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Reference frames during the acquisition and development of spatial memories

Jonathan W. Kelly[1] and **Timothy P. McNamara**[2]
[1]Department of Psychology, Iowa State University
[2]Department of Psychology, Vanderbilt University

Abstract

Four experiments investigated the role of reference frames during the acquisition and development of spatial knowledge, when learning occurs incrementally across views. In two experiments, participants learned overlapping spatial layouts. Layout 1 was first studied in isolation, and Layout 2 was later studied in the presence of Layout 1. The Layout 1 learning view was manipulated, whereas the Layout 2 view was held constant. Manipulation of the Layout 1 view influenced the reference frame used to organize Layout 2, indicating that reference frames established during early environmental exposure provided a framework for organizing locations learned later. Further experiments demonstrated that reference frames established after learning served to reorganize an existing spatial memory. These results indicate that existing reference frames can structure the acquisition of new spatial memories and that new reference frames can reorganize existing spatial memories.

Spatial memory plays a crucial role in everyday navigation and wayfinding. Finding one's way to a campus library without using a navigational aid depends critically on knowing the location of the library within the context of the campus environment. Recent spatial memory research has focused heavily on understanding the organization of this type of long-term spatial memory. One commonly replicated finding in this area is that spatial memories are orientation-dependent, whereby spatial memories are most easily retrieved (e.g., scene recognition judgments and inter-object pointing judgments are faster and more accurate) from one or two specific orientations (for reviews, see McNamara, 2003 and Avraamides & Kelly, 2008). This has led researchers to argue that spatial memories are organized around reference frames centered on the environment, and that those reference frames influence the manner in which spatial memories are accessed. The current study examines the role of reference frames during the acquisition and development of spatial knowledge when learning occurs incrementally, as it often does in naturalistic settings.

The preponderance of evidence from spatial memory research indicates that reference frames are selected on the basis of cues available in the learning environment. Environmental cues such as room walls (Kelly & McNamara, 2008b; Kelly, McNamara, Bodenheimer, Carr & Rieser, 2008; Shelton & McNamara, 2001), city streets (Montello,

Address correspondence: Jonathan W. Kelly, Department of Psychology, W112 Lagomarcino Hall, Iowa State University, Ames, IA 50011-3180, Phone: (515) 294-2322, jonkelly@iastate.edu.

1991; Werner & Schmidt, 1999), buildings, and lakes (McNamara, Rump & Werner, 2003) can result in spatial memories organized around reference directions parallel to those environmental structures (and sometimes a second set of reference directions orthogonal to the first). Furthermore, learning from a view that is aligned with one or more environmental structures can serve to highlight and bolster the influence of those cues.

In a prototypical study by Shelton and McNamara (2001), participants learned the locations of seven objects placed on a square mat, which lay on the floor of a rectangular room. The edges of the square mat were aligned with the rectangular walls of the room. All participants studied the object layout from two perspectives, one aligned and one misaligned with the axes defined by the environment (i.e., the mat and the walls), and the learning order was manipulated. After learning, participants performed an imagined perspective-taking task, in which they imagined standing at the location of one object, facing a second object, and pointed to a third object from that imagined perspective. Regardless of the order in which participants experienced the misaligned and aligned study views, perspective-taking performance was best when imagining the aligned perspective, indicating that participants organized their memories around a reference frame consistent with the environmental axes defined by the walls and the mat.

Based on their findings and other related work, Shelton and McNamara (2001) proposed that reference frames are allocentric – fixed relative to the environment – and that egocentric and environmental cues combine to influence selection of allocentric reference frames. The allocentric nature of the reference frame is indicated by the finding that participants who first studied from the view aligned with the room axes selected a reference frame parallel to that aligned view, and subsequent studying from a misaligned view did not change the selected reference frame, indicating that the reference frame was fixed with respect to the environment.

Mou, McNamara, Valiquette, and Rump (2004) have outlined a model of spatial memory that accounts for orientation dependency in imagined perspective-taking tasks. According to this model, the bearings, or directions, between objects are represented in terms of reference directions in the spatial reference frame. People can retrieve the represented bearing when the imagined perspective is the same as the spatial reference direction but need to infer the bearing in terms of the imagined perspective when it is different from the spatial reference direction. Inference requires additional cognitive processing, which introduces error and increased latency to performance (e.g., Klatzky, 1998). It follows that performance should be worse on imagined perspectives misaligned with the spatial reference direction than on headings aligned with the spatial reference direction.

Much is now known about how reference frames are established during initial learning, and the relative roles of various cues when selecting those reference frames. In contrast, considerably less is known about the role of reference frames during subsequent development of spatial knowledge, despite the fact that memories for most real-world environments develop incrementally over repeated explorations. For example, a visitor learning a new campus might walk along multiple intersecting paths while traveling different routes to relevant buildings. Learning the campus layout during these explorations occurs gradually. In some cases, the visitor will encounter the same building or landmark from multiple directions, but he or she will rarely see the entire campus simultaneously. Within this naturalistic learning context, spatial memories acquired at different times and from different views might become integrated within a unitary reference frame, or they might be stored separately, each within a unique frame of reference. This is in contrast to most laboratory work on reference frames, in which participants typically study spatial layouts that are visible in their entirety from all studied perspectives (e.g., Shelton &

McNamara, 2001). The current experiments explore the role of reference frames during the acquisition and development of spatial knowledge, when learning occurs incrementally.

Previous work on the integration of multiple remembered spaces has produced mixed results as to whether or not separately learned spaces are integrated within a single reference frame. In a frequently used paradigm, participants first learn two separate spatial layouts or routes, and they later learn the relationship between those two spaces. Those experiments commonly compare accuracy of distance and direction judgments for pairs of within- and between-layout locations in order to assess whether the two layouts were organized into a single reference frame or two separate reference frames. Some studies report larger errors for between- versus within-layout pairs, indicating a failure to fully integrate the two spaces (Golledge, Ruggles, Pellegrino & Gale, 1993; Hanley & Levine, 1983; Ishikawa & Montello, 2006; Montello & Pick, 1993). Between-layout judgments are thought to take longer due to the additional cognitive effort required when reconciling the different reference frames, perhaps similar to the costs incurred during mental rotation of small-scale objects (Shepard & Metzler, 1971). However, other studies have found comparable performance for within- and between-layout pairs, indicating that participants successfully integrated the two separately learned spaces within a single reference frame during learning (Holding & Holding, 1988; Maguire, Burke, Phillips & Staunton, 1996; Moar & Carlton, 1982). These equivocal findings could be due to methodological differences across studies, including differences in environmental scale and differences in the spatial relationships between the two environments and between the pairs of test objects. For example, judgments of within-layout object relationships are known to depend greatly on whether those objects are aligned or misaligned with environmental axes (e.g., Werner & Schmidt, 1999), and so within- and between-layout pairs need to be carefully selected with this variable in mind. Furthermore, comparison of within- and between-layout pairs may not be the most appropriate method for understanding the role of reference frames during spatial learning. For example, both spatial and temporal separation during learning are known to influence judgments of inter-object distances (McNamara, Halpin & Hardy, 1992). Therefore, studies reporting larger errors for between- than within-layout pairs might have been influenced by similar temporal distance effects, and the results may have had little to do with differences in spatial reference frames.

