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Intrinsic Frames of Reference in Spatial Memory

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Three experiments investigated the frames of reference used in memory to represent the spatial structure of the environment. Participants learned the locations of objects in a room according to an intrinsic axis of the configuration; the axis was different from or the same as their viewing perspective. Judgments of relative direction using memory were most accurate for imagined headings parallel to the intrinsic axis, even when it differed from the viewing perspective, and there was no cost to learning the layout according to a nonegocentric axis. When the shape of the layout was bilaterally symmetric relative to the intrinsic axis of learning, novel headings orthogonal to that axis were retrieved more accurately than were other novel headings. These results indicate that spatial memories are defined with respect to intrinsic frames of reference, which are selected on the basis of egocentric experience and environmental cues.

The concept of location is inherently relative. One cannot describe the location of an object without establishing a frame of reference. For example, to describe locations on the surface of the earth, we customarily use coordinates of latitude and longitude. Just as frames of reference are required to specify location and orientation in physical space, human memory systems must also use frames of reference of some kind to specify the remembered locations of objects.

For the purposes of understanding spatial cognition, it is useful to divide spatial reference systems into two categories (e.g., Pani & Dupree, 1994): egocentric and environmental reference systems. *Egocentric reference systems* are those in which location is specified with respect to the observer. Examples include (but are not limited to) retinal, head, and body coordinates. *Environmental reference systems* are those in which location is specified with respect to objects other than the observer. Examples include parallels of latitude and meridians of longitude, scene-centered reference frames (e.g., Hinton & Parsons, 1988), and landmarks.

A growing body of evidence suggests that memories of room-sized and smaller layouts are mentally represented in terms of egocentric reference systems (e.g., Diwadkar & McNamara, 1997; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Shelton & McNamara, 1997). For example, Shelton and McNamara (1997) had participants learn two orthogonal views of a collection of seven objects in a large room. Subsequently, they made judgments of relative direction using their memories of the layout (e.g., "Imagine you are at the book and facing the wood. Point to the skillet."). Pointing judgments were faster and more accurate for headings parallel to the two study views than for headings parallel to unfamiliar views. These results suggest that participants had formed two egocentric representations of the layout, one from each viewing position.

More recent experiments by Shelton and McNamara (in press; also see Werner & Schmidt, 1999) have shown that the structure of the surrounding environment can affect the nature of spatial memory and can even determine whether a study view is mentally represented. In one experiment, participants learned the layout of objects in a room from two stationary points of view, one of which was aligned and the other of which was misaligned with environmental frames of reference (the edges of a mat on which objects were placed and the walls of the surrounding room). Performance in subsequent judgments of relative direction indicated that the aligned view was represented in memory but the misaligned view was not. In another experiment, participants learned a layout in a round room from three views (0°, 90°, and 225°). Performance in judgments of relative direction was best for the heading parallel to the first study view (0° or 225°), but performance for headings parallel to the second and the third study view was no better than performance for unfamiliar headings.

To explain these findings, Shelton and McNamara (in press) proposed that learning and remembering the spatial structure of the surrounding environment involves interpreting the layout in terms of a spatial reference system. They suggested that this process is analogous to determining the "top" of a figure (e.g., Rock, 1973); in effect, conceptual "north" is assigned to the layout, creating privileged directions in the environment. The frame of reference for this interpretation is selected using cues. The dominant cue, according to Shelton and McNamara (in press), is egocentric experience, but other cues can be used as well, including the structure of the environment itself. They also proposed that egocentric perspectives that are aligned with salient directions, axes, or planes in the environment are preferred to those that are not. An important claim of this theoretical framework is that the spatial reference systems used in memory are anchored in the world, and in this sense are allocentric, even though they may be initially defined by egocentric experiences.

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As an example, consider their interpretation of the results of the "round-room" experiment. According to Shelton and McNamara (in press), when observers were taken to the first viewpoint, they interpreted the spatial structure of the layout in terms of the most salient reference system available, namely, their own egocentric perspective. The conjecture is that when participants viewed the layout from the second and the third points of view, they continued to interpret the spatial structure of the layout in terms of the reference system defined by the first point of view, just as if they were viewing a (now) familiar object at novel orientations. This reference system remained the dominant one, even when participants were moved to the next two points of view, because no other point of view was aligned with a salient axis in the environment.

In this article, we offer an extension and refinement of Shelton and McNamara's (in press) theoretical framework. We propose that when people learn a spatial layout, they interpret the spatial structure in terms of an intrinsic reference system, one that is defined by the layout itself. The particular intrinsic reference system that is chosen is determined by spatial and nonspatial properties of the objects, the structure of the surrounding environment, the observer's point of view, and even verbal instructions. Hence, whereas Shelton and McNamara's (in press) proposal would, in principle, allow any environmental frame of reference to be used, we propose that spatial layouts are represented in terms of reference systems intrinsic to the collection of objects.

At least two observations suggest that intrinsic frames of reference may play an important role in spatial memory. First, there is compelling evidence that object shape is often defined with respect to an intrinsic axis (e.g., Hinton, 1979; Hinton & Parsons, 1988; Mach, 1914/1959; Palmer, 1989; Rock, 1973). For example, a square that is tilted 45° can be seen as either a tilted square or an upright diamond depending on whether an edge or a vertex is identified as the top. The fact that people can interpret the same figure in two different ways indicates that shape is defined with respect to an intrinsic axis. As another example, Wiser (cited in Palmer, 1989) showed that changing the orientation of a figure between study and test was less disruptive to recognition for figures that had a salient intrinsic axis (e.g., a candlestick) than for figures missing such an axis (e.g., an asymmetrical inkblot). Put another way, shape constancy was better maintained for figures possessing a well-defined intrinsic axis.

