Locomotion, incidental learning, and the selection of spatial reference systems

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In three experiments, we examined the effects of locomotion and incidental learning on the formation of spatial memories. Participants learned the locations of objects in a room and then made judgments of relative direction, using their memories (e.g., "Imagine you are standing at the clock, facing the jar. Point to the book"). The experiments manipulated the number of headings experienced, the amount of interaction with the objects, and whether the participants were informed that their memories of the layout would be tested. When participants were required to maintain a constant body orientation during learning (Experiment 1), they represented the layout in terms of a single reference direction parallel to that orientation. When they were allowed to move freely in the room (Experiment 2), they seemed to use two orthogonal reference axes aligned with the walls of the enclosing room. Extensive movement under incidental learning conditions (Experiment 3) yielded a mixture of these two encoding strategies across participants. There was no evidence that locomotion, interaction with objects, or incidental learning led to the formation of spatial memories that differed from those formed from static viewing.

Knowledge of the spatial organization of the environment is necessary for many of our daily activities. An important property of spatial knowledge is that it can be retrieved and utilized efficiently from familiar perspectives, but when we are required to access spatial knowledge from an unfamiliar point of view, we may have difficulty creating and maintaining a coherent representation of the environment (e.g., Levine, Jankovic, & Palij, 1982). For example, when we drive to work on the usual route, relatively little attention to the path and to landmarks is required to stay oriented. But if a detour requires that we approach a familiar street from an unfamiliar direction, mental effort may be required to stay oriented or even to recognize where we are. A long-term goal of the research described in this article is to determine why spatial knowledge may have these properties.

The purpose of these experiments was to investigate the role of locomotion in the formation of spatial memories. The experiments were motivated by a theory of spatial memory proposed by Shelton and McNamara (2001a) and by Mou and McNamara (2002; see also Werner & Schmidt, 1999). This theoretical framework states that upon first experiencing a new environment, people interpret the spatial structure of the locations of objects in terms of a spatial reference system (e.g., Rock, 1973; Tversky, 1981). Directions or axes intrinsic to the collection of objects are se-

lected using egocentric and environmental cues (e.g., Tversky, 1981). The rows and columns formed by chairs in a classroom constitute an example of an intrinsic reference system. These cues include, but are not limited to, viewing perspective, instructions, properties of the objects (e.g., they may be grouped on the basis of proximity or similarity), and the structure of the surrounding environment (e.g., the walls of an enclosing room). Egocentric cues are dominant because the spaces in which humans typically navigate rarely have axes or directions as salient as those specified by egocentric experience. Unlike honeybees, for example, humans cannot perceive magnetic fields (e.g., Collett & Baron, 1994). Selection of an intrinsic reference system takes place when a space is initially encountered and is modified only when a subsequent experience is congruent with a more salient environmental frame of reference.

As an example, consider Shelton and McNamara's (2001a) third experiment. They required participants to learn the locations of objects in a room from two points of view. The objects were located on a square mat oriented with the walls of the room (see Figure 1A). One viewing position was aligned and the other was misaligned with the mat and the walls of the room (0° and 135°, respectively). After learning, the participants were taken to a different room on a different floor of the building and were asked to make judgments of relative direction, using their memories (e.g., "Imagine you are standing at the book and facing the wood. Point to the shoe"). Performance in this task indicated that the aligned view was represented in memory but the misaligned view was not: Angular error in pointing was low for the familiar heading of 0° but was no different for the familiar heading of 135° than for unfamiliar headings. There was no behavioral evidence that the

Preparation of this manuscript and the research reported in it were supported in part by NIMH Grant R01-MH57868. This article was improved as a result of the comments of two anonymous reviewers. Correspondence concerning this article should be sent to T. P. McNamara, Department of Psychology, Vanderbilt University, 111 21st Avenue South, Nashville, TN 37203 (e-mail: t.mcnamara@vanderbilt.edu).

Figure 1. Examples of layouts of objects used by Shelton and McNamara (2001a). (Real objects were used, not names.)

participants had even seen the misaligned view, even for those who had learned the misaligned view first. These results did not occur because of some inherent difficulty in learning the layout of objects from a misaligned point of view. In another experiment, Shelton and McNamara (2001a, Experiment 2) required participants to learn the same layouts of objects, but only from the misaligned view (i.e., only 135° in Figure 1A). The results of this experiment showed that the participants had represented the layout from this single familiar view (these data are reproduced in Figure 2, “135° in Figure 1A”).