In light of the challenges in interpreting existing work, the experiments presented here take a unique approach to understanding whether multiple layouts, learned incrementally, are integrated within a single reference frame, and how that integration occurs. Rather than focusing on differences in judgments of between- and within-layout pairs of objects (the standard approach used in previous work), we examined whether learning one spatial layout, organized around one reference frame, could influence the reference frame used to organize a second, subsequently learned layout. By manipulating the reference frame used to store the first layout, we could then measure the influence of the first reference frame on memories for the second layout, and vice versa. An influence of one reference frame on another would provide evidence that the two spatial memories were interdependent, and this would also shed light on whether people are biased toward using one or multiple reference frames to organize sequentially learned spatial memories. All four experiments focus on layouts learned within room-sized environments, since this work draws heavily on spatial memory theories based largely on evidence from room-sized spaces.

Experiment 1

Experiment 1 explored whether a reference frame used to organize one spatial layout would influence the reference frame selected to organize a second spatial layout. Participants learned two spatially overlapping layouts within a single room. They first learned Layout 1 from one of two possible views, one aligned with an environmental axis and one misaligned with that axis. The learning perspective was expected to influence the reference frame selected to organize memories of Layout 1. Participants later learned Layout 2, and the learning perspective for this layout was held constant for all participants.

After learning both layouts, participants performed a perspective-taking task that required pointing to objects from different imagined perspectives using their memories of the learned layouts. Perspective-taking performance served as an index of the reference frames used to organize participants' spatial memories. Perspective-taking trials were constructed using only within-layout objects, in order to individually assess the reference frames used to organize each of the two layouts. If newly learned locations from Layout 2 become integrated into an existing reference frame used to organize Layout 1, then perspective-taking performance for Layout 2 should depend on the reference frame used to organize Layout 1 (i.e., the perspective from which the Layout 1 reference frame was originally established).

Method

Participants—Sixteen men and sixteen women participated in exchange for monetary compensation or for course credit. Average participant age was 19.9 years.

Stimuli and Design—Learning stimuli (see Figure 1) consisted of two spatially overlapping layouts of seven objects each, bounded by a floor-to-ceiling black curtain forming a 4 m diameter circle that occluded the walls of the surrounding room. The seven objects of Layout 1 were arranged around an incomplete 3×3 grid containing a bilateral symmetry axis along 0°-180°, and the objects were separated by a minimum distance of 1 m. The layout structure was chosen in order to achieve good experimental control during the perspective-taking phase of the task, which followed the learning phase. Specifically, the layout regularity allowed for an even distribution of imagined perspectives around the layout. It also allowed for an even distribution of the correct pointing direction during imagined perspective-taking, which can influence pointing performance (Hintzman, O'Dell & Arndt, 1981;Kelly & McNamara, 2009;Shelton & McNamara, 1997;Sholl, 1987,1999). Furthermore, the same layout structure has been used in previous experiments (e.g., Shelton & McNamara, 2001), and this allows for more direct comparison with the results of those experiments.

Layout 2 had the same relative structure as Layout 1 but was rotated by 180° relative to Layout 1. In order to fit Layout 2 among the Layout 1 objects, Layout 2 was scaled to half the size of Layout 1 (Layout 2 objects were separated by a minimum distance of .5 m) and was shifted by .71 m along the 135°-315° axis.

Participants first studied Layout 1 and later studied Layout 2 in the presence of Layout 1. There were two viewing conditions. Participants in the two-views condition first studied Layout 1 from 0° and then studied both Layouts 1 and 2 from 135°. Participants in the one-view condition studied Layout 1 from 135° and then studied both Layouts 1 and 2 from the same 135° view.

During subsequent testing, participants performed an imagined perspective-taking task in which they were instructed to imagine standing at the location of one object, facing a second object, and then point to a third object from that imagined perspective. Participants imagined different perspectives evenly spaced around the layout (every 45° from 0° to 315°). Triplets of objects comprising a single trial were all drawn from the same layout (i.e., there was never any mixing between the two layouts on a given trial). Pointing direction was counterbalanced across imagined heading: for each imagined perspective and for both

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layouts, six unique trials were constructed requiring egocentric pointing directions (i.e., the direction of the correct response relative to the imagined perspective) of 45°, 90°, 135°, 225°, 270° and 315°. Participants completed a total of 96 trials (two layouts × eight imagined perspectives × six pointing directions). Trials were presented in a new random sequence for each participant.

The dependent measures were pointing error, measured as the absolute angular difference between the pointing direction and the correct direction, and pointing latency, measured as the time between trial presentation and the pointing response. Data were collected on a laptop computer using Vizard software (WorldViz, Santa Barbara, CA).

Procedure

Learning phase: After providing informed consent, participants were blindfolded and led into the learning environment, which initially contained objects from Layout 1 only. Participants in the two-views condition were first led to the 0° position and participants in the one-view condition were led to the 135° position. Upon arrival at the appropriate learning location, participants lifted their blindfolds and began studying Layout 1. After studying for 30 s, participants closed their eyes and pointed to the seven objects from Layout 1 in a random order. This study-test sequence was repeated until participants successfully pointed to all objects twice (pointing success was judged visually by the experimenter).

After reaching the learning criterion for Layout 1, participants were blindfolded again while the experimenter added the objects from Layout 2 among the Layout 1 objects. Participants in the two-views condition were then led to the 135° viewing position, whereas participants in the one-view condition simply remained at 135°. Participants then lifted their blindfolds and began studying the Layout 2 objects. After 30 s of studying, participants closed their eyes and attempted to point to the objects from Layouts 1 and 2 (i.e., they pointed to all 14 objects). This study-test sequence was repeated until participants successfully pointed to all objects twice.

Testing phase: After learning, participants were led to another room on a different floor of the building and performed the imagined perspective-taking task. On each trial, participants were asked to imagine standing at the location of one object, facing a second object, and to point toward a third object from that imagined perspective. Trials were presented as a sentence on a computer monitor (e.g., “Imagine standing at the book, facing the car. Point to the can.”). Participants pointed by moving a joystick (Logitech Freedom 2.4, Freemont CA) in the intended direction. A response was recorded when the joystick was deflected by 30° from vertical.

Analysis—Facilitated retrieval from one perspective over others will be considered as evidence that a spatial memory was organized around a reference direction parallel to that facilitated perspective (e.g., Klatzky, 1998; Mou et al., 2004). Participants in the current experiments studied from two perspectives, and the primary goal during data analysis was to identify which of those two studied perspectives corresponded with the selected reference direction (i.e., which of the two studied perspectives was easier to imagine during retrieval). Data in all experiments were analyzed with omnibus ANOVAs for exploratory analyses. In all cases, more specific contrasts were also conducted to identify the relative performance from 0° and 135°, the two studied perspectives, in order to evaluate specific experimental hypotheses.

Results

There was no indication of speed-accuracy tradeoff in any of the experiments reported here. Correlations between response latency and angular error ranged from 0.46 to 0.56 across the four experiments. In the interest of brevity we focus on the angular error data.

