Reference Frames Influence Spatial Memory Development within and Across Sensory Modalities

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Abstract. Research on spatial memory indicates that locations are remembered relative to reference frames, which define a spatial reference system. Reference frames are thought to be selected on the basis of environment-based and experience-based cues present during learning. Results from new experiments indicate that reference frames provide scaffolding during the development of spatial memories: the reference frame used to organize locations studied from one perspective was also used to organize new locations studied from another perspective. Further results indicate that the role of reference frames during spatial memory development can cross sensory modalities. Reference frames that organized memories of a visually-experienced environment also organized memories of haptically-experienced locations studied within the same environment. These findings indicate a role for reference frames during spatial memory development, and demonstrate that reference frames influence cross-modal spatial learning.

Keywords: Reference frames, Spatial memory development, Perspective taking, Multi-modal learning.

1 Introduction

Spatial memories are critical to everyday navigation. Simple tasks such as locating one's keys before leaving home and more complex tasks such as finding a new route to avoid traffic congestion all depend on the navigator's ability to recall spatial memories of those environments. Mounting evidence indicates that spatial memories are orientation dependent, with privileged access during recall to orientations aligned with the reference frame in which the memory was stored (see McNamara, 2003, for a review). Reference frames are thought to be selected on the basis of cues present during learning, including environment-defined cues such as city street grids and experience-defined cues such as studied perspectives. The relative roles of those cues in selecting reference frames are discussed in more detail in Section 2.

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Much of the research investigating reference frames in spatial memory has been conducted using environments in which the to-be-learned spatial layout is visible in its entirety from all learning perspectives. In contrast, natural spatial learning often involves incremental exposure to different parts of a scene or an environment. For example, someone relocating to a new neighborhood might first learn the locations of other homes and businesses on the same block as their new residence. Over time they explore the neighborhood and experience different views of their own street as well as other streets that they had not previously seen. After a couple of weeks they will have constructed a spatial memory of the neighborhood without ever experiencing the entire environment from a single view. Spatial memories of larger environments such as parks and neighborhoods, which are commonly learned in this piecemeal fashion, have also been shown to be orientation-dependent (McNamara, Rump & Werner, 2003; Montello, 1991; Werner & Schmidt, 1999).

Recent work from our labs has investigated the role of reference frames during the acquisition and development of spatial memories when learning occurs incrementally across multiple views. This research focuses on whether parts of a spatial layout learned from different views are remembered using different local frames of reference or whether they are integrated into a single global reference frame. These experiments, described in Section 3, indicate that reference frames established from an initial learning view can be used to organize new locations learned from other views, such that all locations are remembered within the same global reference frame. Further experiments indicate that reference frames can cross sensory modalities, whereby a reference frame used to remember a set of visually-learned objects also influences the reference frame used to remember another set of objects experienced later through touch. These findings establish a role for reference frames during the development of spatial memories. The findings also indicate that spatial reference frames may be amodal, and not specific to any individual sensory modality.

2 Reference Frames in Spatial Memory

Spatial locations are necessarily relative (e.g., the sink is *left of* the refrigerator, Iowa is *west* of Illinois, etc.), and so memories for spatial layouts must be stored in the context of a spatial reference system. Research indicates that spatial memories are commonly organized around allocentric reference frames centered on the environment (Avraamides & Kelly, 2005, 2008; Hintzman, O'Dell and Arndt, 1981; Kelly, Avraamides & Loomis, 2007; Kelly & McNamara, 2008; McNamara, 2003; McNamara, Rump & Werner, 2003; Montello, 1991; Mou & McNamara, 2002; Shelton & McNamara, 2001; Valiquette, McNamara & Smith, 2003; Werner & Schmidt, 1999; but see Wang & Spelke, 2000, 2002; Waller, Lippa & Richardson, 2008; Waller, Montello, Richardson & Hegarty, 2002, for evidence of egocentric reference frames centered on the body, head, eyes, etc.).