A second reason to suspect that spatial memories may be defined with respect to intrinsic axes can be found in studies of the hierarchical structure of spatial memory (e.g., Hirtle & Jonides, 1985; McNamara, 1986; McNamara, Hardy, & Hirtle, 1989; Stevens & Coupe, 1978). When people learn locations of objects in an environment, they tend to group the objects into clusters, and the clusters into higher-order clusters, on the basis of spatial and nonspatial properties of the objects (e.g., interobject distance and semantic relations, respectively), properties of the environment (e.g., barriers), and idiosyncratic organizational principles. One way to interpret these findings is that people represent interobject spatial relations with respect to locally defined intrinsic frames of reference, and these frames of reference are then related to each other in higher-order frames of reference (e.g., Poucet, 1993). For example, locations of objects in a room might be represented by an intrinsic frame of reference local to the room. Such a reference frame could then serve as an "object" in a reference frame defining the spatial relations among the rooms on the same floor of a house; these could then serve as "objects" in a reference frame relating floors of the house to each other (e.g., Plumert, Pick, Marks, Kintsch, & Wegesin, 1994).

A collection of objects will have an infinite number of possible intrinsic axes, but because of perceptual grouping principles, such as proximity and similarity, some of these will be much more salient than others. For example, the layout in Figure 1 has natural axes corresponding to 0°–180°, 90°–270°, 135°–315°, and so forth. In addition, the structure of the surrounding environment, such as the walls of the enclosing room, may make some axes, such as 0°–180°, more salient than others. Egocentric experience will also make some axes more salient than others. An observer standing at the location marked 315° in Figure 1 might see the 135°–315° axis more readily than other possible intrinsic axes. The spatial layouts learned by participants in our experiments were composed of small, moveable objects. In general, however, a spatial layout could be composed of large or stationary objects, such as mountain peaks, trees, buildings, doors, windows, and so forth. We would still expect in such cases for intrinsic axes to be identifiable, and for some to be more salient than others. In sum, spatial and nonspatial properties of the objects, the structure of the surrounding environment, and the experiences of the observer will all contribute to making some intrinsic organizations more salient than others.

In all of our experiments, participants first learned the locations of objects in a room from a single viewpoint and then made judgments of relative direction using their memories of the layouts. Performance in this task was used to assess which views of the layouts were more or less accessible. We assume that spatial relations that are explicitly specified with respect to a particular spatial reference system can be retrieved from memory, whereas spatial relations that are not explicitly specified in terms of that spatial reference system must be inferred. These inferential processes

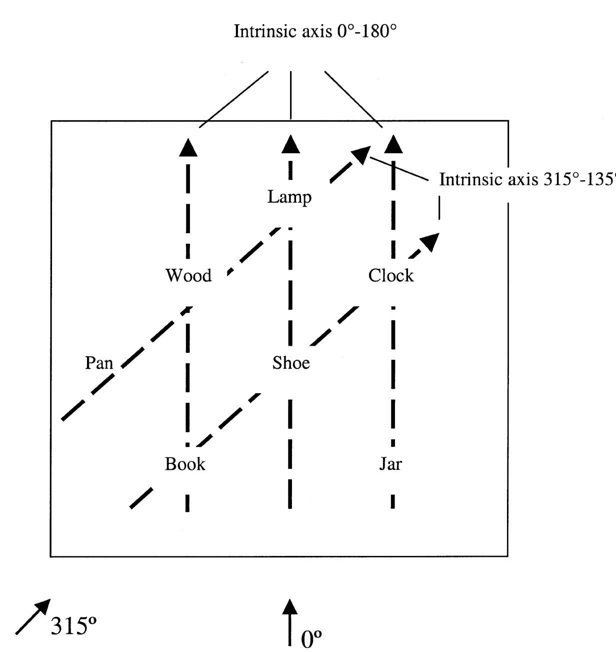

Figure 1. Examples of intrinsic axes in a collection of objects.

produce measurable costs in terms of latency and error. Judgments based on retrieved spatial relations will therefore be faster and more accurate than judgments based on inferred spatial relations. Therefore, we can use the cost associated with judgments of relative direction as an index of the extent to which spatial relations were inferred.

In Experiment 1, we dissociated an intrinsic orientation from the egocentric orientation by making one intrinsic axis very salient. Because of the extensive body of research demonstrating the important role of egocentric perspective in the formation of spatial memories, we were concerned that participants would have great difficulty representing a layout nonegocentrically. Hence, we used several cues to make the intrinsic axis salient (see Figure 2): (a) The layout contained an axis of bilateral symmetry; (b) letters of the alphabet were used as objects and were placed in alphabetic order within columns of the layout parallel to the intrinsic axis; (c) all of the disks within the same column had the same color, and each column had a unique color; and (d) the intrinsic axis was aligned with two external frames of reference, a local frame of reference defined by a rectangular mat and a global frame of reference defined by the walls of the room. Participants viewed the layout from the position marked 315°, but they were instructed to learn the layout according to the 0°–180° axis and were required to point to and name the letters in a manner consistent with this organization.

