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Layout Geometry in the Selection of Intrinsic Frames of Reference From Multiple Viewpoints

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Four experiments investigated the roles of layout geometry in the selection of intrinsic frames of reference in spatial memory. Participants learned the locations of objects in a room from 2 or 3 viewing perspectives. One view corresponded to the axis of bilateral symmetry of the layout, and the other view(s) was (were) nonorthogonal to the axis of bilateral symmetry. Judgments of relative direction using spatial memory were quicker for imagined headings parallel to the symmetric axis than for those parallel to the other viewing perspectives. This advantage disappeared when the symmetric axis was eliminated. Moreover, there was more consistency across participants in the selection of intrinsic axes when the layout contained an axis of bilateral symmetry than when it did not. These results indicate that the layout geometry affects the selection of intrinsic frames of reference supporting the intrinsic model of spatial memory proposed by W. Mou and T. P. McNamara (2002) and by A. L. Shelton and T. P. McNamara (2001).

Keywords: spatial memory, intrinsic frames of reference, layout geometry, viewing directions

As people learn the spatial layout of their surrounding environment, they must establish spatial reference systems in memory to remember the locations of objects and landmarks. McNamara and his colleagues (McNamara, 2003; Mou & McNamara, 2002; Mou, Zhang, & McNamara, 2004; Shelton & McNamara, 2001; see also Hintzman, O'Dell, & Arndt, 1981; Tversky, 1981; Werner & Schmidt, 1999) have proposed that people use intrinsic frames of reference to specify locations of objects in memory. According to their theory, learning the spatial structure of a new environment involves interpreting it in terms of a spatial reference system. This process is analogous to determining the top of a figure or an object (e.g., Rock, 1973). Reference directions or axes are selected, and spatial relations are represented in those terms (e.g., Tversky, 1981). McNamara and his colleagues hypothesized that the spatial reference system is intrinsic in the layout itself (e.g., the rows and columns formed by chairs in a classroom). A collection of objects will have an infinite number of possible intrinsic axes, but particular ones are selected on the basis of several types of cues, such as participants' viewing perspective and other experiences (e.g., instructions), properties of the layout (e.g., the objects may be grouped together on the basis of similarity or proximity), and the structure of the environment (e.g., geographical slant).

According to their theory, interobject spatial relations are represented with respect to the intrinsic reference axes selected. For example, the angular direction from one object to another might be defined with respect to the intrinsic axis (e.g., Mou, McNamara, Valiquette, & Rump, 2004). Spatial judgments that invoke one of these intrinsic axes are able to use spatial relations that are explicitly represented in memory, whereas spatial judgments that invoke another reference axis must use spatial relations that are inferred (e.g., Klatzky, 1998). Inferential processes are assumed to produce measurable costs in terms of latency and error. Hence, spatial judgments that depend on the intrinsic axes used to represent the layout of the space will be faster and more accurate than those that depend on alternative axes.

The influence of environmental and experiential cues in the selection of intrinsic axes has been carefully examined in recent years (Mou & McNamara, 2002; Shelton & McNamara, 1997, 2001). For example, Shelton and McNamara (2001, Experiment 3) showed that the edges of a mat on which objects were placed and the walls of an enclosing room influenced which intrinsic axes participants selected. Participants learned the locations of objects in a large room from two points of view. One viewing position was aligned (0°) and the other was misaligned (135°) with the mat and the walls of the room. Order of learning was counterbalanced across participants (0°–135° vs. 135°–0°). After participants pointed to objects accurately from both viewing positions, they were taken to a different room to make judgments of relative direction using their memories (e.g., "Imagine you are standing at the book, facing the lamp. Point to the vase."). This task required participants to judge the direction of a target object relative to an imagined heading, which corresponded to an assumed reference direction. Judgments were much more accurate for the imagined heading parallel to the aligned view (0°) than for other imagined

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headings, including the heading parallel to the misaligned view (135°). This pattern of results occurred regardless of which view was learned first. These results indicated that participants were strongly biased to represent the layout of the objects with respect to an intrinsic axis aligned with environmental frames of reference.

In the absence of salient environmental cues, the first egocentric view seems to be the dominant cue in selecting intrinsic reference axes. Shelton and McNamara (2001, Experiment 7) required participants to learn the layout of objects in a cylindrical room from three points of view (0°, 90°, and 225°). Order of learning was counterbalanced across participants (0°–90°–225° vs. 225°–90°–0°). Participants could point to objects accurately at each study view before being tested on their spatial memory in a different room. Accuracy of judgments of relative direction was highest for the imagined heading parallel to the first study view (0° or 225°), indicating that an intrinsic axis parallel to the first study view was used to represent the layout of the objects.

In another investigation of the effects of experiential cues, Mou and McNamara (2002) showed that participants could be instructed to select an intrinsic axis that differed from their viewing perspective. They instructed participants to learn the layout of a collection of objects along an intrinsic axis that was different from or the same as their viewing perspective. After learning, participants made judgments of relative direction using their memories. Pointing judgments were more accurate for imagined headings aligned with the learning axis, even when it differed from the viewing perspective, than for other imagined headings, and there was no apparent cost to learning a layout along a nonegocentric axis.

By contrast, the influence of properties of the layout of objects in the selection of intrinsic axes has never been examined in the spatial memory literature. In Mou and McNamara's (2002) experiments, the nonegocentric axis was an axis of bilateral symmetry of the layout. However, this axis was also explicitly identified by the instructions to participants, so it was not clear whether the intrinsic property of the layout alone would influence the selection of the intrinsic axis.

Lack of empirical work directly investigating the influence of such intrinsic cues on the selection of intrinsic axes undermines the validity of the intrinsic model of spatial memory. The model predicts the influence of intrinsic cues, such as layout geometry, in the selection of intrinsic axes. Furthermore, in the literature of form perception from which the intrinsic model was derived originally, the roles of internal properties of a shape in selection of the orientation of an intrinsic frame of reference are well documented. For example, it is well demonstrated that an axis of bilateral symmetry and an axis of elongation were selected as the intrinsic orientation of the shape (e.g., Boutsen & Marendaz, 2001; Palmer, 1999, p. 375; Rock, 1973; Quinlan & Humphreys, 1993; Sekuler & Swimmer, 2000). Hence, systematic investigation of the influence of intrinsic cues on the selection of intrinsic axes in spatial memory is crucially needed to verify the validity of the intrinsic model.