According to the theory, the participants who had first learned the aligned view represented the layout in terms of an intrinsic reference system aligned with their viewing

perspective, the edges of the mat, and the walls of the room. When they moved to the misaligned view, they still interpreted the layout in terms of the reference system selected at the aligned view, just as if they were looking at a (now) familiar object at a novel orientation. The observers who had first learned the misaligned view also must have interpreted the layout in terms of a reference system selected at that view. This conclusion follows from the results of the experiment in which the participants had learned a single misaligned view. According to the theory, when participants were taken to the aligned view, they *reinterpreted* the spatial structure of the layout in terms of a reference system defined by the aligned view because it was aligned with salient axes in the environment (e.g., the edges of the

Figure 2. Angular error in judgments of relative direction as a function of imagined heading in Shelton and McNamara's (2001a) Experiments 2 and 4. (A) Mat appeared square from study view. (B) Mat appeared diamond-shaped from study view.

mat and the walls of the room) and with egocentric experience (albeit, a new experience).

The primary goal of the experiments reported in this article was to investigate how visually guided locomotion at the time of learning would influence the selection of spatial reference systems. To our knowledge, only two published studies have reported data relevant to this issue (McNamara, Rump, & Werner, in press; Richardson, Montello, & Hegarty, 1999). Because those studies differed in many important ways from the present experiments (e.g., large-scale vs. small-scale spaces) and because the present experiments were not designed as follow-ups to those studies, we reserve discussion of McNamara et al.'s (in press) and Richardson et al.'s (1999) experiments for the General Discussion section.

In Experiment 1 of the present report, participants studied the locations of objects in a large room from a stationary point of view and then were asked to place the objects at their correct locations while maintaining the same body orientation as that for the original study view. In Experiment 2, we removed the constraint that the participants maintain a fixed body orientation while replacing the objects, allowing them to move about in the room as they pleased. In Experiment 3, the participants learned the layout incidentally by picking up and replacing the objects, starting each time from a different location; they therefore experienced many different views of the layout, with no single view designated for study. Across experiments, we were therefore able to examine the effects of constraints on locomotion, the extent of interaction with objects, the number of views experienced, and whether learning was intentional or incidental on how the spatial structure of the layout of objects was mentally represented.

After learning, the participants in all three experiments made judgments of relative direction, using their memories of the layout. Angular error and latency of pointing judgments provided objective measures of the difficulty of retrieving or inferring the spatial structure of the layout from various perspectives. 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 (e.g., Klatzky, 1998). These inferential processes 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. Hence, we can use performance in judgments of relative direction as an index of the extent to which spatial relations were inferred, with poorer performance corresponding to a greater dependence on inferred, as opposed to retrieved, spatial relations. Similar conceptual analyses underlie the interpretation of data in related domains of inquiry, such as visual object recognition (e.g., Biederman & Gerhardstein, 1993; Bülthoff, Edelman, & Tarr, 1995).

We were particularly interested in the patterns of performance across imagined headings as a function of the conditions at the time of learning. Our reference points

were findings reported by Shelton and McNamara (2001a) and by Mou and McNamara (2002). In Shelton and McNamara's (2001a) second and fourth experiments, participants learned the locations of objects on a square mat from a single stationary point of view. The mat was aligned with the walls of the room or rotated by 45° (Figures 1A and 1B, respectively). Half of the participants in each experiment learned the layout from 0°, and half learned it from 135°. Hence, for half of the participants, the layout appeared to be *square*, whereas for the other half, it appeared to be *diamond-shaped*. Angular error in judgments of relative direction for these conditions is reproduced in Figure 2 (these data are grouped by the perceived form of the layout, not by experiment). As is shown in Figure 2, when the layout appeared to be diamond-shaped (Figure 2A), performance was best for the single familiar heading, and performance for novel headings was either uniformly poor or depended on the angular distance to the familiar heading. When the layout appeared to be square (Figure 2B), performance was best for the single familiar heading (0° or 135°) and was better for novel headings orthogonal or opposite to the familiar heading than for other novel headings, producing a distinctive sawtooth pattern (the only exception is 45° for the participants who learned Figure 1B from 135°). Similar results were obtained by Mou and McNamara under analogous conditions.

Our explanation of these findings is that the sawtooth pattern arises when participants are able to represent the layout, to some extent, along two intrinsic axes. The pattern indicates that spatial relations are represented more strongly or with higher fidelity for the single familiar heading (0° or 135°) than for the opposite and the orthogonal headings. We believe that this intrinsic structure of the layout was made salient by the combination of the edges of the mat and the viewing perspective. The pattern in the diamond groups indicates that the participants used a single reference direction parallel to their study view. Apparently, the internal structure of the layout was not sufficiently salient for the participants in this condition to use two reference axes, nor were the edges of the mat a sufficiently strong cue for the participants to organize their spatial memories along axes parallel to the mat. Importantly, there is no evidence that the patterns of results for the diamond groups were caused by competition between alternative reference systems, since overall performance was as good in these groups as in the square groups.

The logic of the present experiments was similar, although instead of manipulating the alignment of viewing perspective and external frames of reference, we examined the effects of locomotion, the level of interaction with the objects, the number of orientations the participants experienced, and whether the participants knew in advance that their memories would be tested.

EXPERIMENT 1

The participants in Experiment 1 experienced a room-sized spatial layout by alternately studying it from a fixed

Figure 3. An example of one of the layouts used in the present experiments.

position and then moving about the room, maintaining a fixed heading while interacting with the objects.