If spatial memories are organized according to egocentric frames of reference, then performance should be better on the imagined heading parallel to the study view, 315°, than on all other imagined headings, including 0° or 180°, which correspond to the intrinsic axis of learning. Performance on the heading parallel to the intrinsic axis may be better than performance on other novel headings, but performance on the egocentric orientation should still be best. However, if the spatial structure of the layout is represented in terms of the intrinsic axis, then performance on the imagined headings parallel to the intrinsic axis of 0°–180° should be better than performance on other headings, including the study view. As described subsequently, the learning procedures encouraged participants to learn the layout in the direction defined by the

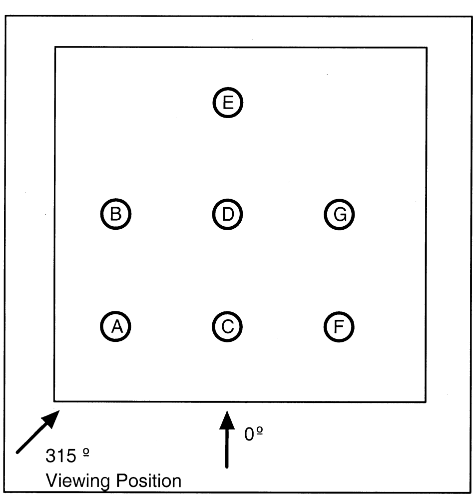

Figure 2. The layout of letters and disks used in Experiment 1. 315° indicates the viewing position; 0° indicates the intrinsic axis.

0° heading. We therefore predicted that performance would be better on the imagined heading of 0° than on the imagined heading of 180°. It is possible that spatial memories would be organized according to reference frames defined by egocentric experience and by the intrinsic axis, in which case performance might be equally good on headings of 315° and 0°.

In Experiment 2, we replaced the letters and colored disks with real objects to make the display more natural. Otherwise, the layouts and procedures were similar to Experiment 1. However, this experiment also included a control condition in which the learning view and the intrinsic axis were the same. The principal means of establishing the intrinsic orientation was by instructions. Participants were asked to learn the layout either along the 0°–180° axis or along the 315°–135° axis. All participants viewed the layout from 315°.

In Experiment 3, we set up the display in a round room. This allowed us to remove the frames of reference defined by the mat and by the rectangular walls of the room. Participants viewed the layout from 315° but were instructed to learn it according to the 0°–180° axis. The major question we considered was whether participants would be able to learn the layout according to a nonegocentric intrinsic axis in the absence of cues provided by the surrounding room.

Experiment 1

In Experiment 1, participants learned the display of disks from the point of view labeled 315°. The 0°–180° axis was established as the intrinsic orientation. The main purpose of the experiment was to determine whether participants would represent the display with respect to their egocentric frame of reference or with respect to the intrinsic frame of reference.

Method

Participants

Twenty undergraduates (10 men, 10 women) participated as partial fulfillment of a requirement for their introductory psychology courses.

Materials and Design

The layout consisted of a configuration of seven colored disks (see Figure 2). Diameters of the disks were approximately 14 cm. Each disk was labeled with a unique letter, *A–G*, and colored in the following manner: *A* and *B* were blue; *C*, *D*, and *E* were green; and *F* and *G* were red. The disks were placed on a 3.3-m × 3.3-m mat that filled one half of a large room. The mat was oriented to be congruent with the room. The distances between the adjacent disks, in the directions aligned with the mat, were 91.4 cm.

Each test trial was constructed from the names of three objects in the display and required participants to point to an object as if standing in a particular position within the display; for example, "Imagine you are at the *A* facing the *D*. Point to the *G*." The first two disks established the imagined standing location and facing direction (e.g., *A* and *D*) and the third disk was the target (e.g., *G*). Imagined translations (e.g., from the actual viewing position to the imagined viewing position) were expected to have small effects relative to the effects of imagined rotation (e.g. Easton & Sholl, 1995; Presson & Montello, 1994; Rieser, 1989) and were not examined.

The primary independent variable was imagined heading. Eight equally spaced headings were used. To facilitate exposition, headings were arbitrarily labeled counterclockwise from 0° to 315° in 45° steps beginning with the position labeled 0° in Figure 2. For example, 0° corresponds to all views oriented in the same direction as the arrow labeled 0° (e.g., at *A* facing *B*; at *C* facing *D*); and 315° corresponds to all views oriented in the same direction as the arrow labeled 315° (e.g., at *A* facing *D*; at *C* facing *G*).

Pointing direction (the direction of the target object relative to the 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. Participants were given a total of 48 trials, 6 trials at each of eight imagined headings. These trials were chosen based on 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.

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

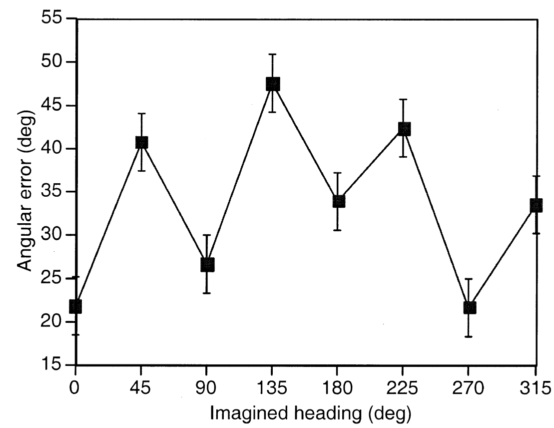

Figure 3. Angular error in judgments of relative direction as a function of imagined heading in Experiment 1. All participants viewed the layout from 315° and were instructed to learn it along the 0°–180° axis. Error bars are confidence intervals corresponding to ±1 standard error of the mean as estimated from the analysis of variance. deg = degrees.