The goal of this project was to test two key predictions of the hypothesis that layout geometry (in particular, bilateral symmetry) has an effect on the selection of the intrinsic directions. In Experiments 1 and 3, we had participants learn a layout with an axis of bilateral symmetry in a cylindrical room from two or three viewing perspectives, one of which corresponded to the symmetric axis. The axis of bilateral symmetry was 225°–45° (see Figure 1). In Experiments 2 and 4, we added two objects to the configuration so that the axis of symmetry in Experiments 1 and 3 was eliminated. In all experiments, participants were tested with judgments of relative directions in a different room.

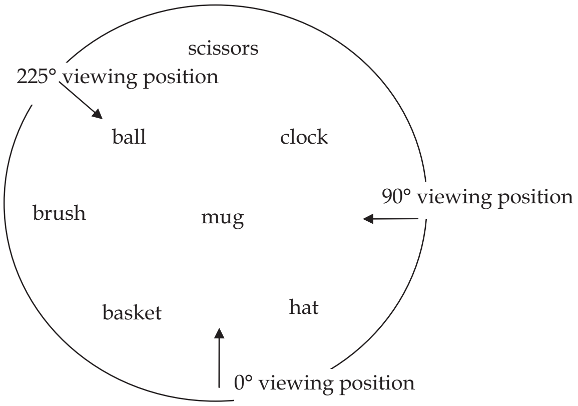

Figure 1. Layout of objects used in Experiments 1 and 3.

If the geometry of the layout has a strong effect on the selection of the intrinsic directions, performance in judgments of relative direction in Experiments 1 and 3 should be best for the heading parallel to the symmetric axis of the layout (225°). However, in Experiments 2 and 4, performance for the same heading should not be better, on the average, than performance for other headings because the layout does not have an axis of bilateral symmetry.

A second prediction of the hypothesis that layout geometry will influence the selection of intrinsic directions is that the selection of intrinsic directions should be more consistent across participants when the object array contains a salient intrinsic cue, such as bilateral symmetry, than when it does not. This prediction cannot be tested by examining the data in an experiment with only a few trials at each imagined heading for each participant because this feature of the design makes results at the level of individual participants highly variable and therefore of limited use in examining individual differences in patterns of performance. In Experiments 3 and 4, each of a relatively small number of participants was tested for a large number of trials, thereby allowing analyses of each participant's data separately. These experiments permitted us to examine whether there were more individual differences in which intrinsic axis was used to represent the locations of objects when there was no salient intrinsic cue than when there was a salient cue.

Both predictions were confirmed by the results of the experiments described subsequently, demonstrating that the geometry of the layout has a strong influence on the selection of the intrinsic directions.

Experiment 1

In Experiment 1, participants learned the locations of seven objects (illustrated in Figure 1) from three viewpoints (0°, 90°, and 225°) in a cylindrical room. The intrinsic axis 225°–45° of the layout was the only axis of bilateral symmetry. Participants were never instructed to select any intrinsic axis. The main purpose of this experiment was to determine whether participants would select the symmetric intrinsic axis to establish the intrinsic frame of reference without environmental cues and verbal instructions.

Method

Participants

Forty-eight university students (24 men, 24 women) participated in return for monetary compensation.

Materials and Design

The layout was presented in a cylindrical room (3.0 m in diameter) that was constructed from a reinforced cloth and a black fabric that blocked the lights from outside. The layout consisted of a configuration of seven objects (see Figure 1). Objects were selected with the restrictions that they be visually distinct, fit within approximately 0.3 m on each side, and not share any obvious semantic associations. The 225°–45° intrinsic axis was the only axis of bilateral symmetry.

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

The primary independent variable was imagined heading. Eight equally spaced headings were used. To facilitate exposition, we arbitrarily labeled headings counterclockwise from 0° to 315° in 45° steps beginning with the position labeled 0° in Figure 1. For example, 0° corresponds to all views oriented in the same direction as the arrow labeled 0° (e.g., at the hat facing the clock, at the basket facing the ball), and 225° corresponds to all views oriented in the same direction as the arrow labeled 225° (e.g., at the brush facing the basket, at the scissors facing the clock). The second important independent variable was learning order. Two learning orders were used: 0°–90°–225°, in which participants first learned the layout from the view of 0°, then from 90°, and finally from 225°, and 225°–90°–0°, in which participants learned the layout in the reverse order.

Pointing direction (the direction of the target object relative to the imagined heading) was varied systematically by dividing the space into three areas: front (45°–0° and 0°–315°), sides (315°–225° and 135°–45°, not including endpoints of intervals), and back (135°–180° and 180°–225°). Participants were given a total of 48 trials, six trials at each of eight imagined headings. These trials were chosen according to the following rules: (a) three pairs of standing objects and facing objects were used for each heading; (b) two target objects were used in each direction of front, sides, and back; (c) of the six target objects used for each heading, one was pointed to twice; and (d) across all headings, each object was used nearly the same number of times as the standing, facing, and pointing objects, respectively. As a result, the pointing directions were equivalent across the imagined headings. For example, pointing directions at the imagined heading of 0° include 45°, 90°, 135°, 225°, 288°, and 315°, clockwise from the imagined heading, whereas pointing directions at the imagined heading of 225° include 45°, 90°, 135°, 225°, 297°, and 315°, clockwise from the imagined heading.

The dependent measures were the response latencies, measured as the latencies from presentation of the name of the target object to the pointing response, and the angular error of the pointing response, which was measured as the absolute angular difference between the judged pointing direction and the actual direction of the target. In this and in the following experiments, angular error was not as sensitive as pointing latency to the effect of imagined heading, but generally there were no accuracy–latency trade-offs, so for brevity the analyses of angular error were not presented in detail. A possible reason that angular error might have been less sensitive in these experiments is provided in the General Discussion section.