Absolute pointing errors (shown in Figure 2) were analyzed in a 2 (viewing condition) × 2 (layout) × 8 (imagined perspective) mixed-model ANOVA. Main effects of layout [$F(1,30)=16.18$, $p<.001$, $\eta_p^2=.35$] and perspective [$F(7,210)=6.56$, $p<.001$, $\eta_p^2=.18$] were qualified by multiple interactions. The perspective by viewing condition interaction was significant [$F(7,210)=5.60$, $p<.001$, $\eta_p^2=.16$]. An interaction contrast directed at the two studied perspectives indicated that participants in the one-view condition performed better from the 135° imagined perspective than from the 0° imagined perspective, whereas participants in the two-views condition showed the opposite pattern [$F(1,30)=28.10$, $p<.001$, $\eta_p^2=.48$]. Simple contrasts confirmed that performance was better from 135° (M=21.56°, SE=3.04) than from 0° (M=44.62°, SE=6.04) in the one-view condition [$F(1,30)=20.64$, $p<.001$, $\eta_p^2=.58$], and was better from 0° (M=24.18°, SE=2.23) than from 135° (M=31.75°, SE=2.92) in the two-views condition [$F(1,30)=7.52$, $p<.001$, $\eta_p^2=.33$]. There was also a significant layout by perspective interaction [$F(7,210)=2.90$, $p=.006$, $\eta_p^2=.09$]. Interaction contrasts indicated that performance from 135° was similar for both layouts, but performance from all other perspectives was worse for Layout 2 than for Layout 1 [$F(1,30)=12.59$, $p=.001$, $\eta_p^2=.30$].

Discussion

The results of Experiment 1 suggest that the reference frames selected to represent one spatial layout can influence the reference frames selected to represent a second spatial layout. As expected, the view from which participants learned Layout 1 influenced the reference frame used to remember Layout 1, replicating previous work on reference frames (Mou & McNamara, 2002; Shelton & McNamara, 2001). During subsequent learning of Layout 2, the reference frame used to remember Layout 2 depended on the reference frame that was previously selected to remember Layout 1. Consistent with McNamara and colleagues' reference frame theory of spatial memory (McNamara, 2003; Mou et al., 2004; Mou & McNamara, 2002; Shelton & McNamara, 2001), we believe that participants in the two-views condition who learned Layout 1 from the 0° view encoded Layout 1 object locations relative to a reference direction along the 0°-180° axis, and possibly a second reference direction orthogonal to that axis (note the facilitated Layout 1 performance from the 90° and 270° perspectives in the two-views condition, Figure 2). Selection of this reference frame was probably influenced by the learning view and its alignment with the bilateral symmetry axis of Layout 1. When participants in the two-views condition subsequently learned Layout 2 from the 135° perspective, they encoded Layout 2 relative to the same reference directions used to organize their memories of Layout 1. In contrast, when participants in the one-view condition learned Layout 1 from the 135° view, those object locations were encoded relative to a reference direction parallel to the 135° learning view. When participants subsequently learned Layout 2, they encoded those locations relative to the same reference direction used to organize Layout 1. Even though participants in both conditions learned Layout 2 exclusively from the 135° view, their prior experiences when learning Layout 1 influenced the organization of their memories for Layout 2.

The finding that errors were overall larger when recalling Layout 2 than Layout 1 from perspectives other than 135° is not surprising. Layout 1 was visible throughout the learning phase of the experiment, whereas Layout 2 was only added after Layout 1 was learned. This difference in exposure time could account for the added difficulty when recalling Layout 2 from non-studied perspectives. Furthermore, learning the Layout 1 objects first could have resulted in proactive interference when learning the Layout 2 objects.

The findings from Experiment 1 suggest that reference frames used to organize spatial memories of previously learned locations can influence the organization of subsequently learned locations, perhaps providing a more parsimonious spatial representation. However, it is also possible that learning Layout 1 from 0° in the one-view condition simply enhanced participants' sensitivity to specific environmental cues, such as the layouts' bilateral symmetry axes. The symmetry axis of Layout 1 was readily apparent when studying from the 0° view and this experience may have led participants in the one-view condition to detect the similar symmetry axis within Layout 2. Therefore, the Experiment 1 findings could be explained as heightened sensitivity to bilateral symmetry axes after learning Layout 1 from the 0° view. Experiment 2 was designed to test this alternative interpretation.

Experiment 2

Similar to Experiment 1, participants in Experiment 2 learned two spatially overlapping layouts, where Layout 2 was added after learning Layout 1. The only difference was that Layout 2 was rotated 45° relative to Layout 1, so that the bilateral symmetry axes of the two layouts were misaligned with one another. If participants establish a reference frame when learning Layout 1 and they carry that reference frame over to Layout 2, then the results should be similar to those from Experiment 1, and performance from 0° in the two-views condition should be facilitated even when recalling Layout 2. However, if participants encode object locations from Layout 2 relative to the layout's bilateral symmetry axis, which they become more sensitive to after studying Layout 1 from 0°, then performance when recalling Layout 2 in the two-views condition should be best along the 45°-225° axis.

Method

Participants—Sixteen men and sixteen women participated in exchange for monetary compensation or course credit. Average participant age was 22.3 years

Stimuli, Design, and Procedure—Design and procedure were identical to those of Experiment 1. The stimuli were modified by rotating Layout 2 by 45° relative to Layout 1 (see Figure 3), so that the symmetry axes of the two layouts were misaligned with one another.

Results

Absolute pointing error (Figure 4) was analyzed in a 2 (viewing condition) × 2 (layout) × 8 (imagined perspective) mixed-model ANOVA. Main effects of layout [$F(1,30)=20.61$, $p<.001$, $\eta^2=.41$] and perspective [$F(7,210)=5.30$, $p<.001$, $\eta_p^2=.15$] were qualified by multiple interactions. The perspective by viewing condition interaction was significant [$F(7,210)=6.90$, $p<.001$, $\eta_p^2=.19$]. An interaction contrast directed at the two studied perspectives indicated that participants in the one-view condition performed better from the 135° imagined perspective than from the 0° imagined perspective, whereas participants in the two-views condition performed similarly from both perspectives [$F(1,30)=14.60$, $p<.001$, $\eta_p^2=.33$]. Simple contrasts confirmed that performance was better from 135° (M=25.39°, SE=1.97) than from 0° (M=44.60°, SE=6.08) in the one-view condition [$F(1,15)=9.35$, $p=.008$, $\eta_p^2=.38$], and was statistically equivalent from 0° (M=24.18°, SE=2.23) and 135° (M=31.75°, SE=2.92) in the two-views condition [$F(1,15)=1.196$, $p=.291$, $\eta_p^2=.07$].

There was also a significant layout by perspective interaction [$F(7,210)=2.85$, $p=.007$, $\eta_p^2=.09$]. An interaction contrast indicated that performance from 135° was similar for both layouts, but performance from all other perspectives was worse for Layout 2 than for Layout 1 [$F(1,30)=18.81$, $p<.001$, $\eta_p^2=.39$].

Discussion

Even though participants only studied Layout 2 from the 135° view, their prior experience when learning Layout 1 influenced their memories for Layout 2. When Layout 1 was learned from the 0° view, memories for Layout 1 were organized around a reference direction parallel to the learning view and the bilateral symmetry axis of the layout, and a second reference direction orthogonal to the first. When Layout 1 was learned from the 135° view, memories for Layout 1 were organized around a reference direction parallel to that learning view. Those reference frames used to remember Layout 1, which varied with viewing condition, carried over to Layout 2. Retrieval of Layout 2 was more accurate from the 0° imagined perspective after first studying Layout 1 from 0° than after first studying Layout 1 from 135°. Unlike Experiment 1, these findings cannot be explained by enhanced sensitivity to bilateral symmetry axes after studying from 0°. If learning Layout 1 from 0° simply increased participants' sensitivities to bilateral symmetry axes, then those participants should have shown facilitated retrieval of Layout 2 along its 45°-225° bilateral symmetry axis, but this did not occur.