Procedure

Learning phase. Before entering the study room, each participant was instructed to learn the locations of the letters for a spatial memory test. The participant was blindfolded and led to the viewing point (315° in Figure 2). The blindfold was removed and the participant was asked to learn the locations of the letters according to the columns in the 0°–180° direction, as indicated by the experimenter. The participant viewed the display for 30 s before being asked to point, with eyes closed, to the disks named by the experimenter. The experimenter named the disks in each column in alphabetic order, although the order of the columns varied unsystematically from trial to trial (e.g., *A–B–F–G–C–D–E, C–D–E–A–B–F*–G). Once participants could accurately point to the locations twice (as judged visually by the experimenter), they were asked to name and point to each object in any order. All participants named and pointed to the objects in an order consistent with the intrinsic axis.

Testing phase. After learning the spatial layout, participants were taken to another room to be tested. The test trials were presented on a Macintosh computer. Participants first received instructions on using the joystick and on four practice trials involving locations on the campus. The participant initiated each trial by pulling the joystick trigger. Trials proceeded as follows: The imagined standing location, facing object, and target object were given simultaneously in text on the computer monitor (e.g., "Imagine you are at the *A* and facing the *B*. Point to the *D*."). The text appeared in the upper third of the monitor, approximately centered horizontally. Nothing else appeared on the monitor. 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 described.

Results

Pointing error was analyzed in mixed-model analyses of variance (ANOVAs) with terms for gender, imagined heading (0° to 315° in 45° steps), and pointing direction (front, sides, and back). Imagined heading and pointing direction were within-participant. In this and all subsequent experiments, latency showed the same general pattern as angular error. There was no evidence of speed-accuracy trade-offs. In the interest of brevity, we only report pointing accuracy.

Mean absolute angular error is plotted in Figure 3 as a function of imagined heading. As shown in the figure, there were two major findings. First, participants were more accurate pointing to letters from the imagined heading of 0°, which corresponded to the intrinsic axis, than from the imagined heading of 315°, which corresponded to the learning view. In other words, performance was better on a novel view than on a familiar view. Second, participants were more accurate pointing to letters from imagined headings of 90°, 180°, and 270°, which were aligned with frames of reference defined by the intrinsic axis, mat, and room, than from imagined headings of 45°, 135°, and 225°, which were misaligned with these environmental frames of reference.

All of these conclusions were supported by statistical analyses. The overall effect of imagined heading was significant $F(7, 126) = 8.38$, $p < .01$, $MSE = 667.39$. No other main effects or interactions were reliable. Pairwise comparisons showed that accuracy was higher for the heading of 0° than for all other headings, $t(126) \geq 2.47$, with the exception of 90° and 270°, $t(126) \leq 1.02$. The comparison of novel aligned headings (90°, 180°, 270°) to novel misaligned headings (45°, 135°, 225°) was significant, $F(1, 126) = 35.27$, $p < .01$. This result indicates that participants might have encoded the spatial structure of the layout in terms of orthogonal directions or axes, 0°–180° and 90°–270°.

Discussion

The results of Experiment 1 indicate that participants represented the layout in terms of a reference system that was not defined by or oriented with a learning view. To our knowledge, this is the first such demonstration in the spatial memory literature. Because the intrinsic axis of the display was aligned with the edges of the mat and the walls of the room, we do not know whether the reference system was defined by the display, by the mat, by the room, or by some combination of these. However, we do know that participants were able to represent the layout in terms of a nonegocentric frame of reference. This by itself is an important discovery.

Experiment 2

The purpose of Experiment 2 was to determine whether participants could represent the layout nonegocentrically under more natural conditions. The disks and letters were replaced by real objects. Otherwise, the space remained the same, including the presence of the local and the global frames of reference. Another purpose of Experiment 2 was to compare a condition in which participants learned the layout according to a nonegocentric frame of reference with a condition in which participants learned the layout according to an egocentric frame of reference. To this end, one group of participants was instructed to learn the layout along the 0°–180° axis, whereas the other group was instructed to learn the layout along the 315°–135° axis. All participants viewed the layout from 315° as in Experiment 1.

Method

Participants

Forty-eight undergraduates (24 men, 24 women) participated as partial fulfillment of a requirement for their introductory psychology courses.

Materials, Design, and Procedure

The materials were similar to those used in Experiment 1 except that seven objects replaced the disks and letters (see Figure 4A). Objects were selected with the restrictions that they be visually distinct, fit within approximately 1 ft^2, and not share any obvious semantic associations.

Three independent variables were manipulated: First, participants were instructed to learn the layout according to the nonegocentric 0°–180° axis or the egocentric 315°–135° axis. Second, in judgments of relative direction, imagined heading and pointing direction were manipulated. Pointing direction and latency were recorded, but the principal dependent measure was absolute pointing error.