Method

Participants. Twenty-four undergraduates participated as part of a course requirement. Data from 1 participant were lost due to equipment failure. Another participant's data were eliminated because this individual revealed a pattern completely different from the remaining participants and unduly affected the analysis. The final sample included 22 participants (11 females).

Materials and Design. The materials were similar to those used by Shelton and McNamara (1997), with a few minor modifications. We used two configurations of seven objects each (for an example, see Figure 3). The objects were selected with the restrictions that they be visually distinct, fit within approximately 1 square foot, and share no primary semantic associations. The objects were placed on the floor at one end of a 5 × 7 m room; the collection of objects occupied a space of approximately 3 × 3 m. The objects were placed in unsystematic orientations (e.g., the clock sometimes "faced" the wood, sometimes "faced" the jar, etc.) to avoid giving the participants cues as to how the configurations could be spatially organized. The floor was carpeted but, otherwise, bare, except for the objects. Small sticky markers were placed on the carpet to show the experimenter where the objects belonged. Locations of objects in unrelated experiments were marked in the same manner, resulting in a total of 28 markers in the 3 × 3 m space. On the rare occasions (<10% of the participants in Experiments 1 and 2 and none in Experiment 3) on which the participants appeared to be using the markers to determine where to place the objects or asked about the markers, they were told that the markers were used for other experiments and that they should focus on the spatial relations among the objects. One viewing position was selected that was equidistant from two walls of the room, 5 m from the facing wall and aligned with the walls of the room (0° in Figure 3).

Each test trial was constructed from the names of three objects in the room and required the participants to point to an object as if they were standing in a particular position within the room; for example, "Imagine you are standing at the jar and facing the shoe; point to the

clock." The first two objects established the imagined heading (e.g., *jar* and *shoe*), and the third object was the target (e.g., *clock*). Imagined translations (e.g., from an original viewing position to an imagined vantage point) were expected to have small effects, relative to the effects of imagined rotation, and were not examined (see, e.g., Easton & Sholl, 1995; Presson & Montello, 1994; Rieser, 1989).

The primary independent variable was imagined heading. Eight equally spaced headings were used. Headings were identified counterclockwise from 0° to 315° in 45° steps, beginning with the position labeled 0° in Figure 3. For example, *book-wood* and *jar-clock* correspond to the 0° heading; *jar-shoe* and *book-banana* correspond to the 45° heading, and so forth.

Pointing direction, defined as the direction of the target object relative to the imagined heading, was varied systematically by dividing the space about a given heading into three regions: front (0°–60° and 300°–360°), sides (60°–120° and 240°–300°), and back (120°–240°). Pointing direction was approximately counterbalanced across imagined headings. The participants received a total of 72 trials, 9 at each of the eight imagined headings.

The principal dependent measure was 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. Response latencies were also collected, to check for speed-accuracy tradeoffs, but because the judgments were not speeded, the most important dependent variable was angular error.

Procedure. Eleven participants learned each layout (6 females and 5 males learned one, 5 females and 6 males learned the other). Before entering the study room, each participant was instructed to learn the objects and their locations for a spatial memory test. The participant was blindfolded and led into the study room to the 0° viewing position. The blindfold was removed, and the participant viewed the display for 30 sec before being asked to close his or her eyes. While the participant's eyes were closed, the experimenter collected the objects in a cardboard box and placed the box directly in front of the participant. The participant was then instructed to open his or her eyes and to place the objects at their original locations. The participant was instructed to maintain the fixed heading from which he or she had studied the objects while placing the objects. The participant was required to walk forward or backward and to step to the right or the left to move about the configuration, approaching the objects from a single direction. The participants were allowed to turn their heads, but not their bodies. The instructions were repeated as needed throughout the learning phase. No constraints were placed on the speed with which or the order in which the objects were placed. When the participant was satisfied that the objects were placed on the correct locations, he or she was instructed to stand at the viewing position (which was marked on the floor of the room), with eyes closed. The experimenter then placed the objects at their original positions, and the participant was instructed to study their locations for another 30 sec. The learning phase was completed when the participant had placed each object at a location no more than 10 cm away from its original location on three consecutive attempts. The participant was then blindfolded and led from the room. After leaving the learning room, the blindfold was removed, and the participant was escorted to another room to be tested.

The test trials were presented on a Macintosh computer. The participants first received instructions on using the program and four practice trials involving locations on campus. Each test trial was initiated by the participant and proceeded as follows. The statement specifying the imagined vantage point and the target object was displayed (e.g., "Imagine you are standing at the jar, facing the shoe. Point to the clock") along with a simulated dial and pointer (see, e.g., Shelton & McNamara, 1997). The participant used the mouse to position the pointer on the dial to indicate the direction of the target object relative to the imagined heading, which corresponded to *up* in the display. The participant clicked the mouse to finish the response. Both response time and pointing direction were measured.