Similar to Experiment 1, errors when recalling Layout 2 were generally higher than for Layout 1, with the exception of the 135° imagined perspective. This could be due to the longer amount of study time for Layout 1, which was studied first in isolation and then was still visible throughout the learning of Layout 2, and could also be due to proactive interference from Layout 1.

The major findings of Experiment 2 replicate those of Experiment 1, and indicate that reference frames selected to represent one spatial layout can influence the reference frames selected to represent a second spatial layout. According to our interpretation, the second layout was encoded relative to the same reference frame selected when learning the first layout. These findings indicate a role for reference frames during the microgenesis of spatial knowledge, whereby new perceptual information (e.g., a newly encountered object location) is interpreted within an existing spatial framework. The unique experimental paradigm used here circumvents some of the complications when interpreting studies in which participants learn two layouts and then make between- and within-layout judgments of relative locations. Those experiments typically argue that differences in errors or latencies when making between- versus within-layout judgments can be interpreted as differences in the reference frames used to represent those layouts. However, temporal and physical separations of objects during learning are known to influence inter-object judgments (McNamara, Halpin & Hardy, 1992). Those effects of temporal and spatial separation might underlie the equivocal findings from studies using that particular paradigm.

Experiment 3

Whereas Experiments 1 and 2 demonstrated that new object locations could be organized and remembered in the context of a previously established spatial reference frame, Experiment 3 explored the possibility that spatial memories originally organized around one reference frame could later be reorganized around a new reference frame. This was accomplished by reversing the order of events from Experiment 2: using the same object layouts, participants studied both layouts from the 135° perspective, and then studied Layout 1 in isolation from either the 135° view or from the 0° view. We expected the initial learning of both layouts from 135° to result in selection of a reference direction from 135°. We also expected that participants who later studied Layout 1 from 0° would reorganize their memories for Layout 1, since the 0° view was aligned with the bilateral symmetry axis of Layout 1. The critical question was whether studying Layout 1 from 0° would also cause participants to reorganize their memories of Layout 2, even though it was only ever experienced from 135°. If this did occur, it would provide evidence that spatial memories can be reorganized on the basis of new spatial information (in this case, recognition of Layout 1's bilateral symmetry axis), even when some of the remembered locations are no longer visible. Anticipating that this type of reorganization might require additional attention directed toward the locations of the removed objects, a condition was included in which participants pointed to the removed objects after walking to the second, aligned view.

Experiment 3 can also be considered an extension of previous work by Valiquette, McNamara and Labrecque (2007), who had participants learn a single layout of objects placed on a rectangular mat aligned with a rectangular surrounding room. The influence of the environmental cues provided by the mat and the room walls is similar to the influence of the bilateral symmetry axes used in Experiments 1 and 2 (Kelly & McNamara, 2008b). In their experiments, Valiquette et al. had participants learn the layout of objects from two views, first from a view misaligned with the environmental axes (misaligned with the axes defined by the mat and the room walls) and then from a view aligned with those environmental axes. Participants performed two blocks of perspective-taking trials, one after studying from the misaligned view and the second after studying from the aligned view. After studying from the misaligned view, perspective-taking performance was better when imagining the misaligned study view than when imagining the aligned study view. After viewing from the aligned view for just 30 s, performance in the second block of trials was best from the aligned view, and performance from the misaligned view was no better than performance from other misaligned perspectives that were never experienced. The authors interpreted this as evidence that reference directions aligned with salient environmental axes (like room walls or bilateral symmetry axes) are preferred over other potential reference directions, and that studying from the second view caused participants to reinterpret the scene. However, it is unclear whether participants actually reorganized their existing spatial memory (acquired from the misaligned view) or whether they purged their memories of the layout from the first studied view and replaced them with new memories from the second view. Experiment 3 was designed to determine whether spatial memories acquired from one view could be reorganized after experiencing a second view that highlighted an environmental axis, even when the relevant objects were no longer visible from that second view.

Method

Participants—Twenty-four men and twenty-four women participated in exchange for monetary compensation or for course credit. Average participant age was 21.4 years.

Stimuli, Design and Procedure—Learning stimuli consisted of the same two spatially overlapping layouts used in Experiment 2 (see Figure 3). All participants first learned Layouts 1 and 2 (i.e., all 14 objects were simultaneously visible) from 135°, and later studied Layout 1 in isolation (after removal of Layout 2). Participants studied the visible objects for 30 s and then pointed to those objects with eyes closed until reaching the learning criterion. There were three viewing conditions. In the one-view condition, participants first studied both layouts from the 135° view and then studied Layout 1 in isolation from the same 135° view. In the two-views condition, participants first studied both layouts from 135° and then studied Layout 1 in isolation from the 0° view. When studying from the 0° view, participants in the two-views condition were only instructed to study the remaining Layout 1 objects, and subsequently pointed only to the Layout 1 objects during the eyes-closed learning assessment. The two-views pointing condition was identical to the two-views condition, except that participants were instructed to study the visible objects and also to visualize the locations of the objects that had been removed (i.e., the Layout 2 objects). After 30 s of studying, participants in the two-views pointing condition were instructed to point to *all* objects with eyes closed, even though only Layout 1 was visible from the second viewing perspective. The task of pointing to all objects was included in this condition to induce greater elaboration (e.g., Craik & Lockhart, 1972;Hunt & Einstein, 1981), wherein spatial relations among Layout 2 objects could be interpreted in the context of the 0° view. Participants in this condition did not receive feedback on their pointing responses to the Layout 2 objects, and criterion pointing performance was evaluated based on their responses to the Layout 1 objects. After learning, the perspective-taking task was exactly the same as in the previous two experiments, regardless of learning condition.

Results

Absolute pointing error (Figure 5) was analyzed in a 3 (viewing condition) × 2 (layout) × 8 (imagined perspective) mixed-model ANOVA. A significant main effect of layout [$F(1,45)=26.46$, $p<.001$, $\eta_p^2=.37$] indicated overall superior pointing performance for Layout 1 (M=30.85°, SE=1.90) compared to Layout 2 (M=37.99°, SE=1.97). The main effect of perspective [$F(7,315)=5.83$, $p<.001$, $\eta_p^2=.12$] was qualified by a two-way perspective by condition interaction [$F(14,315)=1.95$, $p=.021$, $\eta_p^2=.08$]: performance was better from 135° (M=22.29°, SE=2.20) than from 0° (M=38.80°, SE=6.25) for participants in the one-view condition, but did not differ for participants in the two-views condition (0° perspective: M=31.35°, SE=2.45; 135° perspective: M=27.82°, SE=2.61) or the two-views pointing condition (0° perspective: M=30.62°, SE=2.45; 135° perspective: M=36.58°, SE=5.85).