Participants were randomly assigned to the two axis conditions such that each group contained an equal number of men and women. At the beginning of the learning session, the objects were named by the experimenter in columns appropriate to the learning axis (e.g., for 0°–180°, scissors, clock, wood, shoe, jar, etc.; for 315°–135°, clock, jar, scissors, shoe, etc.). Participants were told to memorize the layout column by column, consistent with the appropriate axis condition.

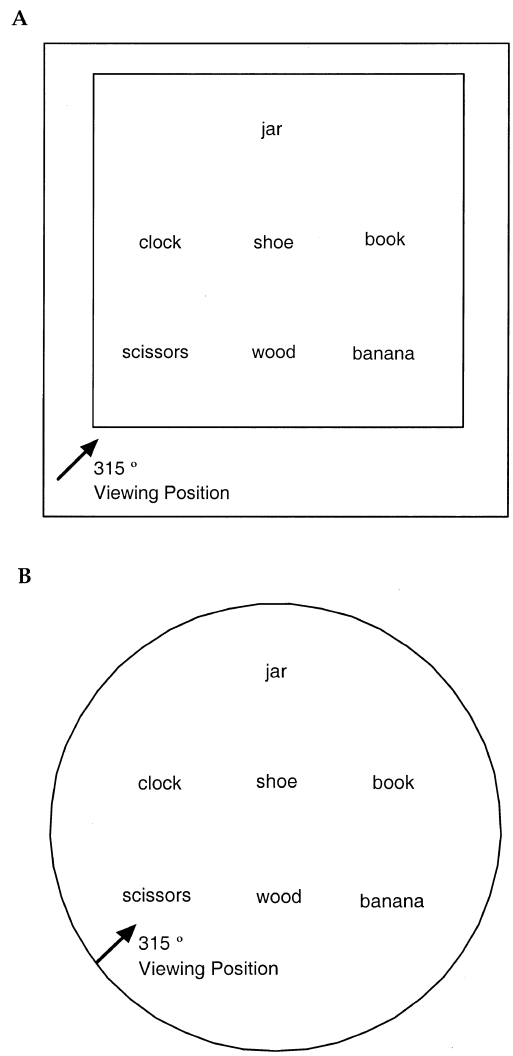

Figure 4. Panel A: The layout of objects used in Experiment 2. 315° indicates the viewing orientation. One group of participants learned the layout along the 315°–135° axis; the other group learned it along the 0°–180° axis. Panel B: The layout of objects used in Experiment 3. 315° indicates the viewing orientation. All participants learned the layout along the 0°–180° axis.

Results

Pointing error was analyzed in mixed-model ANOVAs, with variables corresponding to learning axis (0°–180° vs. 315°–135°), gender, imagined heading (0°–315°), and pointing direction (front, sides, back). Imagined heading and pointing direction were within-participant.

Mean absolute angular error is plotted in Figure 5 as a function of imagined heading and learning axis. As shown in the figure, there were two major findings. First, participants who were instructed to use the nonegocentric axis of 0°–180° axis were more accurate pointing to objects from the imagined heading of 0° than from the imagined heading of 315° (which corresponded to the learning view), whereas participants instructed to use the egocentric axis of 315°–135° axis were most accurate pointing to objects from the imagined heading of 315°. Second, being required to use the nonegocentric axis, which was aligned with the walls of the room and the edges of the mat, produced some benefit for novel aligned headings relative to novel misaligned headings, producing a sawtooth pattern across novel headings. This benefit for novel aligned headings was not evident when participants were required to learn the layout along the 315°–135° axis.

These conclusions were supported by statistical analyses. The main effect of heading was significant, $F(7, 315) = 4.99$, $p < .01$, $MSE = 688.10$, as was the interaction between learning axis and imagined heading, $F(7, 315) = 3.06$, $p < .01$. The interaction contrast comparing the difference in performance for headings of 0° and 315° across groups was reliable, $t(315) = 2.45$, $p < .05$. Another interaction contrast showed that the difference in performance on aligned (90°, 180°, 270°) and misaligned (45°, 135°, 225°) novel headings was different for the two learning conditions, $t(315) = 3.14$, $p < .01$.

Simple effects of imagined heading were also analyzed. In the 315°–135° axis condition, the overall effect of imagined heading

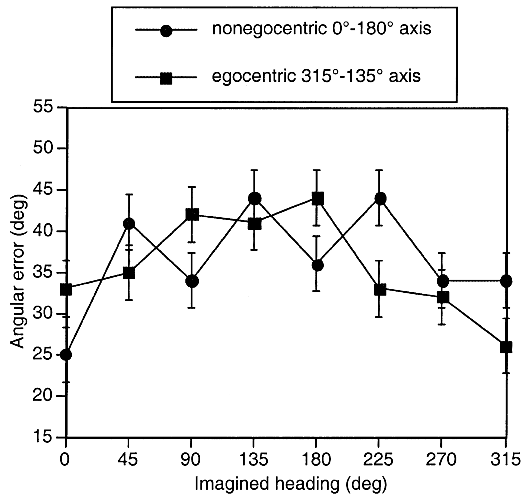

Figure 5. Angular error in judgments of relative direction as a function of imagined heading and learning axis in Experiment 2. All participants viewed the layout from 315°. Participants were instructed to learn the layout along the egocentric 315°–135° axis or the nonegocentric 0°–180° axis. deg = degrees.

was significant, $F(7, 315) = 3.86$, $p < .01$, $MSE = 688.10$. To investigate further the quantitative relation between heading and performance, we redefined headings in terms of their angular distance from 315° and their direction (clockwise vs. counterclockwise). For example, 270° was redefined as 45° clockwise and 0° was redefined as 45°counterclockwise. (The imagined heading of 135° was not included in this analysis because it was equidistant from 315° in both clockwise and counterclockwise directions and therefore could not be assigned uniquely to a direction condition.) The distance effect was significant, $F(3, 135) = 10.81$, $p < .01$, $MSE = 644.81$. Specifically, the linear portion was significant, $t(135) = 5.51$, $p < .01$; all other polynomial effects were not reliable. Neither the main effect of direction nor the interaction between distance and direction was reliable. This analysis shows that angular error in pointing judgments increased with the angular distance between the imagined heading and the study view.