Shelton and McNamara (2001) conducted a series of studies investigating spatial memory organization. In a paradigmatic experiment, participants viewed seven objects placed on a square mat surrounded by a rectangular room. The edges of the mat were parallel with the room walls. Participants studied the objects from two views separated by 135°, and all seven objects were visible from both views. One view was aligned and one was misaligned with the environmental axes defined by the mat and the walls. Half of the participants studied from the aligned view first and from the misaligned view second and half of the participants studied in the opposite order. After studying, participants were led to another room for the retrieval test. On each trial, participants were asked to imagine standing at one object, facing a second object, and to point to a third object from that imagined perspective. Participants imagined different perspectives spaced evenly (every 45°) around the layout. Regardless of the viewing order during learning, perspective-taking performance was best when imagining the aligned study perspective and performance on the misaligned study perspective was no better than on other perspectives that were never experienced. Those results contrast with a subsequent experiment in which the mat on the floor was misaligned with the room walls, thereby disrupting the global environmental axes. Participants again studied from two views separated by 135°: one view was aligned with the axes of the room and the other view was aligned with the axes of the mat. During subsequent perspective taking, performance when imagining the two experienced views was better than non-experienced views, and performance on the first learning view was better than the second view, regardless of its alignment with the environmental cues.

Based on those studies, Shelton and McNamara (2001) proposed that spatial relations are stored within spatial reference frames selected on the basis of cues available during learning. Salient environmental cues (such as the mat on the floor aligned with the room walls) result in reference frames aligned with those environmental structures, especially when learning occurs from a view aligned with the environmental axes. When consistent environmental cues are lacking (as when the mat on the floor was misaligned with the room walls) egocentric cues dominate and reference frames are selected from the initially experienced view. But in both cases, the reference frame is thought to be fixed with respect to the environment, and therefore allocentric in nature.

Mou and McNamara (2002) presented evidence that reference frames can be intrinsic to the remembered layout. In their experiments, participants studied an object layout with a bilateral symmetry axis. The bilateral symmetry axis defined a salient environmental cue. After learning, participants were better able to imagine perspectives aligned with the intrinsic axis of the layout. This was true even when participants studied from a view misaligned with the symmetry axis of the layout.

Based in part on the evidence reviewed above, McNamara and colleagues have proposed that locations are remembered in the context of a spatial reference frame, selected on the basis of cues available during learning. Those cues can be broadly categorized as egocentric (experience-defined) cues, extrinsic (environment-defined) cues, and intrinsic (layout-defined) cues.

3 Reference Frames in Spatial Memory Development

Most of the work described in Section 2 focused on spatial memories of environments in which the entire environment was visible from all studied perspectives. In contrast, most real-world spatial learning occurs piecemeal, often due to the presence of occluding obstacles such as walls and tables in smaller environments and buildings, trees and hills in larger environments. The role of reference frames is unclear when environments are learned in this piecemeal manner. One possibility is that different parts of the environment, visible from different views, are encoded in separate local reference frames. Another possibility is that those different parts of the same environment are encoded in the same global reference frame.

One way in which this question has been addressed is by asking participants to learn two separate routes or layouts and later showing participants how the two spaces relate to one another. Subsequent judgments of between-layout and within-layout pairs of locations have been used as an indication of whether the two routes were represented in separate reference frames or in a common reference frame. For example, Hanley and Levine (1983) had participants learn two separate layouts on a tabletop environment. Each layout consisted of three points (points A, B, and C in one layout and points 1, 2, and 3 in the other layout) connected by two lines, forming V-shape patterns with different orientations. After learning both layouts, participants were shown that the two layouts actually contacted one another, such that point C from one of the V-shapes was spatially coincident with point 2 from the other V-shape. After studying the relationship between the two layouts, participants made judgments of distance and direction between pairs of points within the same layout or across the two layouts. The latter judgments required integration across the two layouts. If the layouts were stored in separate reference frames established during learning, then judgments should have been better for within- compared to between-layout judgments, since between-layout judgments would require mental rotation to bring the two layouts into alignment (e.g., Shepard & Metzler, 1971). In contrast, if the two layouts were integrated into a single reference frame then judgments should have been similar for within- and between-layout judgments. The data indicated that participants represented the layouts in separate reference frames, with superior performance on within-layout judgments. Superior within-layout performance has since been shown in other experiments varying in the learning conditions and environmental sizes (Golledge, Ruggles, Pellegrino & Gale, 1993; Ishikawa & Montello, 2006; Montello & Pick, 1993).