Contrasts were conducted to further evaluate performance at the 0° and 135° studied perspectives. A three-way interaction contrast comparing performance from 0° and 135° across viewing condition and layout was significant [$F(2,45)=4.66$, $p=.014$, $\eta_p^2=.17$]. This was followed up with separate two-way interaction contrasts for each layout. The perspective by condition interaction contrast for Layout 1 was significant [$F(2,45)=3.68$, $p=.033$, $\eta_p^2=.14$], reflecting the greater accuracy from 0° than from 135° in the two-views and two-views pointing conditions compared to the greater accuracy from 135° than from 0° in the one-view condition. The perspective by condition contrast for Layout 2 was also significant [$F(2,45)=6.26$, $p=.004$, $\eta_p^2=.22$], reflecting the greater accuracy from 135° than from 0° in the one-view and two-views conditions compared to the greater accuracy from 0° than 135° in the two-views pointing condition.

Discussion

Experiment 3 demonstrated that spatial memories originally organized around one reference frame can be reorganized around a new reference frame. This conclusion is stronger than conclusions from previous work showing that memories for layouts studied from one perspective can be reorganized after studying from a second perspective (e.g., Shelton & McNamara, 2001). Those experiments only indicate that spatial layouts can be reinterpreted on the basis of new views, and the memory for the reinterpreted layout can replace the original spatial memory. In contrast, Experiment 3 indicates that spatial memories can be reorganized on the basis of experiences that occur after the memory has been formed. According to our interpretation, when participants — regardless of their viewing condition — studied Layouts 1 and 2 together from the 135° perspective, they represented those locations relative to a reference frame parallel to 135°. Participants in the one-view condition then continued studying Layout 1 from 135°, and this experience did not change their representations of either layout. Participants in the two-views group walked to the 0°

view to continue studying Layout 1. This experience caused them to reorganize their memories for Layout 1 around a reference direction parallel to the 0° view, which was also aligned with the bilateral symmetry axis of the layout. However, this experience did not result in reorganization of their memories for Layout 2, which remained organized around the 135° reference direction. Participants in the two-views pointing condition also walked to 0° to continue studying Layout 1, and were then instructed to visualize and point to the object locations from Layout 2. This manipulation was sufficient to cause reorganization of both Layouts 1 and 2 around a reference direction parallel to 0°, indicating that spatial memories can be reorganized even when the remembered locations are obscured from view.

The results of Experiment 3 extend our understanding of the role of reference frames in spatial memory development, indicating that reference frames can exert their influence over remembered, but unseen, object locations. These results also extend previous work in which learning occurred from views aligned and misaligned with salient environmental structures (Shelton & McNamara, 2001; Valiquette et al., 2007). In those experiments, viewing a layout from an aligned perspective was sufficient to override a reference frame established from a misaligned view. Here we show that perceptually experiencing the objects from the second, aligned view is not actually a necessary condition, and that imagining the objects while standing at a second viewing location can be sufficient to reorganize the previously learned locations.

Results from the two-views pointing condition indicate that spatial memories are malleable, and that their organization can change when new environmental information is acquired. Interestingly, reorganization of Layout 2 did not occur in the two-views condition, in which participants simply studied Layout 1 from 0° but were not explicitly told to imagine and point to the Layout 2 objects. Instead, reorganization required additional attentional resources: reorganization only occurred in the two-views pointing condition, in which participants studied Layout 1 from 0° and also imagined and pointed to Layout 2 object locations from 0°.

Although performance when recalling Layout 2 did depend on the viewing condition, the results were not completely consistent with the original hypothesis. If participants in the two-views pointing condition initially organized Layout 2 around a 135° reference direction, and later reorganized their memories around a 0° reference direction, then perspective-taking performance for Layout 2 should have been 1) better from the 0° perspective and 2) worse from the 135° perspective relative to the one-view control group. However, only evidence for the latter effect was found, and performance from 0° was not significantly improved. One possible explanation is that participants' memories for Layout 2 were indeed reorganized around the 0° reference direction, but the original representation was quite noisy, and that noise obfuscated any benefit that might have otherwise occurred from 0°. This conjecture is supported by the fact that, in Experiments 1-3, errors when retrieving Layout 2 were somewhat larger than those found in previous work using single layouts of 7-8 objects (Avraamides & Kelly, in press; Kelly, Avraamides & Loomis, 2007; Kelly & McNamara, 2008a, 2008b; McNamara et al., 2003; Mou & McNamara, 2002; Shelton & McNamara, 2001; Valiquette et al., 2007). The larger number of objects used in the current experiments may have resulted in greater interference and confusion between different objects. Experiment 4 sought to identify more consistent evidence of spatial memory reorganization in the two-views pointing group by using fewer objects and a slightly modified paradigm.

Experiment 4

To reduce the cognitive demands of remembering 14 object locations, participants in Experiment 4 learned a single layout of 7 objects placed on a rectangular mat surrounded by a rectangular room. The layout was studied from only one view, which was misaligned with the rectangular environmental structures. After learning from the misaligned view, the objects were removed, and half of the participants (those in the two-views condition) walked to a second view aligned with the primary axes of the room and a mat on the floor, whereas the other half of the participants (those in the one-view condition) remained at the misaligned view. All participants were then told to continue visualizing the object locations and later pointed to those locations even though the objects were no longer present.

If previously acquired spatial memories can be reorganized on the basis of new environmental information, then participants who visualize and point to the remembered objects from the aligned view might reorganize their memories around a reference direction selected from that aligned view. If such reorganization occurs, then subsequent perspective-taking should reveal superior performance by participants in the two-views condition when imagining the aligned view.

Method

Participants—Sixteen men and sixteen women participated in exchange for monetary compensation or for course credit. Average participant age was 22.0 years.

Stimuli, Design and Procedure—Learning stimuli (see Figure 6) consisted of a single set of seven objects arranged on a 3.3 m^2 mat placed on the floor. The edges of the mat were aligned with the walls of the surrounding 5 × 7 m rectangular room. All participants learned the layout from the 135° view. Participants studied the objects for 30 s and then pointed to those objects with eyes closed until reaching the learning criterion. All objects were removed after criterion pointing performance was achieved. Participants assigned to the two-views pointing condition were then led to the 0° view. Participants assigned to the one-view pointing condition remained at 135°. All participants were then instructed to visualize the locations of the objects. After 30 s of visualization, participants were instructed to close their eyes and point to the remembered object locations. Participants did not receive feedback on their pointing accuracy. After three repetitions of the visualizing-pointing sequence, participants were blindfolded and led out of the room to perform the perspective-taking task.

Results

Absolute pointing error (Figure 7) was analyzed in a 2 (viewing condition) × 8 (imagined perspective) mixed-model ANOVA. A significant main effect of perspective [$F(7,210)=6.82$, $p<.001$, $\eta_p^2=.19$] was qualified by a two-way interaction between perspective and condition [$F(7,210)=4.35$, $p<.001$, $\eta_p^2=.13$]: performance was better from 135° (M=18.62°, SE=4.83) than from 0° (M=44.24°, SE=4.92) for participants in the one-view condition, and was better from 0° (M=27.85°, SE=4.92) than from 135° (M=34.21°, SE=4.83) for participants in the two-views condition [$F(1,30)=16.88$, $p<.001$, $\eta_p^2=.36$].