In the 0°–180° group, the overall effect of imagined heading was significant, $F(7, 315) = 4.19$, $p < .01$, $MSE = 688.10$. Performance for the imagined heading of 0° was better than performance for 315°, $t(315) = 2.04$, $p < .05$. Average performance for headings of 90°, 180°, and 270° was better than average performance for headings of 45°, 135°, and 225°, $t(315) = 3.20$, $p < .01$.

In the omnibus analysis, the effect of pointing direction was significant, $F(2, 90) = 5.15$, $p < .01$, $MSE = 760.36$. Pointing to the sides was significantly better than pointing to the front, $t(90) = 2.85$, $p < .01$, and to the back, $t(90) = 2.70$, $p < .01$. This effect probably occurred because trials classified as pointing to the sides were typically easier (very close to ±90°) than trials classified as pointing to the front or to the back (never 0° or 180°). The three-way interaction between learning axis, heading, and pointing direction was reliable, $F(14, 630) = 1.76$, $p < .05$, $MSE = 372.94$. In the 0°–180° condition, the sawtooth pattern in Figure 5 appeared for each pointing direction, and simple effects showed that the interaction between heading and pointing direction was not reliable. In the 315°–135° condition, pointing to the front and to the back showed the same effect of heading as the overall pattern (see Figure 5), but pointing to the sides revealed a sawtooth pattern, with higher accuracy for 45°, 135°, 225°, and 315°, than for 0°, 90°, 180°, and 270°; simple effects revealed that this interaction was statistically reliable, $F(14, 630) = 2.76$, $p < .01$. We suspect that this interaction occurred because of the combined effects of how trials were classified as sides, front, and back, and how participants represented the layout in this learning condition. As noted above, trials classified as "sides" were easier than trials classified as "front" and as "back." In addition, participants in this condition seem to have represented the layout along the egocentric 315°–135° axis but not along the orthogonal 225°–45° axis.

Discussion

Experiment 2, like Experiment 1, showed that participants were able to learn the layout according to a nonegocentric frame of reference. Participants in the 0°–180° group were best able to imagine the layout from 0°, even though this heading was not directly experienced. Of importance, the fidelity of spatial memories in the 0°–180° condition, in which participants learned the layout according to a nonegocentric reference frame, was just as high as the fidelity of spatial memories in the 315°–135° condition. There was no evidence that learning the layout according to a nonegocentric frame of reference interfered with participants' abilities to accurately represent the spatial structure of the layout.

A second important finding existed in the dramatically different patterns of results for the two learning groups. Participants who learned the layout along the 0°–180° axis were more accurate pointing to objects from headings of 90°, 180°, and 270° than from headings of 45°, 135°, and 225°. This pattern indicates that participants represented, at least partially, the spatial structure of the layout from 0°, 90°, and 180°. Because these headings were aligned with a salient intrinsic axis of the layout, the edges of the mat, and the walls of the room, we cannot determine which of these external reference frames was the cause of the results. In the 315°–135° condition, however, angular error increased with angular distance from the study view, 315°, and there was no consistent evidence of savings at headings aligned with the intrinsic structure of the layout, the edges of the mat, or the walls of the room. We propose an explanation of the different patterns of results in the General Discussion.

Considered together, results from the two learning conditions indicate that performance was determined primarily by how the layout was interpreted and represented at the time of learning, not by how its spatial structure was processed at the time of test. Both groups of participants learned the same layout, from the same point of view, and were tested using the same task and materials. The only difference between the two learning conditions existed in the instructions to participants on how to interpret and represent the spatial structure of the layout.

The purpose of Experiment 3 was to determine whether the facilitation on aligned novel headings relative to misaligned novel headings in the 0°–180° group was caused by the intrinsic structure of the layout or by the structure of the mat and the room. To this end, we had participants learn the same layout in a round room.

Experiment 3

In Experiment 3, participants learned the same display used in Experiment 2 from the view of 315° but in a round room. As in Experiment 1, the nonegocentric 0°–180° axis was established as the intrinsic orientation. The primary purpose of this experiment was to determine whether participants would still be able to represent the layout according to a nonegocentric frame of reference when the cues provided by the mat and the rectangular walls of the room were removed. In addition, we sought to determine whether the sawtooth pattern would be present in the absence of these salient external frames of reference.

Method

Participants

Twenty undergraduates or staff members (10 men, 10 women) participated in return for monetary compensation.

Materials, Design, and Procedure

The materials were similar to those used in Experiment 2 except that the layout was enclosed by a cylinder 3.2 m in diameter constructed from reinforced painter's cloth (Figure 4B). The cloth completely obscured the walls of the surrounding room. The objects were placed on the floor, which was carpeted but otherwise bare.