Figure 4. Experiment 1: Angular error in judgments of relative direction as a function of imagined heading. (Error bars are confidence intervals corresponding to ± 1 standard error of the mean as estimated from the analysis of variance.)

Results and Discussion

In this and all the subsequent experiments, latency showed the same general pattern as angular error, but the effects tended to be smaller and more variable. There was no evidence of speed–accuracy tradeoffs.

Mean absolute angular error collapsed across participants is plotted in Figure 4 as a function of imagined heading. The major result, shown in Figure 4, was that performance was dependent on orientation. People were more accurate for the imagined heading of 0° , which corresponded to the orientation of the initial study view and their body during learning, than for novel imagined headings. There was no apparent benefit for headings orthogonal or opposite to 0° .

Statistical analyses supported these conclusions. Mean absolute angular error in pointing was computed for each participant and each condition and was analyzed in split-plot analyses of variance (ANOVAs) with terms for layout, gender, imagined heading (0° – 315° in 45° increments), and pointing direction (front, sides, or back). Layout and gender were between-subjects factors. Because of the large number of main effects and interactions in the design, $\alpha = .01$ was used for omnibus effects.

The main effect of imagined heading was significant [$F(7,126) = 5.31$, $MS_e = 581.67$]. As is shown in Figure 4, the participants were most accurate on views oriented with the 0° heading. Pairwise comparisons showed that performance at 0° was significantly better than performance at all other headings [$ts(126) \geq 2.87$]. Pairwise comparisons between novel headings showed that performance at 225° was worse than that for headings of 45° , 90° , and 315° [$ts(126) \geq 2.66$] but did not differ significantly from performance for the remaining novel headings.

The main effect of pointing direction was significant [$F(2,36) = 16.74$, $MS_e = 420.72$], such that pointing to the front was more accurate than pointing to the sides and

pointing to the sides more accurate than pointing to the back. As is shown in Figure 5, however, the interaction between heading and pointing direction was also significant [$F(14,252) = 4.09$, $MS_e = 336.56$]. For pointing judgments to the sides, error was lower for headings of 0° , 90° , 180° , and 270° than for other headings, producing a saw-tooth pattern. Pointing judgments to the front and to the back did not show this pattern. For all pointing directions, the best performance (numerically, if not statistically) occurred for the imagined heading of 0° .

The main effect of gender was significant [$F(1,20) = 9.54$, $MS_e = 40,601.62$], with males being more accurate than females, producing mean angular errors of 22.0° and 39.9° , respectively.

Finally, there was a reliable interaction between heading, pointing direction, layout, and gender [$F(14,252) = 2.41$]. This interaction did not admit to straightforward interpretation. Because it was not statistically reliable using Greenhouse–Geisser corrected degrees of freedom ($\epsilon = .46$; Kirk, 1995), we did not consider it further.

The results of Experiment 1 indicated that when people experienced a spatial layout from a large number of views but were limited to a single heading, their mental representation of the layout was organized around a single reference direction parallel to the study view and to their fixed body orientation. The results were similar to those obtained by Shelton and McNamara (2001a) in the *diamond* groups (see Figure 2). These findings will be discussed in greater detail in the General Discussion section.

EXPERIMENT 2

The purpose of Experiment 2 was to determine how the selection of a spatial reference system would be affected if the participants were allowed to move freely in the room at the time of learning. Repeated exposure to a number of

Figure 5. Experiment 1: Angular error in judgments of relative direction as a function of imagined heading and pointing direction. (Error bars are confidence intervals corresponding to ± 1 standard error of the mean as estimated from the analysis of variance.)

Figure 6. Experiment 2: Angular error in judgments of relative direction as a function of imagined heading. (Error bars are confidence intervals corresponding to ± 1 standard error of the mean as estimated from the analysis of variance.)

views, gained as the participants walked about the room, might have led to the selection of a spatial reference system that incorporated more of the experienced views.

Method

Participants. Twenty-five undergraduates (13 females) participated in partial fulfillment of a requirement for their introductory psychology courses.

Materials and Procedure. The materials and procedure were similar to those used in Experiment 1. The same object configurations were used, in the same room. The participants initially viewed the configuration from the 0° viewing position. No instructions were given to maintain a fixed orientation of the body while placing the objects. The participants were allowed to turn any direction they wished. Otherwise, the study and test procedures were conducted as in Experiment 1.

Results and Discussion

Mean absolute angular error is plotted in Figure 6 as a function of imagined heading. The participants were more accurate for the imagined heading of 0° than for other imagined headings. Benefits for headings aligned with the walls of the room and for headings closer in angular distance to 0° were also evident.