Discussion

Participants who initially studied object locations from a view misaligned with the rectangular environmental structure and later visualized the remembered objects from an aligned view were better able to recall object locations from that aligned perspective during subsequent testing than were participants who studied and visualized the objects from the misaligned view only. This result represents the first evidence that spatial memories can truly be reorganized after acquisition and without additional perceptual experience with the remembered objects. After learning the layout from the 135° view, participants in both conditions presumably organized their spatial memories around a reference direction parallel to that learning view, and possibly a second reference direction orthogonal to the learning view which resulted in the facilitated performance along the 45°-225° axis in the one-view condition. Participants in the two views condition experienced a subsequent view of the environment (but not the objects themselves) from 0°, which highlighted the strong environmental axes defined by the rectangular room walls and the square mat on the floor. After visualizing the objects within this context, participants' spatial memories were reorganized around this environmentally-defined reference frame.

Past work has shown that studying object locations from a view aligned with salient environmental axes after previously studying from a misaligned view can cause participants to reinterpret the spatial layout from that environmentally-aligned view (e.g., Shelton & McNamara, 2001). However, it was unclear whether spatial memories were truly reorganized, or whether the original spatial memory acquired from the misaligned view was forgotten and replaced with a new spatial memory acquired when studying from the view aligned with the environmental axes. Experiment 4 provides clear evidence that spatial memories can be reorganized without ever viewing the layout from a view aligned with environmental axes, and that visualizing from such an aligned view can have the same effect on spatial memory organization as visually studying from that view.

General Discussion

The goal of this project was to investigate the role of reference frames during the acquisition and development of spatial memories. Experiments 1 and 2 demonstrated that a reference frame used to organize spatial memories of one layout can influence the reference frame selected to organize spatial memories of a second layout in the same spatial region as the first. These findings demonstrate that reference frames can provide scaffolding for the acquisition of new spatial memories. After establishing a stable environmental reference frame, newly experienced locations can then be added into the existing reference frame.

In Experiments 1 and 2, participants in the two-views conditions first experienced one layout of objects from a view aligned with that layout's bilateral symmetry axis. Views aligned with environmental axes are known to be especially salient cues for selecting reference directions aligned with those axes, perhaps because environmental characteristics are highlighted by the aligned view (e.g., Shelton & McNamara, 2001). Participants in the two-views condition therefore organized their memories of Layout 1 around a reference direction parallel to the axis of the layout. Participants later studied Layouts 1 and 2 together from a misaligned view. Participants in the two-views condition remembered those new objects using the reference frame previously established when learning Layout 1. In contrast, participants in the one-view condition learned both layouts from the misaligned view only (i.e., they never experienced the aligned view), and their memories were organized around a reference direction parallel to the misaligned study view. Despite the fact that both groups of participants studied Layout 2 from the same misaligned view, their memories for Layout 2 depended on the reference frame established when they learned Layout 1. Experiments 1 and 2 identified a role for reference frames during the microgenesis of spatial knowledge, and showed that newly learned locations can be stored in the context of previously established reference frames.

A bias toward representing interconnected or overlapping spaces within a common reference frame might benefit performance on spatial tasks involved in navigation. For example, path planning between two remembered locations involves estimating travel distance and direction, and those judgments should be faster and more accurate when the locations are contained within the same spatial reference frame. Judging relationships between locations in different reference frames requires cognitive effort in the form of mental rotation to bring the two frames into alignment with each other (e.g., Shepard & Metzler, 1971). Although the current experiments did not test between-layout judgments of distance and direction, future experiments comparing between-layout judgments for layouts that are stored in a common reference frame versus different reference frames could elucidate the value of using a common reference frame for navigation-relevant tasks.

Earlier work on the integration of multiple spaces has typically focused on comparisons of relative location judgments using pairs of locations contained in a single space versus multiple spaces. Comparisons of errors on between- and within-environment judgments have been used to evaluate whether or not the two spaces were integrated within a common reference frame. However, those studies have produced equivocal results (cf. Golledge, Ruggles, Pellegrino & Gale, 1993 and Moar & Carlton, 1982), and methodological considerations such as the temporal delay between learning of between- and within-environment locations cloud their interpretation. In contrast, the present research compared the specific reference frames used to organize two different layouts. Those reference frames were evaluated separately for each layout (i.e., evaluation was based solely on within-layout location judgments), and the analysis did not depend on comparison of within- versus between-layout judgments.

The influence of previously established reference frames on newly acquired spatial memories might be limited to cases in which the layout is spatially ambiguous. In Experiment 2, Layout 2 could be interpreted as comprising two columns of two objects and one column of three objects (e.g., as interpreted from the 45° view), or it could be interpreted as comprising three columns of two objects and one column of one object (as interpreted from the 0° view). Spatial layouts with less ambiguity and stronger axes might be remembered using separate reference frames for each layout, or perhaps a dominant reference frame would be selected even when multiple salient reference frames are available. Experiments by Kelly and McNamara (2008b) explored reference frame selection in the presence of multiple environmental reference frames that were incongruent with one another. In those experiments, participants remembered the scene using a reference frame selected from the initially experienced view, rather than one of the incongruent environmental reference frames. Based on those results, it is possible that multiple layouts with clearly incongruent axes would not be represented independently from one another, but rather would be represented within a common reference frame selected on the basis of experienced views instead of environmental axes.

Experiments 3 and 4 showed that spatial memories initially organized around one reference frame could be reorganized when subsequent experiences highlighted salient environmental features consistent with a new reference frame. In those experiments, some participants learned a spatial layout from one view and later experienced another view which highlighted an environmental axis defined by the layout itself (Experiment 3) or by the surrounding room (Experiment 4). In both cases, experiencing a view aligned with an environmental axis and also visualizing the previously learned objects from that aligned view caused reorganization of the previously learned (but no longer visible) object locations. Simply experiencing the aligned view was insufficient to cause this reorganization. Instead, reorganization required visualization and pointing to the remembered objects from the aligned view. In the absence of pointing and visualization instructions, participants did not need to recall the object locations from the aligned view, and reorganization did not occur. Therefore, recall through visualization and pointing appears important for reorganization in the absence of perceptual information indicating the actual object locations. The additional visualization and pointing procedures might be considered a kind of elaboration (e.g., Craik & Lockhart, 1972; Hunt & Einstein, 1981), wherein spatial relations among the objects are interpreted in the context of a new reference frame aligned with the egocentric perspective and environmental axes.

Previous work on reference frames has typically used locations that are simultaneously visible from a single vantage point. In contrast, natural spatial learning often involves learning different locations from different vantage points. This is true in environments where large objects such as trees or buildings obstruct viewing of the full environment, and it is also true in environments where the objects are so numerous that people can only attend to a few objects at a time. The current experiments extend reference frame theory beyond limited cases where the entire environment is learned from one or two views, indicating that reference frames characterize spatial memories under a variety of learning conditions.

Conclusions based on these experiments are limited to spatial layouts learned separately within a common environment. These experiments do not address how memories for separate environments are integrated into a common spatial framework. For example, Ishikawa and Montello (2006) had participants learn two separate neighborhoods and later showed participants the connecting route between the two neighborhoods. Some participants quickly integrated the two spaces after being shown the connecting route, evidenced by relatively low errors when judging spatial relationships of between-neighborhood locations. Other participants, however, failed to integrate even after repeated presentations of the connecting route. The current experiments indicate that new locations can be remembered within the context of existing reference frames used to represent that environment, but they do not address how two different reference frames used to organize two different environments can be integrated into a unitary reference frame.