Participants were blindfolded before entering the laboratory and then escorted into the cylinder. Participants wore a cap to obscure their view of the ceiling. The study procedures were the same as in the 0°–180° condition of Experiment 2. Test procedures were identical to those used in Experiments 1 and 2.

Results

Pointing error was analyzed in a mixed-model ANOVA with variables corresponding to gender, imagined heading (0°–315° in 45° steps), and pointing direction (front, sides, back). Imagined heading and pointing direction were within-participant.

Mean absolute angular error in pointing is plotted in Figure 6 as a function of imagined heading. There were two major findings in Experiment 3. First, participants were more accurate pointing to target objects from the imagined heading of 0°, which corresponded to the intrinsic axis of learning, than from the imagined heading of 315°, which corresponded to the study view. Second, as in Experiment 1 and the 0°–180° condition of Experiment 2, participants were more accurate pointing to objects from novel aligned headings (90°, 180°, 270°) than from novel misaligned headings (45°, 135°, 225°). These conclusions were supported by statistical analyses.

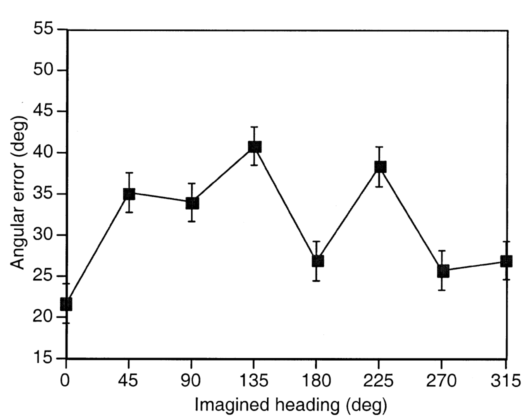

Figure 6. Angular error in judgments of relative direction as a function of imagined heading in Experiment 3. All participants viewed the layout from 315° and were instructed to learn it along the 0°–180° axis. deg = degrees.

The overall effect of imagined heading was significant, $F(7, 126) = 8.11$, $p < .01$, $MSE = 339.95$. Performance for 0° was better than performance for 45°, 90°, 135°, and 225°, $t(126) \geq 3.61$, but did not differ reliably from performance for 180°, 270°, and 315°, $t(126) \leq 1.51$. A separate analysis limited to the 0° and 315° data revealed a significant difference between these two conditions, $t(18) = 2.40$, $p < .05$.

The comparison of novel aligned headings (90°, 180°, 270°) to novel misaligned headings (45°, 135°, 225°) was significant, $F(1, 126) = 22.57$, $p < .01$.

As in Experiment 2, there was an advantage for the learning view of 315° relative to the novel view of 45°, $F(1, 126) = 5.98$, $p < .05$. This comparison shows that the learning view was represented to some extent in memory.

The effect of pointing direction was significant, $F(2, 36) = 3.46$, $p < .05$, $MSE = 451.42$. Results indicated that pointing to the side was more accurate than pointing to the front or to the back.

The interaction between heading and pointing directions was significant, $F(14, 252) = 2.22$, $p < .01$, $MSE = 281.25$. When pointing to objects in front, participants were equally accurate on imagined headings of 0° and 90°, but when pointing to objects to the sides or in back, participants were less accurate for the imagined heading of 90° than for the imagined heading of 0°. This interaction did not alter any of the major conclusions about the effects of imagined heading.

Discussion

There were two results of Experiment 3 that were most important. First, as in Experiments 1 and 2, participants were able to learn the layout according to a nonegocentric frame of reference. Participants were best able to imagine the layout from headings of 0°, even though this heading was not experienced. Second, the sawtooth pattern across the novel imagined headings was observed in the absence of salient external frames of reference.

These results strongly disconfirm the possibility that the nonegocentric spatial memories demonstrated in Experiments 1 and 2 were defined with respect to the mat or the walls of the room. The results further indicated that participants could encode the spatial structure of the layout in terms of orthogonal directions or axes, 0°–180° and 90°–270°. The external frames of reference (the walls and the mat) might make the orthogonal axes of the layout more salient rather than cause the sawtooth pattern itself.

The results furthermore indicated that the learning view contributed to the representation of the display even when it was misaligned with the intrinsic axis of learning. Performance was better on 315° than on 45°, even though both headings were equidistant from the intrinsic axis of 0°–180°. However, performance on 315° was no better than performance on the unfamiliar headings of 180° and 270°.

General Discussion

The goal of this project was to investigate whether spatial memories are organized with respect to reference frames defined by egocentric experience or reference frames defined by the layout itself. The results supported the latter conclusion. In each experiment, participants were able to mentally represent the layout in terms of an intrinsic axis, even when that intrinsic axis differed in orientation from their egocentric orientation while viewing the layout. Experiment 2 showed that there was no apparent cost to representing the layout nonegocentrically. The results of Experiment 3 demonstrated that an intrinsic axis could be selected using an instructional cue in the absence of environmental cues provided by local (the mat) or global (the room) frames of reference. In Experiments 1 and 3, and in the 0°–180° condition of Experiment 2, there were savings in angular error for headings of 90°, 180°, and 270°, relative to 45°, 135°, and 225°. The fact that this pattern appeared even in the absence of environmental frames of reference, such as the mat and the walls of the room, suggests that it was caused by the internal structure of the layout itself. Apparently, participants were able to represent, at least partially, the spatial relations among objects in directions orthogonal to the intrinsic axis of learning.