Procedure

Learning phase. Participants were randomly assigned to the two learning order conditions such that each group contained an equal number of men and women. Before entering the study room, each participant was instructed to learn the locations of the objects for a spatial memory test and trained how to use a joystick to make a relative direction judgment. The participant was blindfolded and led to the first viewing position. The blindfold was removed, and the participant was asked to learn the locations of the objects as accurately as possible. The participant viewed the display for 30 s before being asked to name and point to, with eyes closed, the objects in any order they preferred. After five such viewing–pointing sessions, the participant was blindfolded again and escorted by the experimenter to the second learning position. As at the first learning position, the participant had five viewing–pointing sessions before moving to the third learning position with eyes blindfolded. The participant was blindfolded and led by the experimenter to the testing room after five viewing–pointing sessions at the last learning position.

Testing phase. Seated in a chair, the participant wore an earphone and held a joystick. The test trials were presented via the earphone attached to a PC computer. The participant first initiated each trial by pressing a button of the joystick. Trials began with the imagined standing location and facing object given aurally (e.g., “Imagine you are standing at the brush facing the basket.”). The participant was instructed to pull the joystick trigger when he or she had a clear mental image of where he or she was standing and what he or she was facing. The target object was immediately presented aurally when the participant pulled the trigger (e.g., “Point to the ball”). 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 to keep the joystick forward when he or she pointed. Pointing accuracy was emphasized, and speedy responses were not encouraged.

Results

Pointing latency was analyzed in mixed-model analyses of variance (ANOVAs) with terms for imagined heading (0° to 315° in 45° steps) and learning order (0°–90°–225° or 225°–90°–0°). Imagined heading was within-subject.

Mean pointing latency is plotted in Figure 2 as a function of imagined heading and learning order. As illustrated in Figure 2, there were four major findings. First, the overall patterns were similar in both learning orders. Second, participants were quicker to point to objects from the imagined heading of 225°, which corresponded to the symmetric intrinsic axis, than from the imagined headings of 0° and 90°, which did not correspond to the symmetric intrinsic axis, although all of these headings were experienced an equal amount of time. Third, participants were not quicker (indeed, they were slower) to point to objects from the imagined headings of 0° and 90°, which were experienced, than from the headings of 45°, 135°, and 315°, which were novel but were aligned with (i.e., parallel or orthogonal to) the symmetric intrinsic axis 225°–45°. Fourth, participants were quicker to point to objects from the novel headings of 45°, 135°, and 315°, which were aligned with the symmetric intrinsic axis 225°–45°, than from the novel imagined headings of 180° and 270°, which were misaligned with the symmetric intrinsic axis 225°–45°.

All of these conclusions were supported by statistical analyses. The overall effect of imagined heading was significant, *F*(7,

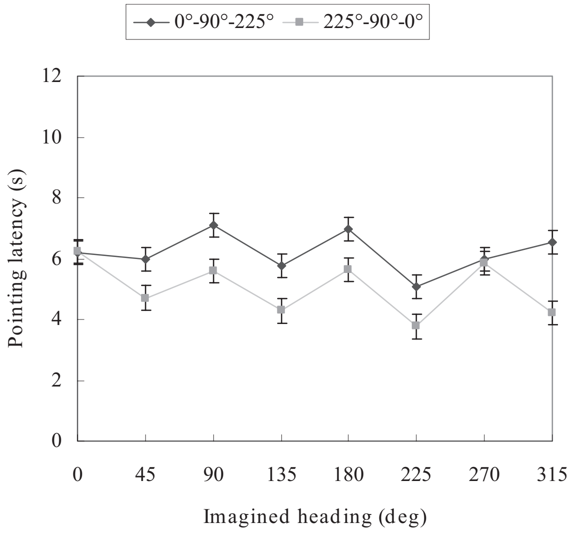

Figure 2. Pointing latency as a function of imagined heading and learning order in Experiment 1. (Error bars are confidence intervals corresponding to ± 1 *SE*, as estimated from the analysis of variance.)

322) = 6.36, $p < .001$, $MSE = 3.63$. The interaction between imagined heading and learning order was not significant, $F(7, 322) = 1.92$, $p > .05$. The effect of learning order was not significant, $F(1, 46) = 2.32$, $p > .05$, $MSE = 56.12$. The planned comparison of the heading of 225° with the headings of 0° and 90° was significant, $t(322) = 5.52$, $p < .001$. The planned comparison of the headings of 0° and 90° with the novel headings 45°, 135°, and 315°, which were aligned with the learning view of 225°, was significant, $t(322) = 4.13$, $p < .001$. The planned comparison of the novel headings 45°, 135°, and 315°, which were aligned with the learning view of 225°, with the novel headings of 180° and 270°, which were aligned with the learning views of 0° and 90°, was significant, $t(322) = 3.43$, $p < .001$.

Mean angular error is presented in Table 1 as a function of imagined heading and learning order. Neither of the main effects was significant, nor was the interaction.

Discussion

The results of Experiment 1 suggest that participants might have encoded the spatial structure of the layout in terms of orthogonal directions or axes (225°–45° and 315°–135°) and indicate that participants represented the layout in terms of a reference system that was determined by the symmetric intrinsic axis of the layout. This conclusion would be strengthened if the learning view of 225° was not preferred when it did not correspond to the symmetric axis of the layout.

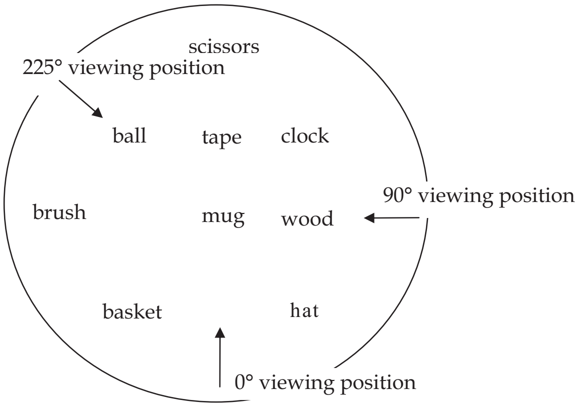

Figure 3. Layout of objects used in Experiments 2 and 4.

