconstrained and naturalistic, and revealed that the egocentric orientation during learning defined the sole reference axis for haptically encoded spatial memory unless other spatial cues were present. This is consistent with the prediction derived from the intrinsic reference theory (i.e., in the absence of any salient cues, the first egocentric orientation experienced by observes defines the primary reference axis), and it parallels findings from spatial memories acquired through other sensory modalities such as vision (Shelton & McNamara, 2001), audition (Yamamoto & Shelton, 2009a), and proprioception (Yamamoto & Shelton, 2005) as well as non-sensory sources such as spatial language (Mou, Zhang, & McNamara, 2004). This convergence also supports the hypothesis that a type of spatial memory that is coherently described by the intrinsic reference theory is independent of modalities in which spatial information is acquired.

In conclusion, the present study extended the intrinsic reference theory (Mou & McNamara, 2002; Shelton & McNamara, 2001) to include spatial memory encoded through haptic exploration. The geometric structure of a spatial layout influenced selection of reference frames in a manner virtually identical to what was observed in previous studies, in which spatial layouts were always learned by simultaneous viewing of all objects. By contrast, in haptic spatial learning utilized in the present study, object locations were experienced sequentially and the entire structure of the spatial layout was not immediately apparent. This finding suggests that the conceptual framework put forth by the intrinsic reference theory can provide a general explanation for the organization of spatial memories acquired through a variety of encoding conditions. Moreover, converging evidence from studies using different learning modalities indicates a possibility that this theory may offer a coherent description of spatial memories that are independent of modalities. Further research should be conducted to test this hypothesis.

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