The experiments presented here took a unique approach to understanding whether multiple layouts, learned incrementally, are integrated within a single reference frame or multiple reference frames. To that end, the results indicate that people are biased toward representing multiple layouts of objects within an environment relative to a single reference frame, and that reference frames established during initial exposure to an environment can provide structure for the acquisition of new memories within that space. Furthermore, salient reference directions established after learning can serve to reorganize previously acquired spatial memories. These results indicate that reference frames structure the acquisition of new spatial memories and also reorganize existing spatial memories.

Acknowledgments

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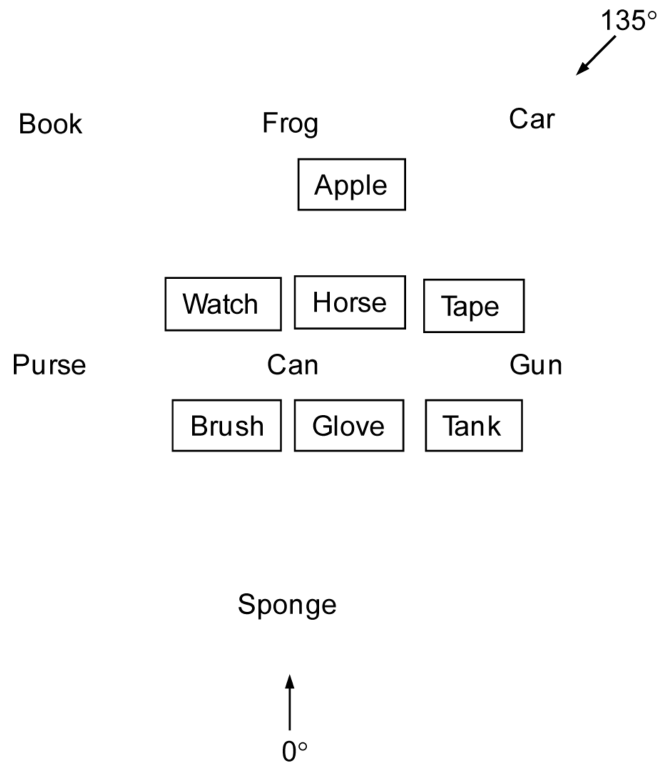

Figure 1.
Object layouts used in Experiment 1. Layout 2 objects are surrounded by small square boxes, whereas Layout 1 objects are borderless. The arrows indicate possible viewing locations.

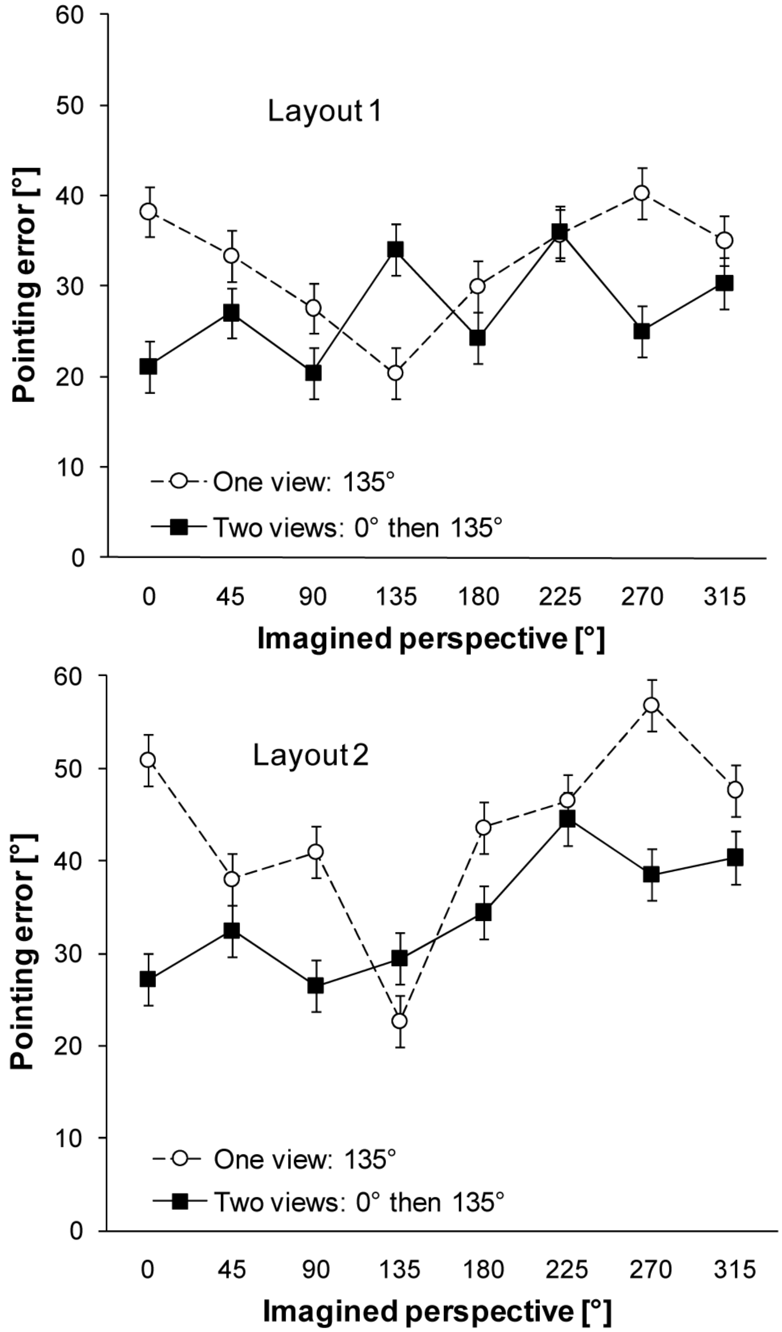

Figure 2.
Absolute pointing error as a function of object layout, learning condition and imagined perspective in Experiment 1. Error bars are standard errors estimated from the ANOVA.

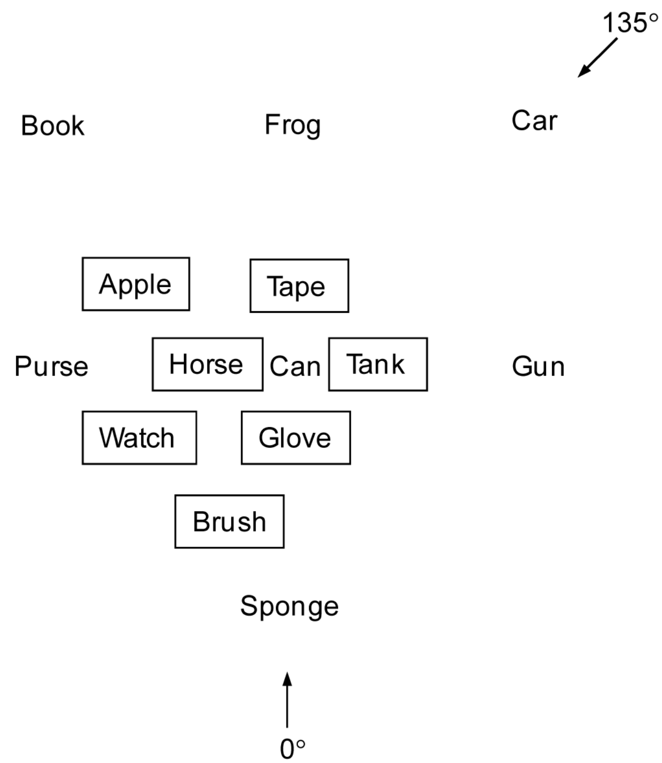

Figure 3.
Object layouts used in Experiments 2 and 3. Layout 2 objects are surrounded by small square boxes, whereas Layout 1 objects are borderless. The arrows indicate possible viewing locations.