However, comparison of within- and between-layout judgments is complicated by the finding that spatial judgments can be influenced by both the temporal and spatial separation between objects during learning (McNamara, Halpin & Hardy, 1992), and this effect could be independent of the actual reference frame used to represent those locations. Further complicating matters are the discrepant results from experiments showing similar performance for within-layout and between-layout judgments, suggesting that layouts learned separately are, under some circumstances, integrated into a single reference frame (Holding & Holding, 1988; Maguire, Burke, Phillips & Staunton, 1996; Moar & Carleton, 1982). These discrepant findings could potentially be accounted for by differences in experimental design, including differences in temporal and spatial separation of layouts and differences in the cues known to influence reference frame selection (reviewed above in Section 2). Even more challenging to explain is the finding that switching between two imagined perspectives is faster when the two perspectives are from different environments compared to when they are from the same environment (Brockmole & Wang, 2002). However, this could be due to interference during the switching process (e.g., May, 1996, 2004) rather than reference frames per se.

In light of the methodological challenges associated with comparing within- and between layout judgments, we have recently developed a new method to address the influence of reference frames during the development of spatial memories. In one such experiment, participants learned two overlapping spatial layouts, shown in Figure 1. The layouts were surrounded by a circular room in order to limit the number of environmental cues that might influence reference frame selection. First, participants studied layout one (object names drawn with an oval border in Figure 1) in isolation from 0° or from 135°. Next, layout two (object names drawn without a border in Figure 1) was added to the environment. All participants studied layout two from the 135° view only. Layout one was present throughout learning, even when studying layout two. After learning, participants performed a perspective-taking task in which they imagined standing at one object, facing a second object, and then pointed to a third object from that imagined perspective. Triplets of objects comprising a single trial always came from the same layout (i.e., all three objects were drawn from layout one or all three objects were drawn from layout two). Both layouts were tested, but a single trial never mixed objects between layouts. Of critical importance was the comparison of perspective-taking performance for layout two across the layout one learning conditions. Any changes in the pattern of layout two perspective-taking performance would indicate that participants' memories of layout two were influenced by their experiences when learning layout one.

As expected, perspective-taking performance for trials testing layout one (Figure 2, left panel) depended on the layout one learning condition. Participants who first studied layout one from 0° were better able to recall layout one from perspectives of 0°, 90°, 180° and 270°, compared to 45°, 135°, 225° and 315°, producing the sawtooth

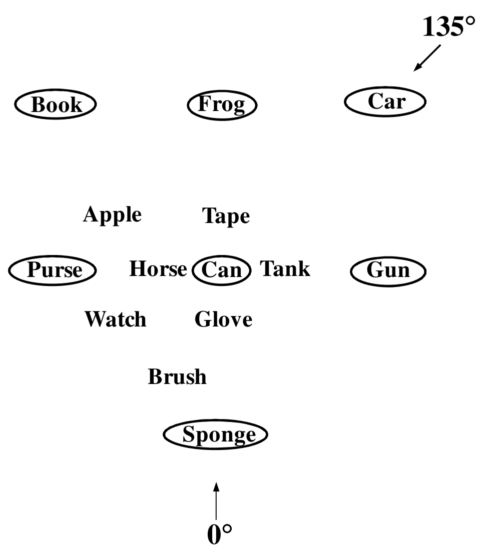

Fig. 1. Illustration of the two overlapping spatial layouts. Layout one (object names with oval borders) was studied from either the 0° view or the 135° view. Layout two (object names with no border) was then added to layout one. Layout two was always studied from the 135° view. The environment was surrounded by a circular room (not shown).

pattern seen in Figure 2. This finding of facilitated performance along orthogonal reference directions has been reported previously (e.g., Mou & McNamara, 2002). Participants who studied layout one from 135° were better able to retrieve layout one from 135° and 315° (the perspective diametrically opposite the studied perspective). The layout one results were expected based on previous research showing the influence of the learning perspective (e.g., Shelton & McNamara, 2001), and they serve as a benchmark for interpreting the results from layout two.