Experiment 2

In Experiment 2, two objects were added to the layout used in Experiment 1 such that it was no longer bilaterally symmetric about the intrinsic axis of 225°–45° (see Figure 3). If participants in Experiment 1 preferred the learning view of 225° because of the symmetric axis of the layout, the preference of the learning view of 225° would not be observed in this experiment. Instead, performance at the heading parallel to the first view would be better if the first egocentric view is a strong cue in the absence of other salient cues, such as instructions (e.g., Mou & McNamara, 2002) and environmental structure (e.g., Shelton & McNamara, 2001).

Method

Participants

Forty-eight university students (24 men, 24 women) participated in return for monetary compensation.

Materials, Design, and Procedure

The materials were similar to those used in Experiment 1 except that two objects (tape and wood) were added in the layout as illustrated in Figure 3. The design was identical to that in Experiment 1. The trials were identical

Table 1
Mean (and Standard Deviation) Angular Error (in Degrees) as a Function of Imagined Heading and Learning Order (First View; FV) in Experiment 1

	Imagined heading									
FV	0°	45°	90°	135°	180°	225°	270°	315°	$F(7, 161)$	p
0°	27.56 (13.47)	25.88 (16.85)	29.44 (13.18)	28.31 (16.43)	29.96 (13.57)	30.42 (21.44)	33.31 (16.40)	29.86 (16.55)	0.88	$> .05$
225°	27.17 (17.06)	27.29 (10.29)	26.04 (13.19)	24.01 (10.88)	28.65 (15.49)	22.77 (16.00)	27.81 (14.00)	21.42 (15.50)	1.18	$> .05$

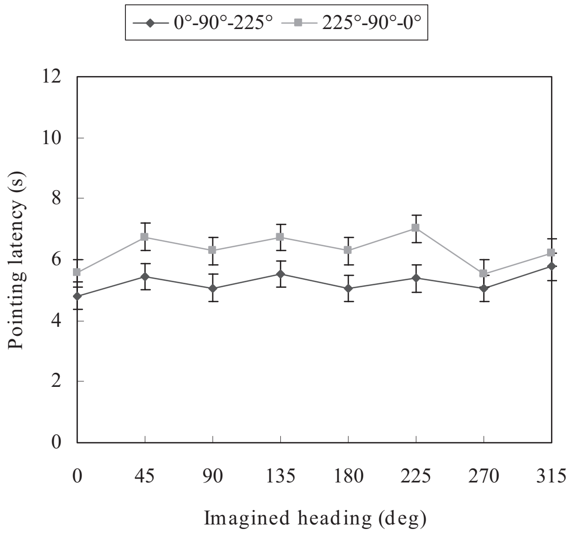

Figure 4. Pointing latency as a function of imagined heading and learning order in Experiment 2. (Error bars are confidence intervals corresponding to ± 1 *SE*, as estimated from the analysis of variance.)

to those used in Experiment 1. In other words, the two new added objects were never involved in the trials. The procedure was similar to that in Experiment 1, except that participants learned two more objects in the learning phase.

Results

Pointing latency was analyzed in mixed-model ANOVAs with terms for imagined heading (0° to 315° in 45° steps) and learning order (0°–90°–225° or 225°–90°–0°). Imagined heading was within-subject.

Mean pointing latency is plotted in Figure 4 as a function of imagined heading and learning order. The effect of imagined heading was not significant, $F(7, 322) = 1.52$, $p > .05$, $MSE = 4.71$. The interaction between imagined heading and learning order was not significant, $F(7, 322) = 0.45$, $p > .05$. The effect of learning order was not significant, $F(1, 46) = 2.59$, $p > .05$, $MSE = 39.32$.

Mean angular error is presented in Table 2 as a function of imagined heading and learning order. Neither of the main effects was significant, nor was the interaction.

Discussion

The results of Experiment 2 indicate there was no evidence suggesting that participants preferred the intrinsic axis of 225°–45° when it was not the symmetric axis. Together with Experiment 1, these results suggest that participants used intrinsic cues of the layout (e.g., symmetry) in establishing intrinsic frames of reference.

Surprisingly, pointing performance in Experiment 2 was essentially orientation free (the effect of imagined heading was also nonsignificant in angular error). This result is inconsistent with Shelton and McNamara's (2001, Experiment 7) finding that performance for the imagined heading parallel to the first egocentric view was best when there were no environmental cues. We will discuss the possible reason for the discrepancy between the findings of this study and the study of Shelton and McNamara (2001), as well as the implications of this finding for the intrinsic model, in the General Discussion.

The observation of orientation-free performance would be striking if it implied that participants formed orientation-free spatial representations, as there is a large body of empirical evidence showing that spatial representations are orientation dependent (e.g., McNamara, 2003, for a review). However, this orientation-free result can also be explained by the second prediction of the intrinsic model described previously. The hypothesis that layout geometry has a strong effect on the selection of the intrinsic directions predicts that participants will differ more in their selection of intrinsic directions when the layout does not contain strong intrinsic cues. Specifically, in Experiment 2, some participants might have established an intrinsic frame of reference determined by the learning views of 0° and 90°, whereas other participants might have established an intrinsic frame of reference determined by the learning view of 225°. Hence, the pattern of results collapsed across the participants would appear to be orientation free. We were not able to test this hypothesis by simply looking at the pattern of results for each participant because the data were too variable at the individual participant level. This variability almost certainly results from having collected only six trials per heading per participant.

In Experiments 3 and 4, we collected a large number of pointing trials for each heading and each participant. Our goals were to examine whether there were fewer individual differences in selecting intrinsic directions in the presence than in the absence of strong intrinsic cues and to assess, at the level of individual participants, the role of layout geometry in the selection of intrinsic frames of reference.