Mean absolute angular error in pointing was computed for each participant and each condition and was analyzed in a split-plot ANOVA with terms for layout, gender, imagined heading, and pointing direction. The main effect of imagined heading was significant [$F(7,147) = 7.09$, $MS_e = 667.91$]. Pairwise comparisons showed that performance for the imagined heading of 0° exceeded performance for all other imagined headings [$ts(147) \geq 1.99$] except for 90° ($t < 1$). A contrast also showed that, excluding the heading of 0°, pointing accuracy was higher for headings aligned with the walls of the room (90°, 180°, and 270°) than for misaligned headings [45°, 135°, 225°, and 315°; $F(1,147) = 9.52$].

The pattern of results in Figure 6 indicates that in addition to the sawtooth pattern across novel headings, performance also decreased with angular distance from 0°. To determine whether the effect of angular distance was reliable, headings were redefined on the basis of their angular distance from 0° (see Figure 7). For example, headings of 45° and 315° were classified as a distance of 45°, headings of 90° and 270° were classified as a distance of 90°, and so forth. An ANOVA revealed an effect of angular distance [$F(4,96) = 10.80$, $MS_e = 667.64$]. The linear and quartic components of this effect were reliable [$F_s(1,96) = 20.85$ and 15.06 , respectively]. The linear contrast is sensitive to the average increase in pointing error with angular distance; the quartic is sensitive to the two nonmonotonicities (i.e., the “dips” at 90° and 180°). A similar analysis in Experiment 1 revealed no reliable effects of angular distance.

The main effect of pointing direction was significant [$F(2,42) = 12.10$, $MS_e = 625.45$]. The results indicated that pointing to the front was more accurate than pointing to the sides, which was more accurate than pointing to the back. However, as is shown in Figure 8, pointing direction interacted significantly with imagined heading [$F(14,294) = 2.37$, $MS_e = 364.76$]. As in Experiment 1, a sawtooth pattern was produced when the participants pointed to the sides. Unlike in Experiment 1, however, pointing to the front and to the back also showed a sawtooth pattern, although less pronounced. As in Experiment 1, the best performance (numerically, if not always statistically) occurred for imagined headings of 0° for all pointing directions.

In summary, the results of Experiment 2 suggested that when no restrictions were placed on the participants’ movements in the room, they represented the layout of objects in terms of two reference axes, 0°–180° and 90°–

Figure 7. Experiment 2: Angular error in judgments of relative direction as a function of angular distance from the study view. (Error bars are confidence intervals corresponding to ± 1 standard error of the mean as estimated from the analysis of variance.)

Figure 8. Experiment 2: Angular error in judgments of relative direction as a function of imagined heading and pointing direction. (Error bars are confidence intervals corresponding to ± 1 standard error of the mean as estimated from the analysis of variance.)

270°. These axes were aligned with the walls of the surrounding room and corresponded to natural intrinsic axes of the layouts learned. In addition, pointing accuracy decreased with the angular distance between the imagined heading and 0°. Overall, the results look remarkably similar to those obtained by Shelton and McNamara (2001a) in the *square* conditions (see Figure 2).

EXPERIMENT 3

Outside of an experimental context, spatial layouts are not often learned by studying them from a fixed position external to the layout. Spatial learning is often not intentional but, rather, a by-product of interaction with the environment. The goal of Experiment 3 was to determine how a layout would be mentally represented if participants learned it incidentally from many views and headings. The study phase was removed from this experiment, as were the instructions to learn the locations of the objects. Instead, the participants' time in the study room was spent moving the objects from place to place.

Method

Participants. Thirty undergraduates participated in partial fulfillment of a requirement for their introductory psychology courses. The first 18 participants learned one configuration of objects. The data from 6 of these participants were lost because of computer failure. A second group of 12 participants was then tested using a second configuration of objects. The final sample contained 24 participants (12 females).

Materials and Procedure. Layouts were the same as those used in Experiments 1 and 2. Before entering the learning room, the participants were instructed that they were to interact with the objects by moving six of the seven objects, one at a time, in no designated order, to the location of the seventh object. When all of the objects were gathered to the seventh, base object, the participants were to place the objects at their original positions. Another object would be desig-

nated the base object, and the procedure would be repeated seven times, with each of the objects serving as the base object once. The participants were not instructed to learn the locations of the objects for a spatial memory test; instead, they were told that upon completing the object interaction task, they would engage in a related computer exercise. To ensure that the participants understood the instructions, they took part in a brief practice session, in the experimenter's office, using objects other than those used in the experiment.

The participant was led into the study room blindfolded and was positioned at the "west" side of the layout facing 315° (e.g., in Figure 3, at *banana*, facing *wood*). Before the blindfold was removed, the experimenter repeated the instructions and requested that the participant begin moving immediately following removal of the blindfold. The order in which the objects were designated as the base object was random and the same for each participant. Pieces of paper indicated the proper locations of the objects. The orientations of the pieces of paper were random, with the restriction that no more than one marker could be oriented with any one heading.