Layout two perspective-taking performance (Figure 2, right panel) also depended on the layout one learning condition. Participants who studied layout one from 0° also showed sawtooth pattern when recalling layout two, with facilitated performance from 0°, 90°, 180° and 270°, and also the 135° perspective from which layout two was studied. In contrast to the sawtooth pattern found when layout one was studied from 0°, participants who studied layout one from 135° showed superior performance when imagining layout two from 135°, with some facilitation also at 315°.

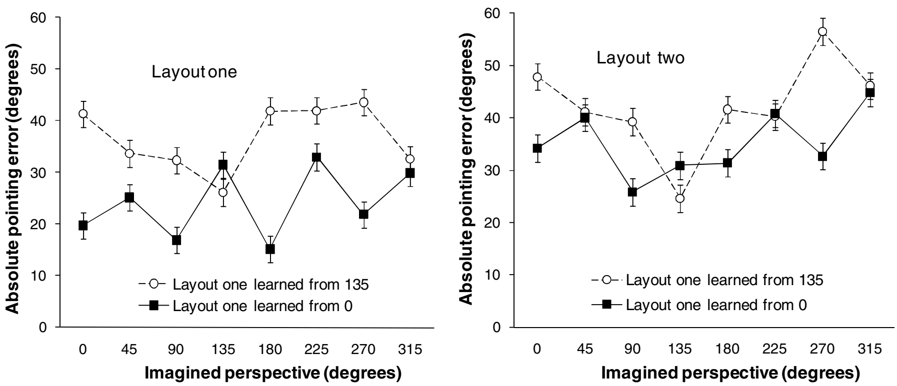

Fig. 2. Absolute pointing error during an imagined perspective-taking task after learning the two spatial layouts shown in Figure 1. Perspective-taking trials tested objects from layout one (left panel) or from layout two (right panel).

The interaction between layout one learning condition and layout two imagined perspective shows that previous experiences with layout one influenced the reference frame used to remember layout two. According to our interpretation, participants established a reference frame from the layout one learning perspective, and used that reference frame to represent the layout two locations learned later. Participants who learned layout one from 0° used a reference frame aligned with the learning perspective and the bilateral symmetry axis of the layout. When viewing layout two from 135°, they interpreted the layout two objects in the same reference frame used to represent layout one. Facilitation when imagining the 135° perspective of layout two suggests participants may have also represented layout two using a second reference frame aligned with the layout two study view. Participants who learned layout one from 135° represented layout one relative to a reference frame aligned with the 135° learning view. When viewing layout two from 135°, they interpreted those new objects in the same reference frame used to represent layout one. These findings specify a role for spatial reference frames during the development of spatial memories. However, it is unknown whether these findings will generalize to objects contained in different environments (e.g., neighboring rooms) or whether they are specific to objects contained within the same environment.

4 Transfer of Reference Frames across Sensory Modalities

The findings presented in Section 3 indicate that reference frames play an important role during the acquisition and development of spatial memories. Although vision is the primary sensory modality for acquiring spatial information, other senses also contribute to spatial learning. Research on learning through non-visual sensory modalities such as touch, proprioception, audition, and spatial language indicates that reference frames are also used to organize spatial memories learned through non-visual inputs (Avraamides, 2003; Avraamides & Kelly, in press; Yamamoto & Shelton, 2005, 2009; Yamamoto & Philbeck, 2008). However, it is unclear whether the *same* reference frames organize spatial memories learned through different sensory modalities. If so, then reference frames for locations learned through one sensory modality might influence learning through another sensory modality.