Table 2
Mean (and Standard Deviation) Angular Error (in Degrees) as a Function of Imagined Heading and Learning Order (First View; FV) in Experiment 2

	Imagined heading									
FV	0°	45°	90°	135°	180°	225°	270°	315°	$F(7, 161)$	p
0°	31.68 (20.97)	31.10 (14.81)	34.92 (17.33)	37.48 (16.97)	29.00 (11.57)	34.37 (17.96)	35.66 (18.13)	36.28 (18.69)	1.17	> .05
225°	22.53 (9.32)	28.60 (9.17)	23.25 (11.16)	30.00 (14.00)	26.39 (12.53)	29.21 (13.77)	27.40 (11.70)	28.43 (12.86)	1.44	> .05

Experiment 3

In Experiment 3, participants learned a layout with an axis of bilateral symmetry, as in Experiment 1. The difference between the two experiments was that trials of Experiment 1 were repeated several times in Experiment 3. By collecting more data per participant, we hoped to determine which intrinsic directions would be selected by each participant. Participants learned the layout used in Experiment 1 from two learning views (0° and 225°). The learning view of 90° was omitted to simplify the design.

Method

Participants

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

Materials, Design, and Procedure

The materials were identical to those used in Experiment 1. The same 48 kinds of trials (six pointing directions for each of the eight imagined headings) used in Experiment 1 were presented repeatedly so that the effect of imagined heading could be examined for each participant. Each participant received five blocks of trials. In each block, each of the six kinds of trials at headings of 0° and 225° was presented three times (18 for the headings of 0° and 225°, respectively), whereas each of the six kinds of trials at all other headings was presented once (6 for each heading). Hence, 72 trials were presented in each block. In this way, equal numbers of trials (18 trials in each block) were used at the heading of 0°; at the heading of 225°; at the novel headings of 45°, 135°, and 315°, which were aligned with the learning view of 225° (henceforth labeled as novel_225° headings); and at the novel headings of 90°, 180°, and 270°, which were aligned with the learning view of 0° (henceforth labeled as novel_0° headings). The trials at each block were presented randomly. The procedure was similar to Experiment 1 except that the participant learned only two views (0° and 225°) in the learning phase and received more test trials in the testing phase. Half of the participants (2 men and 2 women) learned two views in the order of 0°–225°, whereas the other half learned in the reversed order. Participants took breaks between any two blocks if they wished.

Results

For each participant, pointing latency was analyzed in ANOVA with a term for imagined heading (0°, 225°, novel_0°, and novel_225°).

Mean pointing latency for each participant is plotted in Figure 5 as a function of imagined heading. As illustrated in Figure 5, there were three major findings. First, no participant showed that they selected both intrinsic axes parallel to the learning views. Participant 1 seemed to select the intrinsic axis of 0°–180°, and all others seemed to select the intrinsic axis of 225°–45°. Second, participants were not quicker (indeed, they were slower) to point to objects from the heading parallel to the nonpreferred learning view than from the novel headings that were aligned with the preferred learning view. Third, most of the participants showed shorter pointing latencies at the novel headings aligned with the preferred learning view than at the novel headings aligned with the nonpreferred learning view.

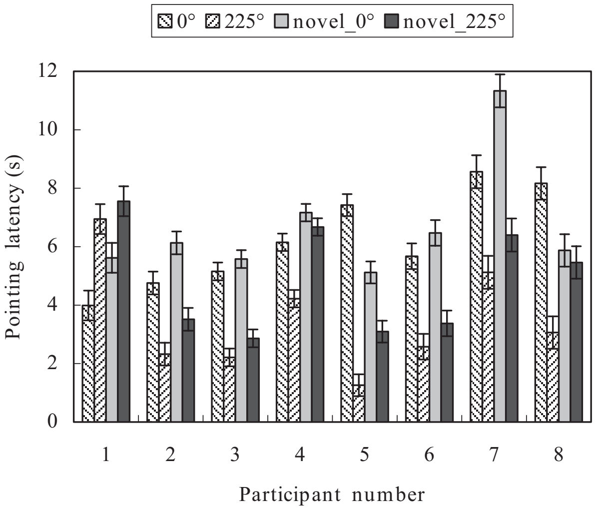

Figure 5. Pointing latency for each participant as a function of imagined heading and learning order in Experiment 3. (Error bars are confidence intervals corresponding to ± 1 *SE*, as estimated from the analysis of variance.)

All of these conclusions were supported by statistical analyses. All participants showed a significant main effect of imagined heading, *F*s(3, 356) ≥ 9.58, *p*s < .01. The planned comparisons of Heading 0° to Heading 225° were significant, *t*s(356) ≥ 4.32, *p*s < .001. Participant 1 was quicker at the heading of 0° than at the heading of 225°, whereas all others were quicker at the heading of 225° than at the heading of 0°. All participants were slower at the heading of 0° than at the novel_225° headings, *t*s(356) ≥ 2.26, *p*s < .05, except for Participants 1 and 4, who showed no difference, *t*s(356) ≤ 1.84, *p*s > .05. The planned comparisons of novel_0° headings with novel_225° headings were significant, *t*s(356) ≥ 3.81, *p*s < .001, except for Participants 4 and 8, *t*s(356) ≤ 1.17, *p*s > .05.

Mean angular error for each participant is presented in Table 3 as a function of imagined heading. As illustrated in Table 3, 4 participants showed significant effects of imagined heading. None of them showed a latency–accuracy trade-off.

Discussion

As in Experiment 1, the results of Experiment 3 indicate that participants selected the symmetric intrinsic axis to establish an intrinsic frame of reference. A novel and important result is that participants were very consistent in selecting intrinsic axes when there was a strong intrinsic cue. Seven of 8 participants selected the symmetric intrinsic axis as the preferred learning view. Most participants seem to have encoded the spatial structure of the layout in terms of orthogonal directions or axes (e.g., Mou & McNamara, 2002): 6 of 8 participants were quicker at the novel headings aligned with the preferred learning view (225°) than at the novel headings aligned with the nonpreferred learning view (0°). No participant seemed to select both intrinsic axes parallel to the learning views. There was no evidence suggesting that participants represented the nonpreferred learning view (0°). All participants showed that performance at the nonpreferred learning view was not better (and was actually, in most cases, worse) than at the novel headings aligned with the preferred learning view.