When all of the objects had been returned to their original locations for the fourth time, the instruction was given for the participant to stand at the fifth base object with eyes closed. The experimenter then removed the pieces of paper marking the objects' proper locations. The participant was then instructed to continue collecting and replacing the objects. Removing the markers served a dual purpose. As the participant repeated the procedure for the remaining three base objects, the experimenter could assess whether the locations of the objects had been learned. In addition, it was hoped that the participant would interpret this as the test phase of the experiment and, therefore, not actively attempt to maintain the information acquired during the learning phase in memory. When the gathering-replacing phase was completed, the participants were told to stand at the final base object, facing in the 135° direction, and were blindfolded and led from the room.

Except when removing the position markers from the floor, the experimenter remained in the "southeast" corner of the layout (e.g., to the right and below the *jar* in Figure 3), facing approximately in the 45° direction. Participants typically turned toward the experimenter when being told the name of the next base object and, therefore, probably experienced the layout from the 225° heading more often than from other headings. The participants were tested using the same task and apparatus as those in Experiments 1 and 2.

Results and Discussion

The study phase in Experiment 3 differed from those in Experiments 1 and 2 in that the participants were not instructed to study the layouts repeatedly from a viewing position aligned with the 0° heading. It was therefore possible that the participants in this experiment would show a preference for a heading other than 0°.

To explore this possibility, each participant's *best* imagined heading (the imagined heading showing the least angular error) was identified and defined as 0°. All the other headings were then relabeled from 45° to 315° in 45° counterclockwise steps. For 20 of the 24 participants, the best imagined heading was one aligned with the walls of the room (8 at 0°, 4 at 90°, 4 at 180°, and 4 at 270°). Four of the participants had their best imagined heading misaligned with the walls (1 each at 45°, 135°, 225°, and 315°). A visual inspection of individual participants' data revealed sawtooth patterns for the 12 participants whose best heading was 0° or 90°. The other 12 participants' data revealed a pattern in which performance was good at one heading and poor at all the remaining headings; there was

Figure 9. Experiment 3: Angular error in judgments of relative direction as a function of heading and group. Imagined headings were redefined so that each participant's best heading corresponded to 0°. (Error bars are confidence intervals corresponding to ± 1 standard error of the mean as estimated from the analysis of variance.)

some evidence of reduced angular error for the heading opposite to the best heading. Means for these two groups are plotted in Figure 9 as a function of imagined heading. Similar analyses in Experiments 1 and 2 showed that the group pattern was reflected at the level of individual participants.

Mean absolute angular error was computed for each participant and each condition and was analyzed in a split-plot ANOVA with terms for layout, group as defined by best heading (0° or 90° vs. all the other headings), gender, imagined heading (best, best + 45°, best + 90°, etc.), and pointing direction. Between 2 and 4 participants were in each of the eight subgroups formed by layout, group, and gender.

The effect of imagined heading was statistically reliable [$F(7,112) = 10.11$, $MS_e = 309.66$], as was the interaction between imagined heading and group [$F(7,112) = 3.51$]. It appeared that half of the participants in Experiment 3 represented the layouts along orthogonal axes parallel to the walls of the room, whereas the other half of the participants represented the layouts along a single reference axis, which bore no consistent relation to the walls of the room. The only other reliable effect was pointing direction [$F(2,32) = 17.75$, $MS_e = 510.99$]. Pointing to the front was more accurate than pointing to the sides, which was more accurate than pointing to the back ($Ms = 23.7, 31.4$, and 37.0, respectively).

The patterns in Figure 9 are similar to those observed in Experiments 1 and 2. To explore these relations more systematically, an ANOVA was conducted on the data from all three experiments, divided into four groups corresponding to Experiment 1, Experiment 2, and the two subgroups of Experiment 3. This analysis revealed a significant interaction between heading (0°/best, 45°/best + 45°, etc.) and group [$F(21,469) = 1.86$, $MS_e = 181.93$]. The existence of the sawtooth pattern was assessed with a con-

trast that compared performance on *aligned* headings (0°, 90°, 180°, 270°) to performance on *misaligned* headings (45°, 135°, 225°, and 315°). Interaction contrasts showed that the value of this contrast did not differ reliably between Experiment 1 and the *single-axis* subgroup of Experiment 3 or between Experiment 2 and the *dual-axis* subgroup of Experiment 3 ($F_s \leq 1.05$), suggesting that the patterns of performance within these pairs of groups were similar. An interaction contrast showed that the value of this contrast was, however, different between the two pairs of groups [$F(1,469) = 5.34$]. These analyses indicated that half of the participants in Experiment 3 represented and processed the spatial structure of the layout in a manner similar to that used by the participants in Experiment 1, whereas the remaining participants represented and processed the spatial structure of the layout in a manner similar to that used by the participants in Experiment 2. We will discuss possible causes of these effects in the General Discussion section.

An important result of Experiment 3 was that the participants' spatial memories were orientation dependent even though they experienced the layouts from many views and headings and had extensive experience interacting with the objects. It can also be concluded, from the statistical comparisons of Experiment 3 with Experiments 1 and 2, that incidental learning did not influence the way in which the participants represented and processed the spatial structure of the layouts. It is worth noting that pointing error at the best heading was very low. The participants clearly knew the spatial structure of the layouts very well.