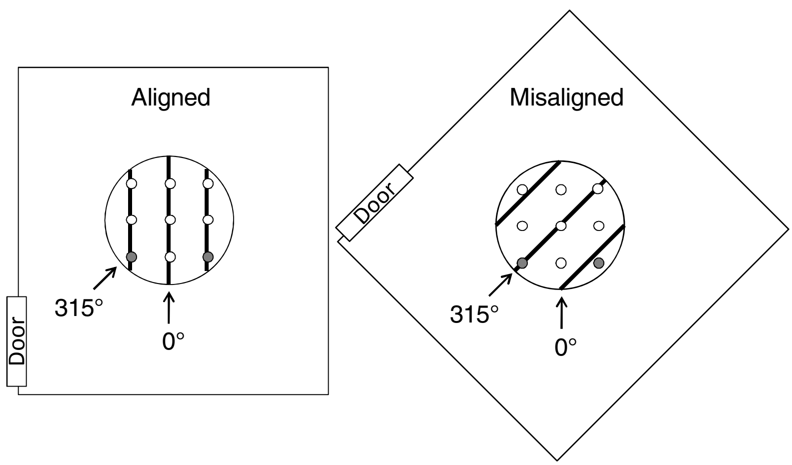

Fig. 3. Filled circles indicate locations of objects learned through vision; open circles indicate locations of objects learned only through touch. Objects were placed on a circular table with three stripes painted on its surface. Participants studied the two visual objects first from the 0° position and then from the 315° position. They then studied the touched objects only from the 315° position. The visual reference frame defined by the room walls and the stripes on the table were either aligned with the object grid (left panel, aligned condition) or misaligned with the object grid (right panel, misaligned condition).

To test whether reference frames exert cross-sensory influence, an experiment was conducted in which participants experienced salient visual cues emphasizing a reference frame before learning object locations through touch. The visual reference frame was defined by three bold stripes drawn on a round table (54 cm in diameter) on which the to-be-learned objects would be placed. The stripes were aligned with one axis of the surrounding rectangular room, providing a consistent visual reference frame. Participants visually studied two objects placed on the striped table (filled circles in Figure 3). The two visual objects were intended to direct participants' attention toward the cues defining the visual reference frame (especially the stripes on the table), and were never used during the perspective-taking task. Participants studied the visual objects from two views: first from the 0° view and then from the 315° view (participants were led 45° clockwise to reach the 315° view). After studying from the second view, participants were blindfolded and seven new objects were added to the table (open circles in Figure 3). Participants then studied all nine objects (the two objects previously studied visually plus the seven new objects) by touching them while seated at the 315° perspective. The nine objects formed a 3×3 grid with axes along 0°-180° and 90°-270°. In the aligned condition (Figure 3, left panel), the visual reference frame was aligned with the layout axes. In the misaligned condition (Figure 3, right panel), the visual reference frame was misaligned with the layout axes. Importantly, participants' egocentric experiences with the touched objects were exactly the same in both conditions, and the visual reference frame cues were blocked by a blindfold worn during the haptic learning phase.

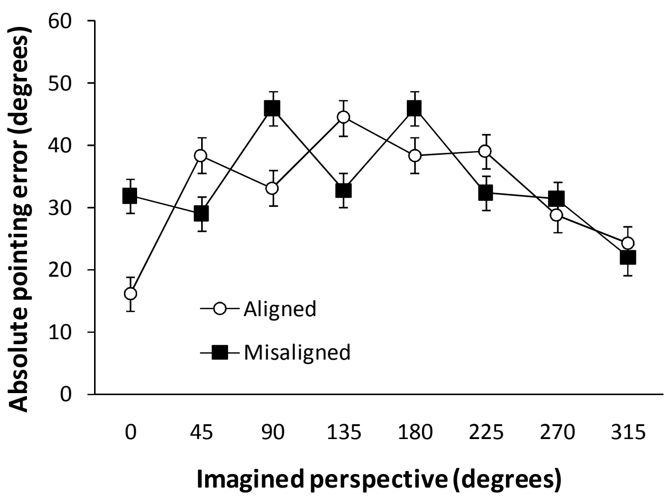

Fig. 4. Absolute pointing error during an imagined perspective-taking task using locations learned through touch (as shown in Figure 3). Participants studied the touched objects after experiencing a visual reference frame that was either aligned or misaligned with the axes of the layout of touched objects.