Table 3
Mean (and Standard Deviation) Angular Error (in Degrees) for Each Participant as a Function of Imagined Heading in Experiment 3

		Imagined heading				
PN	FV	0°	225°	novel_0°	novel_225°	*F*(3, 356)
1	0°	18.78 (20.47)	25.42 (21.15)	25.50 (24.00)	31.97 (33.70)	4.05^{**}
2	0°	34.30 (17.94)	33.00 (23.14)	38.87 (25.78)	30.70 (15.69)	2.41
3	225°	18.26 (14.03)	18.58 (13.49)	18.37 (10.81)	20.02 (17.06)	0.31
4	225°	42.68 (40.21)	29.99 (19.38)	35.42 (29.23)	38.38 (31.89)	2.65^{*}
5	225°	18.62 (14.19)	12.52 (9.77)	21.66 (18.23)	15.11 (12.64)	7.29^{**}
6	225°	24.39 (17.33)	14.63 (12.49)	23.47 (18.12)	17.07 (11.67)	8.95^{**}
7	0°	16.57 (18.81)	10.87 (15.65)	16.77 (21.48)	17.71 (21.35)	2.30
8	0°	21.04 (20.96)	17.77 (22.85)	22.72 (28.30)	18.40 (23.42)	0.83

Note. PN = participant number; FV = first view.
$^{*}p < .05$. $^{**}p < .01$. For all nonasterisked *F* statistics, $p > .05$.

Experiment 4

The purpose of Experiment 4 was to test whether participants would be less consistent in selecting intrinsic axes when there was no salient cue. Participants learned the layout used in Experiment 2 from two learning views (0° and 225°).

Method

Participants

Twelve university students (6 men, 6 women) participated in return for monetary compensation.

Materials, Design, and Procedure

The materials were similar to those used in Experiment 3 except that two objects (tape and wood) were added to the layout as illustrated in Figure 3. The design was identical to that in Experiment 3. The trials were identical to those used in Experiment 3. The procedure was similar to that in Experiment 3, except that participants learned two more objects in the learning phase.

Results

For each participant, pointing latency was analyzed in ANOVA with a term for imagined heading (0°, 225°, novel_0°, and novel_225°).

Mean pointing latency for each participant is plotted in Figure 6 as a function of imagined heading. As illustrated in Figure 6, there were three major findings. First, 8 participants (1, 2, 3, 4, 5, 6, 10, and 11) seemed to select the intrinsic axis of 0°–180°, and 3 participants (7, 8, 12) seemed to select the intrinsic axis of 225°–45°; only Participant 9 seemed to select both intrinsic axes parallel to the learning views. Second, all participants except Participant 9 were not quicker (and in fact were even slower) to point to objects from the heading parallel to the nonpreferred learning view than from the novel headings that were aligned with the preferred

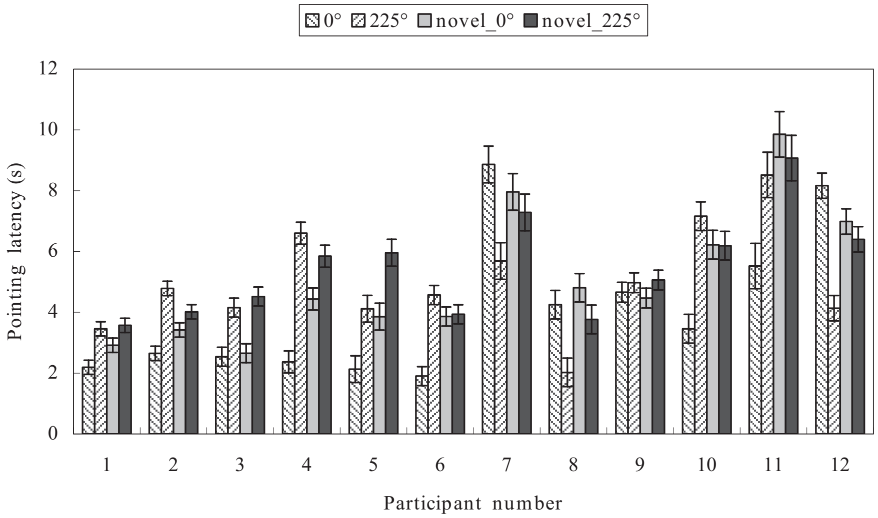

Figure 6. Pointing latency for each participant as a function of imagined heading and learning order in Experiment 4. (Error bars are confidence intervals corresponding to ± 1 *SE*, as estimated from the analysis of variance.)

learning view. Third, few participants showed that pointing latencies were shorter at the novel headings aligned with the preferred learning view than at the novel headings aligned with the nonpreferred learning view.

All of these conclusions were supported by statistical analyses. Significant main effects of imagined heading were observed in all participants, Fs$(3, 356) \geq 4.95$, ps $< .01$, except in Participant 9, $F(3, 356) = 0.72$, $p > .05$. Hence, Participant 9 was not included in the following analyses. The planned comparisons of Heading 0° with Heading 225° were significant, ts$(356) \geq 2.84$, ps $< .01$. Participants 1, 2, 3, 4, 5, 6, 10, and 11 were quicker at the heading of 0° than at the heading of 225°, whereas Participants 7, 8, and 12 were quicker at the heading of 225° than at the heading of 0°. Among those who preferred the learning view of 0°, Participants 2, 3, and 4 were slower at the heading of 225° than at the novel_0° headings, ts$(356) \geq 3.40$, ps $< .001$, whereas the other participants showed no differences between the heading of 225° and the novel_0° headings, ts$(356) \leq 1.62$, ps $> .05$. Among those who preferred the learning view of 225°, Participant 12 was slower at the heading of 0° than at the novel_225° headings, $t(356) = 3.00$, $p < .01$, whereas Participants 7 and 8 showed no differences between the heading of 0° and the novel_225° headings, ts$(356) \leq 1.85$, ps $> .05$. The planned comparisons of novel_0° with novel_225° were significant for only Participants 3, 4 and 5, ts$(356) \geq 2.76$, ps $< .01$.