A post hoc analysis, comparing Experiments 1 and 2 with Experiment 3, revealed a significant interaction between gender and instructions [intentional vs. incidental learning; $F(1,67) = 5.95$, $MS_e = 4,092.53$]. Males produced average angular errors of 23.5 and 30.8 for intentional and incidental learning, respectively, whereas females produced average angular errors of 36.5 and 28.3 for intentional and incidental learning, respectively (cf. Cherney & Ryalls, 1999). There were no other significant interactions with instructions.

GENERAL DISCUSSION

The goal of the experiments reported in this article was to determine how movement at the time of learning and incidental versus intentional learning instructions would influence the formation of spatial memories. There were two major results.

First, regardless of the conditions at the time of learning, the patterns of angular error in pointing judgments indicated that mental representations of the layouts were constructed using one or two reference axes and were, therefore, orientation dependent. The results of Experiment 1 showed a benefit for the imagined heading of 0°, which was the only heading the participants experienced. The results of Experiment 2 showed a benefit for the imagined heading of 0°, as well as for headings aligned with the walls of the study room, and costs for headings

with more angular distance from the study view. The results of Experiment 3 indicated that all the participants had a preferred orientation, with half of the participants also showing better performance on the axis orthogonal to the preferred axis. There was no evidence in any of the experiments that the participants were able to construct view-invariant mental representations.

The second major finding appeared in the different patterns of results in the experiments. In Experiment 1, the participants were required to maintain a fixed body orientation while learning the layout. Performance in judgments of relative direction was good for the familiar heading of 0° and poor for all the remaining headings. In Experiment 2, the participants alternated between viewing the room from a fixed position and then moving freely in the room as they placed objects. Pointing error was lower for headings aligned with the walls of the room (0°, 90°, 180°, and 270°) than for headings misaligned with the walls of the room and increased with angular distance from the study view. In Experiment 3, the participants moved freely in the room, without instructions to study the layouts from any particular view. The results for half of the participants were similar to those in Experiment 1, whereas the results for the remaining participants were more similar to those in Experiment 2.

Our explanation of these findings relies heavily on the principles of spatial memory presented in the introduction. According to this theoretical framework, when people learn the layout of objects in a new environment, 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 egocentric and environmental cues. Because egocentric experience is typically much more salient than other cues in the environment, observers usually select an intrinsic reference system aligned with their viewing perspective. This fact explains why there is such strong evidence of the apparent use of egocentric frames of reference in spatial memory (e.g., Christou & Bühlhoff, 1999; Diwadkar & McNamara, 1997; Easton & Sholl, 1995; Levine et al., 1982; Presson & Montello, 1994; Richardson et al., 1999, map and virtual-walk conditions; Rieser, 1989; Rieser, Guth, & Hill, 1986; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Shelton & McNamara, 1997, 2001a, 2001b; Sholl & Bartels, 2002; Sholl & Nolin, 1997, Experiments 1, 2, and 5; Simons & Wang, 1998; Waller, Montello, Richardson, & Hegarty, 2002). Mou and McNamara (2002), however, showed that observers could learn a spatial layout according to an intrinsic axis that differed from their viewing perspective.

The contrasting patterns of results obtained in Experiment 1 and Experiment 2 were also observed by Shelton and McNamara (2001a) in their diamond and square conditions, as was discussed in the introduction. Mou and McNamara (2002), who obtained similar results under similar conditions, conjectured that seeing the layout as a square highlighted the corresponding orthogonal axes of the layout itself. Participants were, therefore, able to rep-

resent the layout, at least in part, in terms of these orthogonal axes. However, seeing the layout as a diamond highlighted only the axis parallel to the viewing perspective. The intrinsic axis orthogonal to the viewing perspective was not as salient under these conditions, because it was both misaligned with the edges of the mat and not directly experienced.

In Experiment 2 of the present article, the objects were located, not on a mat, but on the floor of a rectangular room. The participants repeatedly viewed the layout from 0° and were allowed to view the layout from many other possible perspectives as well. We hypothesize that these two features of the learning context highlighted intrinsic axes of the layout parallel to the walls of the room. The participants noticed these axes and mentally represented the layout in terms of them.

The layouts and the room were the same in Experiment 1 as in Experiment 2. However, the observers in Experiment 1 were forced to maintain a fixed body orientation during learning. We suspect that this feature of the learning context increased the salience of the axis parallel to the study view, decreased the salience of the orthogonal axes, or both. Either way, the result was that the participants represented the spatial structure of the layout in terms of a single reference direction.

We believe that similar principles can be used to explain each of the two patterns of results appearing in Experiment 3, although we do not know why different groups of participants seemed to represent the layouts differently. It is possible that these two patterns of results were produced by different patterns of interaction with the objects or different patterns of movement in the room.