Subsequent perspective-taking trials used only the seven objects learned exclusively through touch. The visual objects were not used during perspective-taking. Performance is shown in Figure 4 as a function of imagined perspective for the aligned and misaligned conditions. Participants in the aligned condition performed best when imagining the 0° perspective compared to all other perspectives. Furthermore, the sawtooth pattern indicates that they remembered the touched objects using a reference frame composed of orthogonal axes along 0°-180° and 90°-270°. Participants in the misaligned condition performed best when imagining the 315° perspective compared to all other perspectives. In this case the sawtooth pattern suggests that they used a reference frame with orthogonal axes along 135°-315° and 45°-335°. In both conditions, performance from perspectives aligned with the visual reference frame may have been further enhanced by participants' alignment with the walls of the test room during the perspective taking task, similar to accounts of sensorimotor interference/facilitation (Kelly et al., 2007; May, 1996, 2004) The interaction between condition and imagined perspective provides clear evidence that the visual reference frame influenced spatial memories of subsequently touched objects. This indicates that reference frames exert their influence across sensory modalities, consistent with the hypothesis that reference frames are amodal.

5 Summary and Conclusions

Previous research has established the importance of reference frames in spatial memory organization, and has identified how environment-based and experience-based cues influence reference frame selection (e.g., Montello, 1991; Mou & McNamara, 2002; Shelton & McNamara, 2001). Here we extend those findings by describing a role for reference frames during the learning process, when learning occurs through one or more sensory modalities.

Section 3 described a new experiment showing that reference frames are selected when learning one part of an environment and then applied to other parts of that environment learned from different perspectives. Rather than using different reference frames to represent locations learned from different views, participants used a single reference frame to represent all objects in the environment. Once a reference frame had been established from the first view, that reference frame provided scaffolding for interpreting the locations of new objects learned from a different view. Learning in that experiment occurred within a circular room intended to limit the number of potential cues influencing reference frame selection. Future work should determine whether reference frames play a similar role when learning more complex and more natural environments.

Section 4 described a new experiment showing that reference frames exert their influence across sensory modalities. After experiencing a salient visual reference frame, participants used that same reference frame to organize locations of objects learned solely through touch. Similar to the experiment described in Section 3, participants used a single reference frame to represent the entire environment, rather than using separate reference frames to represent parts of the of the environment experienced visually and haptically. One possible mechanism for cross-modal reference frame transfer is that the visual reference frame might have influenced hand movements during subsequent haptic learning, such that the directions of hand movements were consistent with the visual reference frame (e.g., Lederman & Klatzky, 1987), but future research is needed to evaluate this hypothesis. Furthermore, it is unknown whether reference frames acquired through haptic experiences can influence locations subsequently learned through vision, and this is an important research question to help determine whether reference frames are truly amodal.

The present results may at first seem at odds with recent findings reported by Greenauer and Waller (2010). In their study, participants visually studied two adjacent object layouts containing bilateral symmetry axes that were misaligned with the learning view and also misaligned with each other. After learning, participants performed within- and between-layout judgments of relative direction. For both layouts, performance on within-layout judgments was best when imagining perspectives aligned with a layout's bilateral symmetry axis. In contrast, between-layout judgments were best from imagined perspectives aligned with the learning view or with the global geometry of the two layouts. Importantly, these findings occurred even when the layouts were learned sequentially. Overall, Greenauer and Waller's findings build on previous reports of hierarchically organized spatial memories (Hirtle & Jonides, 1985; Maki, 1981; McNamara, 1986; McNamara, Hardy & Hirtle, 1989; Stevens & Coupe, 1978) by showing that the hierarchical organization contains distinct micro-reference frames used to organize locations within spatial layouts and macro-reference frames used to organize spatial relations between layouts. In the current experiments, participants did not establish distinct reference frames to maintain the two sequentially-presented layouts. Instead, they established a single reference frame when viewing the first layout and used it to organize the second layout as well.