There was no apparent relation between the first learned view and the dominant intrinsic reference axis. Among the 8 participants who preferred the learning view of 0°, Participants 1, 4, and 6 learned the 225° view first, and Participants 2, 3, 5, 10, and 11 learned the 0° view first. Among the 2 participants who preferred the learning view of 225° (the preferred axis for Participant 7 was not determinant because this participant had a latency–accuracy trade-off), Participant 8 learned the 225° first, and Participant 12 learned the 0° view first. Overall, there was no nominal correlation between the first learning view and the preferred intrinsic direction, $\Phi = .10$, $p > .05$.

Mean angular error for each participant is presented in Table 4 as a function of imagined heading. As illustrated in Table 4, 5 participants showed significant effects of imagined heading. Only 1 of them (Participant 7) showed a latency–accuracy trade-off.

Discussion

In comparison with the results of Experiment 3, the results of Experiment 4 indicate that participants were less consistent in selecting intrinsic axes when there was no salient intrinsic cue in the layout. Also, after learning a layout without any salient cue, participants still selected only one of the two intrinsic axes parallel to the two nonorthogonal learning views. Eleven of 12 participants showed that performance at the heading parallel to the nonpreferred learning view was not better (actually in many cases worse) than at the novel headings aligned with the preferred learning view. These results also suggest that the orientation-free pattern of results in Experiment 2 should not be interpreted as evidence that participants formed orientation-free spatial representations. This pattern of results was more likely due to greater individual differences in selecting intrinsic axes when there was no axis of symmetry, such that some participants established an intrinsic frame of reference determined by the learning views of 0° and 90°, whereas other participants established an intrinsic frame of reference determined by the learning view of 225°. Researchers should be cautious in concluding that orientation-free results are caused by orientation-free mental representations when data are collapsed across participants.

General Discussion

The primary goal of this project was to test the hypothesis that a geometric property (viz., bilateral symmetry) of the layout of a collection of objects would be used by people as a cue for selecting an intrinsic reference system for representing the locations of the objects in memory. The experiments provided two sources of evidence consistent with predictions of this hypothesis.

First, participants were quicker in judgments of relative direction for the heading parallel to the axis of bilateral symmetry, but the advantage of that heading disappeared when the axis of bilat-

Table 4

Mean (and Standard Deviation) Angular Error (in Degrees) for Each Participant as a Function of Imagined Heading in Experiment 4

		Imagined heading				
PN	FV	0°	225°	novel_0°	novel_225°	$F(3, 356)$
1	225°	17.94 (16.91)	23.17 (21.22)	26.34 (27.57)	19.97 (13.90)	2.89^{*}
2	0°	20.74 (26.73)	23.27 (19.06)	22.12 (22.18)	24.82 (20.97)	0.54
3	0°	14.74 (11.46)	18.33 (23.27)	18.40 (15.31)	18.87 (22.45)	0.93
4	225°	18.34 (16.91)	23.47 (26.23)	24.52 (25.77)	21.17 (17.76)	1.38
5	0°	16.23 (16.13)	15.03 (18.86)	17.89 (15.13)	20.59 (24.47)	1.44
6	225°	21.69 (14.72)	38.23 (26.56)	24.06 (19.38)	31.52 (23.17)	11.09^{**}
7	225°	19.94 (20.36)	26.11 (24.03)	21.01 (13.93)	27.21 (19.76)	3.00^{*}
8	225°	15.39 (15.42)	13.92 (7.69)	15.81 (17.21)	18.19 (24.67)	0.94
9	225°	19.74 (11.93)	21.19 (15.97)	20.79 (15.28)	19.72 (15.22)	0.23
10	0°	14.84 (15.48)	15.48 (12.58)	16.41 (14.57)	14.13 (17.09)	0.37
11	0°	22.00 (15.04)	39.63 (33.11)	32.57 (25.04)	31.71 (31.16)	6.48^{**}
12	0°	48.46 (38.28)	36.58 (28.00)	48.60 (38.21)	34.71 (32.47)	4.23^{**}

Note. PN = participant number; FV = first view.
$^{*}p < .05$. $^{**}p < .01$. For all nonasterisked F statistics, $p > .05$.

eral symmetry was removed. In Experiments 1 and 3, performance at the heading parallel to the symmetric axis (225°) was better than performance at other experienced headings (e.g., 0°). Performance at the experienced headings that were not parallel to the symmetric axis (e.g., 0°) was no better (in most cases, even worse) than performance at novel headings aligned with (i.e., parallel or orthogonal to) the symmetric axis (e.g., 45°, 135°, 315°). Finally, performance at the novel headings aligned with the symmetric axis was better than performance at novel headings aligned with the other experienced headings (e.g., 180°, 270°). However, all of these advantages of the symmetric axis and the axis orthogonal to the symmetric axis were not observed when the axis of bilateral symmetry was removed by adding two objects to the layout in Experiments 2 and 4.

Second, participants were more consistent in selecting an intrinsic axis when the layout contained a strong intrinsic cue than when it did not. Participants consistently selected the intrinsic axis determined by the axis of symmetry of the layout in Experiment 3, whereas participants differed more in selecting an intrinsic axis when the axis of symmetry was removed in Experiment 4.

These two findings for the first time verify a central prediction of the intrinsic model of human spatial memory proposed by McNamara and his colleagues (McNamara, 2003; Mou & McNamara, 2002; Mou, Zhang, & McNamara, 2004; Shelton & McNamara, 2001). According to this model, the spatial reference system is intrinsic in the layout itself, and people should be able to use intrinsic cues (layout geometry) to select intrinsic axes of a layout. These results were also consistent with the findings in the literature of form perception. Although this project demonstrates the importance of layout geometry in selecting intrinsic axes, it does not provide empirical evidence on the relative importance of layout geometry, environmental structure, and viewpoint in selecting intrinsic axes. Additional research is needed to address this issue.