As was noted in the introduction, two other published studies are relevant to the issues investigated in this article. McNamara et al. (in press) required student participants to learn the locations of eight objects in an unfamiliar city park. The participants walked through the park on one of two prescribed paths, which encircled a large rectangular building. The aligned path was oriented with the building; the misaligned path was rotated by 45°. Hence, with respect to the building, the aligned path was square, whereas the misaligned path was a diamond. Qualitatively, the patterns of performance in judgments of relative direction across imagined headings were very similar to those obtained here. The aligned group showed a sawtooth pattern, whereas the misaligned group showed a single best heading corresponding to a familiar orientation.

The other relevant study was published by Richardson et al. (1999). They required participants to learn the interior hallways of a large building by walking through the building. The participants then pointed to target locations from imagined and actual locations in the building. Pointing judgments for headings aligned with the first leg of the path were compared with pointing judgments for other headings, four out of five of which differed from the aligned headings by 180° (A. E. Richardson, personal communication, January 25, 2002). In contrast to McNamara et al.'s (in press) results, judgments in the aligned condi-

tion were no more accurate than judgments in the misaligned condition, suggesting that visually guided locomotion in the building allowed the participants to form orientation-independent representations of the building.

We have two concerns with these results. First, performance in the aligned condition was poor (angular error of approximately 40°). This result indicates that the first leg of the path might not have been the dominant reference axis for all the participants. Second, only two orientation conditions were compared. This feature of the experimental design may raise problems, because performance in contra-aligned conditions can, under certain circumstances, be quite good, even though performance at other misaligned headings clearly shows that the memory representation is orientation dependent (e.g., Mou & McNamara, 2002).

In addition to the major findings summarized previously, two other results are worthy of mention. In all three experiments, when the participants pointed to the sides, a sawtooth pattern emerged across imagined headings, such that pointing error was lower for headings aligned with the walls of the room (0°, 90°, 180°, and 270°) than for headings misaligned with the walls of the room (45°, 135°, 225°, and 315°). This effect was absent or reduced in magnitude when the participants pointed to the front or to the back. We suspect that the interaction between pointing direction and heading might have been caused, at least in part, by how pointing direction was coded. Pointing direction was defined egocentrically. Pointing direction can also be defined allocentrically. In exploratory analyses, we found that irrespective of imagined heading, pointing along the 0°–180° and the 90°–270° axes ($\pm 15^\circ$) was easier than pointing in other allocentric directions. An unanticipated feature of the layouts used in these experiments was that for aligned imagined headings, the *sides* category typically included trials in which the allocentric pointing direction was within 15° of a major axis (e.g., “Imagine you are standing at the shoe, facing the banana; point to the scissors”). For misaligned headings, *sides* never included trials within 15° of a major axis. Regardless of the imagined heading, the categories of *front* and *back* never included trials falling within 15° of a major axis (e.g., “Imagine you are standing at the shoe, facing the banana; point to the wood”). The sawtooth pattern for *sides* might, therefore, have resulted from a benefit of pointing along a major allocentric axis for aligned, but not for misaligned, headings. Experiments testing this possibility are presently being conducted in our laboratory.

This explanation of the interaction between imagined heading and pointing direction reinforces the overall conclusions from these experiments: The spatial reference system used to represent the spatial layout of a collection of objects should be revealed in the efficiency with which views of the layout can be imagined and target locations can be retrieved. Our exploratory analyses confirmed this prediction.

Another intriguing result of our experiments was that angular error in pointing did not decrease as the opportu-

nities to experience the layout from multiple views and headings increased. The mean angular errors of pointing judgments were 31°, 32°, and 31° in Experiments 1, 2, and 3, respectively. These means do not differ from the mean angular errors obtained when the participants learned similar layouts from one, two, or three static viewing positions, as was reported by Shelton and McNamara (2001a). These results indicate that learning the locations of objects by moving among and interacting with them, and experiencing them from multiple points of view, does not seem to improve the overall fidelity of spatial memories.

In summary, the results of these experiments indicate that sighted locomotion through an environment does not, by itself, produce an orientation-independent mental representation of that environment. Our results converge with other recent findings indicating that the spatial structure of the local environment is mentally represented in terms of frames of reference defined by the layout itself (e.g., Mou & McNamara, 2002; Shelton & McNamara, 2001a). Our negative conclusion about the role of locomotion in the learning of novel environments does not imply that locomotion is not important to spatial memory. It is well known that locomotion at the time of testing can facilitate the retrieval of spatial relations from memory (e.g., Presson & Montello, 1994; Rieser, 1989; Simons & Wang, 1998; Waller et al., 2002). For example, judgments of relative direction from novel headings are often as accurate as those from familiar headings if observers are allowed to rotate their bodies to the new heading. Resolving these paradoxical findings on the relations between locomotion and spatial memory remains a puzzle for future research.

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(Manuscript received May 7, 2001;
revision accepted for publication January 27, 2003.)