An important difference between the current experiments and those of Greenauer and Waller (2010) is that the two spatial layouts in the current experiments overlapped within the same space. Those overlapping layouts may have caused participants to organize their spatial memories around a single global reference frame rather than distinct local reference frames. Alternatively, the sequential presentation of one array embedded within another may have led participants to perceive the second array as a subset of the larger configuration. In this case, the current findings are compatible with those of Greenauer and Waller, showing that a macro-reference frame established for a superordinate layout can influence the selection of a micro-reference frame for a subordinate layout. Nevertheless, future research is needed to explore the conditions under which sequential spatial layouts become integrated or are organized separately in spatial memory.

Previous work has demonstrated that spatial memories are organized by reference frames centered on the environment. The research presented here defines a role for reference frames during the spatial learning process, when parts of the environment are encountered from different perspectives and through different sensory modalities. Reference frames provide an organizational structure for previously learned locations and for new locations not previously encountered. Reference frames influence spatial learning across sensory modalities, but further work is needed to determine whether modality-specific reference frames influence spatial learning through other sensory modalities or whether reference frames are truly amodal.

References

1. Avraamides, M.N.: Spatial updating of environments described in texts. Cognitive Psychology 47(4), 402–431 (2003)
2. Avraamides, M.N., Kelly, J.W.: Imagined perspective-changing within and across novel environments. In: Freksa, C., Nebel, B., Knauff, M., Krieg-Brückner, B. (eds.) Spatial Cognition IV. LNCS (LNAI), vol. 3343, pp. 245–258. Springer, Heidelberg (2005)

3. Avraamides, M.N., Kelly, J.W.: Multiple systems of spatial memory: Evidence from described scenes. Journal of Experimental Psychology: Learning, Memory & Cognition (in press)
4. Avraamides, M.N., Kelly, J.W.: Multiple systems of spatial memory and action. Cognitive Processing 9, 93–106 (2008)
5. Brockmole, J.R., Wang, R.F.: Changing perspective within and across environments. Cognition 87, B59–B67 (2003)
6. Golledge, R.G., Ruggles, A.J., Pellegrino, J.W., Gale, N.D.: Integrating route knowledge in an unfamiliar neighborhood: Along and across route experiments. Journal of Environmental Psychology 13, 293–307 (1993)
7. Greenauer, N., Waller, D.: Micro- and macro-reference frames: Specifying the relations between spatial categories in memory. Journal of Experimental Psychology: Learning, Memory, & Cognition (in press)
8. Hanley, G.L., Levine, M.: Spatial problem solving: The integration of independently learned cognitive maps. Memory & Cognition 11(4), 415–422 (1983)
9. Hintzman, D.L., O'Dell, C.S., Arndt, D.R.: Orientation in cognitive maps. Cognitive Psychology 13, 149–206 (1981)
10. Hirtle, S.C., Jonides, J.: Evidence of hierarchies in cognitive maps. Memory & Cognition 13, 208–217 (1985)
11. Holding, C.S., Holding, D.H.: Acquisition of route network knowledge by males and females. Journal of General Psychology 116, 29–41 (1988)
12. Ishikawa, T., Montello, D.R.: Spatial knowledge acquisition from direct experience in the environment: Individual differences in the development of metric knowledge and the integration of separately learned places. Cognitive Psychology 52(2), 93–129 (2006)
13. Kelly, J.W., Avraamides, M.N., Loomis, J.M.: Sensorimotor alignment effects in the learning environment and in novel environments. Journal of Experimental Psychology: Learning, Memory & Cognition 33(6), 1092–1107 (2007)
14. Kelly, J.W., McNamara, T.P.: Spatial memories of virtual environments: How egocentric experience, intrinsic structure, and extrinsic structure interact. Psychonomic Bulletin & Review 15(2), 322–327 (2008)
15. Lederman, S.J., Klatzky, R.L.: Hand movements: A window into haptic object recognition. Cognitive Psychology 19, 342–368 (1987)
16. Maguire, E.A., Burke, T., Phillips, J., Staunton, H.: Topographical disorientation following unilateral temporal lobe lesions in humans. Neuropsychologia 34(10), 993–1001 (1996)
17. Maki, R.: Categorization and distance effects with spatial linear orders. Journal of Experimental Psychology: Human Learning & Memory 7, 15–32 (1981)
18. May, M.: Cognitive and embodied modes of spatial imagery. Psychologische Beitrage 38, 418–434 (1996)
19. May, M.: Imaginal perspective switchers in remembered environments: Transformation versus interference accounts. Cognitive Psychology 48, 163–206 (2004)
20. McNamara, T.P.: Mental representations of spatial relations. Cognitive Psychology 18, 87–121 (1986)
21. McNamara, T.P.: How are the locations of objects in the environment represented in memory? In: Freksa, C., Brauer, W., Habel, C., Wender, K.F. (eds.) Spatial Cognition III. LNCS (LNAI), vol. 2685, pp. 174–191. Springer, Heidelberg (2003)
22. McNamara, T.P., Halpin, J.A., Hardy, J.K.: Spatial and temporal contributions to the structure of spatial memory. Journal of Experimental Psychology: Learning, Memory, & Cognition 18(3), 555–564 (1992)