Another important finding of this study is that we did not observe any evidence that the first viewing perspective was privileged in memory. The results of Experiments 1 and 3 indicate that participants selected the axis of bilateral symmetry rather than the axis defined by the first viewing perspective. Furthermore, in Experiments 2 and 4, in which the symmetric axis was removed, the effect of the first viewing perspective on selection of intrinsic axes was not observed. In Experiment 2, performance at the heading parallel to the first viewing perspective was not better than performance at other headings. Instead, a flat pattern across imagined heading was observed. In Experiment 4, there was no correlation between the first viewing perspective and the selected intrinsic axes.

These results raise doubts about the claim that the first view of a novel environment plays an especially important role in the selection of intrinsic axis when the environment is experienced from multiple perspectives and does not contain salient cues of its own (e.g., Shelton & McNamara, 2001, Experiment 7). The original finding of Shelton and McNamara's Experiment 7 (2001) might have been caused by their learning procedures. In that experiment, participants finished studying the layout from each viewing position when they could point to all objects accurately (with eyes closed) in two consecutive learning–pointing sessions. At the first viewing position, participants had to pass the criterion by learning and remembering the location of each object, whereas at the second and the third viewing positions, participants might have been able to spend less time learning because they could benefit from spatial updating while locomoting to the second and third positions (e.g., Burgess, Spiers, & Paleologou, 2004; Farrell & Robertson, 1998; Mou, Biocca, et al., 2004; Mou, McNamara, Valiquette, & Rump, 2004; Rieser, 1989; Simons & Wang, 1998; Waller, Montello, Richardson, & Hegarty, 2002; Wang & Simons, 1999). Hence, the first viewing perspective might have been privileged because more time was spent there. In our study, in contrast, participants were required to spend the same amount of time at all viewing positions (five viewing–pointing sessions). The results of Experiments 2 and 4 show that the first viewing perspective had no effect on the selection of intrinsic directions when all viewing perspectives were experienced with the same amount of time. The present findings indicate that when people experience multiple views of a novel environment, the first egocentric view may not be as salient as previously conjectured.

Our findings raise the question of how people select an intrinsic axis in the absence of instructions or environmental cues if the first of multiple viewing perspectives is not the dominant cue. We speculate that people will still select an intrinsic axis parallel to one of the viewing perspectives, but that the particular axis selected depends on an individual's perception of the salience of features of the layout geometry. Perceived salience differs across individuals, producing individual differences in which intrinsic axis is used, as observed in Experiment 4. Hence, although results of this study suggest that the first view is not the dominant cue in selecting intrinsic axes, they remain consistent with the key claims of the intrinsic model, which are that the frame of reference is intrinsic to the layout and that different cues (e.g., viewpoints, layout geometry) are used to select an intrinsic frame of reference.

The other important finding of this study is that most participants selected only one intrinsic axis when they learned the layout from two nonorthogonal viewing perspectives. All but 1 of the participants in Experiment 3 selected the intrinsic axis corresponding to the axis of symmetry. All participants except 1 in Experiment 4 selected only one of the two experienced nonorthogonal intrinsic axes when there was no axis of symmetry in the layout. Out of a total of 20 participants in Experiments 3 and 4, only 1 seemed to select both nonorthogonal axes. Further studies are needed to systematically investigate the conditions in which a significant number of participants will be able to select two nonorthogonal axes. For now, we regard the participant who seems to select both nonorthogonal axes as an exception.

Throughout the experiments of this study, angular error was less sensitive than was pointing latency to the effect of imagined heading. We speculate that the participants who did not show a significant effect of imagined heading in angular error were able to infer interobject spatial relations from headings misaligned with the intrinsic reference directions, at the cost of longer latencies, and reached near-ceiling performance in judgments of relative direction (at least using a joystick as a response device). This speculation was supported by the data in Experiments 3 and 4. Among the 11 participants who did not show a significant effect in angular error (2, 3, 7, and 8 in Experiment 3, and 2, 3, 4, 5, 8, 9, and 10 in Experiment 4), all but 1 pointed quite accurately, with angular error less than 25° for all imagined headings. Only 2 of the 9 participants who showed a significant effect of imagined heading had pointing error under 25° for all imagined headings. Across all

20 participants, the average of each participant's best performance was 19°. Across the 11 participants who did not show a significant effect in angular error, the average of each participant's worst performance was 22°. For comparison, in Mou and McNamara's (2002) experiments, the lowest angular errors in judgments of relative direction using a joystick were around 22°. This level of performance may be near ceiling using a joystick as a response device (other response devices may permit better levels of performance in the best conditions; see, e.g., Shelton & McNamara, 2001). The reason that so many participants could reach near-ceiling performance in pointing accuracy might be due to the longer learning time in this study than in our previous studies.

In summary, the major findings from the present experiments are as follows: First, participants were quicker in judgments of relative direction for the heading parallel to the symmetric axis of the layout, and the advantage of that heading disappeared when the symmetric axis of the layout was removed. Second, there was greater consistency across participants in the selection of intrinsic axes when the layout contained a strong intrinsic cue than when it does not. Both findings demonstrate that the geometric property of bilateral symmetry influences the selection of intrinsic reference axes even when participants are not instructed to use it and suggest that the spatial frame of reference used to represent the spatial structure of the layout of a collection of objects is intrinsic to the layout and defined by the object arrays. Third, the first egocentric view seems not to be as strong a cue in selecting the intrinsic directions as the intrinsic model previously claimed. Finally, people do not seem to select two nonorthogonal intrinsic axes, even when neither is an axis of bilateral symmetry and both are experienced the same amount of time. All of these findings extend and refine the intrinsic model of human spatial memory proposed by McNamara, Mou, and Shelton (e.g., Mou & McNamara, 2002; Shelton & McNamara, 2001).

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