These findings provide the basis of an alternative interpretation of Shelton and McNamara's (in press) results. According to the theoretical framework they proposed, learning the spatial structure of the surrounding environment involves interpreting the layout in terms of a spatial reference system. Because environments typically do not have privileged directions, reference systems defined by the viewer's perspective are dominant. These egocentrically defined reference systems are imposed on the environment, forming environment-centered reference systems; in effect, conceptual "north" is established at the time of learning. Shelton and McNamara (in press) further argued, based primarily on empirical evidence, that egocentric reference systems aligned with salient external frames of reference, such as the axes and planes defined by the walls, the floor, the ceiling, the roads, and so forth, are preferred to those that are not so aligned.

We endorse this theoretical framework, but suggest that the spatial structure of the surrounding environment is represented in terms of reference systems defined by the layout itself. Axes intrinsic to the layout are selected and used to represent locations of objects. The particular axis or axes chosen depends on spatial and nonspatial properties of the objects, cues in the surrounding environment, and, as demonstrated in our experiments, instructions.

The difference between the two theoretical frameworks exists in the relative importance of egocentric and intrinsic frames of reference. Whereas Shelton and McNamara (in press) argue that egocentric experience is used to define a reference frame, which is then imposed on the environment, and prescribe no role for intrinsic frames of reference, we are suggesting instead that egocentric experience (in conjunction with other factors) is used to select an intrinsic frame of reference. This difference is subtle but important: If reference systems defined by the viewer's perspective were dominant, performance should always be best on headings parallel to a directly experienced view of the layout. The present results are not consistent with this prediction. Instead, our findings show that people can choose an axis of the layout to define a spatial reference system, even when that axis differs from their viewing perspective.

A second important result of the present experiments existed in the pattern of performance across headings orthogonal to the 0°–180° axis when participants were instructed to represent the layout along that axis. Angular error in pointing judgments was lower for headings of 90°, 180°, and 270° than for headings of 45°, 135°, and 225°. This pattern even occurred in Experiment 3, in which the objects were arranged on a bare floor in a round room. We conclude from this finding that participants were able to represent the layout along two intrinsic axes, 0°–180° and 90°–270°, with the first axis stronger than the second. We suspect that a similar pattern did not occur in the condition in which participants learned the layout according to the 315°–135° axis because the 45°–225° axis is much less salient in the display. Indeed, we suspect that participants did not widely recognize that the layout could be organized along "diagonal" axes unless they actually experienced them because the "major" axes were much more salient; for example, the layout is bilaterally symmetric around 0°–180° but not around 315°–135°.

The model we are proposing shares features with Sholl's model of spatial retrieval (e.g., Easton & Sholl, 1995; Sholl & Nolin, 1997). In particular, both models use intrinsic reference systems to represent interobject spatial relations. Sholl refers to this representation as the *object-to-object system.* An important difference between the two models is that the object-to-object system is orientation independent in Sholl's model but orientation dependent in ours. There may be situations in which people are able to construct orientation independent representations in memory (e.g., Presson, DeLange, & Hazelrigg, 1989; Presson & Hazelrigg, 1984; Sholl & Nolin, 1997, Experiments 3 & 4) but they seem to be the exception rather than the rule; in addition, attempts to replicate these findings have not been successful (e.g., Roskos-Ewoldsen et al., 1998). In our opinion, the balance of evidence supports orientation-dependent coding of interobject spatial relations in memory (in addition to articles cited in the introduction, see Christou & Bülthoff, 1999; Easton & Sholl, 1995; Levine, Jankovic, & Palij, 1982; Presson & Montello, 1994; Richardson, Montello, & Hegarty, 1999; Rieser, 1989; Rieser, Guth, & Hill, 1986; Shelton & McNamara, 2001; Sholl & Nolin, 1997, Experiments 1, 2, and 5; Simons & Wang, 1998).

One possible reason that the intrinsic axis played an important role in the present studies is that the task, judgments of relative direction, depends on spatial relations intrinsic to the collection of objects. Would egocentric effects be stronger in a task that depended more on egocentric spatial relations, such as visual scene recognition (e.g., Diwadkar & McNamara, 1997)? We do not have an answer to this question but acknowledge that it is an important one. We are confident that the general pattern of orientation dependence is not task dependent. However, one might see more benefit for the study view relative to novel views if the task appealed more directly to egocentric experience at the time of learning. Ongoing experiments in our laboratory are investigating this issue.

Although these experiments raised several important questions, they also provided answers to the major issues raised in the introduction. The experiments demonstrated that participants were able to interpret and mentally represent a layout of objects according to a frame of reference defined by the collection of objects, even when the orientation of the dominant axis of this intrinsic frame of reference differed from their egocentric orientation. There was no apparent cost to representing the layout nonegocentrically, and participants were able to select an intrinsic frame of reference even when there were no supporting cues from the surrounding room. These results, in conjunction with recently published findings by Shelton and McNamara (in press), suggest that when people learn locations of objects in a new environment, they use their experiences in the environment, spatial and nonspatial properties of the objects, and cues in the environment to select a frame of reference intrinsic to the layout itself. This frame of reference determines the interpretation, and hence, the memory of the spatial structure of the layout.

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