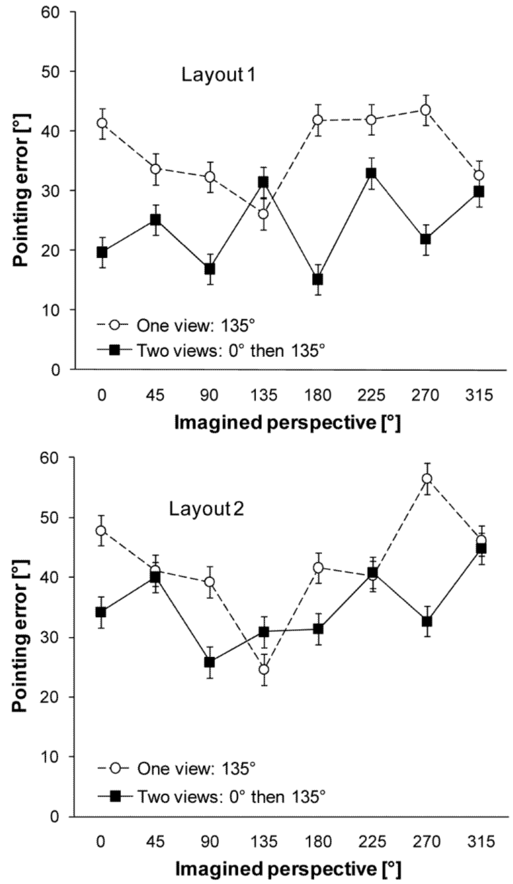

Figure 4.
Absolute pointing error as a function of object layout, learning condition and imagined perspective in Experiment 2. Error bars are standard errors estimated from the ANOVA.

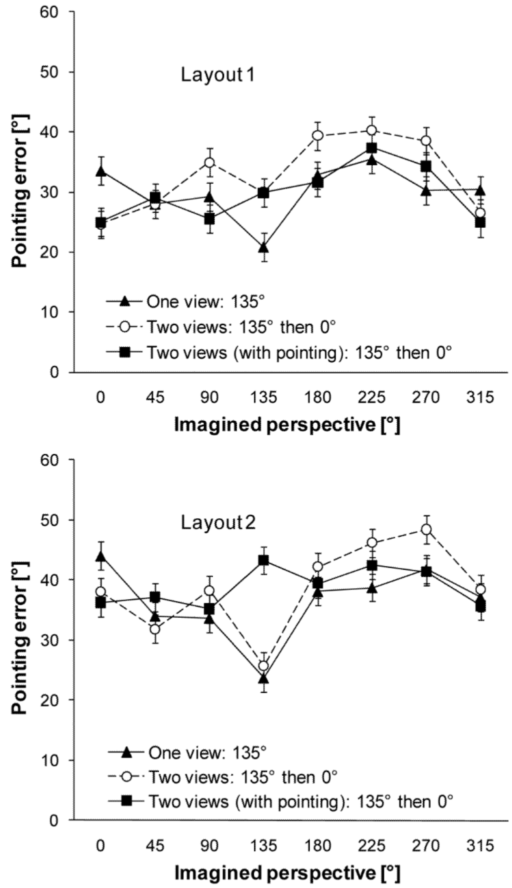

Figure 5.
Absolute pointing error as a function of object layout, learning condition and imagined perspective in Experiment 3. Error bars are standard errors estimated from the ANOVA.

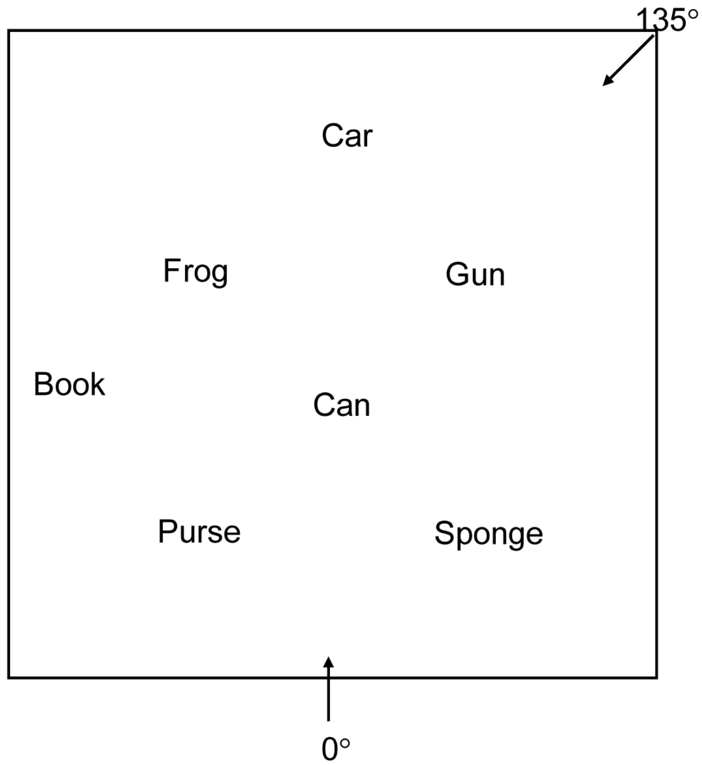

Figure 6.
Object layout used in Experiment 4. Arrows indicate possible viewing locations and the large square indicates the boundary of the mat.

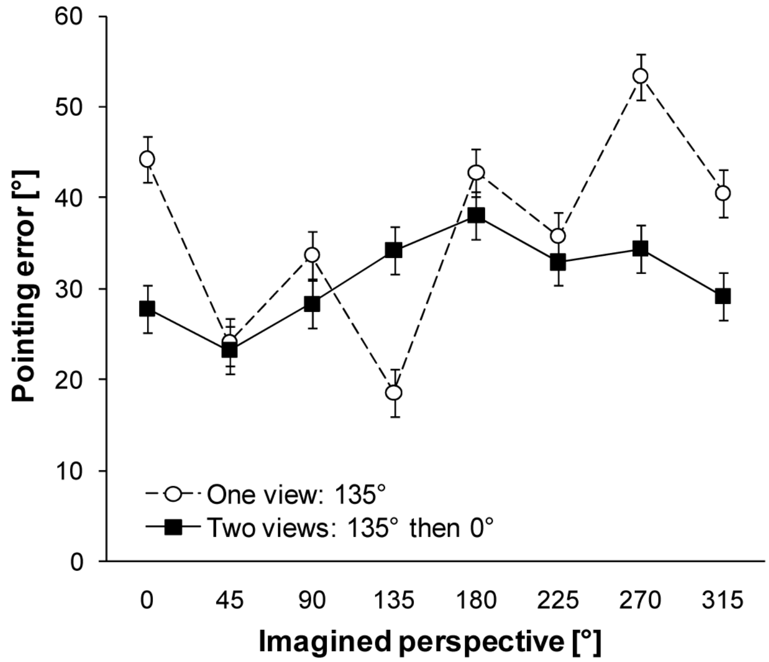

Figure 7.
Absolute pointing error as a function of learning condition and imagined perspective in Experiment 4. Error bars are standard errors estimated from the ANOVA.