23. McNamara, T.P., Hardy, J.K., Hirtle, S.C.: Subjective hierarchies in spatial memory. Journal of Experimental Psychology: Learning, Memory & Cognition 15, 211–227 (1989)
24. McNamara, T.P., Rump, B., Werner, S.: Egocentric and geocentric frames of reference in memory of large-scale space. Psychonomic Bulletin & Review 10(3), 589–595 (2003)
25. Moar, I., Carleton, L.R.: Memory for routes. Quarterly Journal of Experimental Psychology A 34, 381–394 (1982)
26. Montello, D.R.: Spatial orientation and the angularity of urban routes: A field study. Environment and Behavior 23(1), 47–69 (1991)
27. Montello, D.R., Pick, H.L.: Integrating knowledge of vertically-aligned large-scale spaces. Environment and Behavior 25, 457–484 (1993)
28. Mou, W., McNamara, T.P.: Intrinsic frames of reference in spatial memory. Journal of Experimental Psychology: Learning, Memory, and Cognition 28(1), 162–170 (2002)
29. Shelton, A.L., McNamara, T.P.: Systems of spatial reference in human memory. Cognitive Psychology 43(4), 274–310 (2001)
30. Shepard, R., Metzler, J.: Mental rotation of three dimensional objects. Science 171(972), 701–703
31. Stevens, A., Coupe, P.: Distortions in judged spatial relations. Cognitive Psychology 10, 422–437 (1978)
32. Valiquette, C.M., McNamara, T.P., Smith, K.: Locomotion, incidental learning, and the selection of spatial reference systems. Memory & Cognition 31, 479–489 (2003)
33. Waller, D., Lippa, Y., Richardson, A.: Isolating observer-based reference directions in human spatial memory: Head, body, and the self-to-array axis. Cognition 106, 157–183 (2008)
34. Waller, D., Montello, D., Richardson, A.E., Hegarty, M.: Orientation specificity and spatial updating of memories for layouts. Journal of Experimental Psychology: Learning, Memory, & Cognition 28, 1051–1063 (2002)
35. Wang, R.F., Spelke, E.S.: Updating egocentric representations in human navigation. Cognition 77, 215–250 (2000)
36. Wang, R.F., Spelke, E.S.: Human spatial representation: insights from animals. Trends in Cognitive Sciences 6(9), 376–382 (2002)
37. Werner, S., Schmidt, K.: Environmental reference systems for large-scale spaces. Spatial Cognition and Computation 1(4), 447–473 (1999)
38. Yamamoto, N., Philbeck, J.W.: Egocentric and intrinsic frames of reference in haptic spatial learning. Poster presented at the 49th annual meeting of the Psychonomic Society, Chicago, IL (2008)
39. Yamamoto, N., Shelton, A.L.: Visual and proprioceptive representations in spatial memory. Memory & Cognition 33, 140–150 (2005)
40. Yamamoto, N., Shelton, A.L.: Orientation dependence of spatial memory acquired from auditory experience. Psychonomic Bulletin & Review 16(2), 301–305 (2009)