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Move to learn: Integrating spatial information from multiple viewpoints

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ABSTRACT

Recalling a spatial layout from multiple orientations – spatial flexibility – is challenging, even when the global configuration can be viewed from a single vantage point, but more so when it must be viewed piecemeal. In the current study, we examined whether experiencing the transition between multiple viewpoints enhances spatial memory and flexible recall for a spatial configuration viewed simultaneously (Exp. 1) and sequentially (Exp. 2), whether the type of transition matters, and whether action provides an additional advantage over passive experience. In Experiment 1, participants viewed an array of dollhouse furniture from four viewpoints, but with all furniture simultaneously visible. In Experiment 2, participants viewed the same array piecemeal, from four partitioned viewpoints that allowed for viewing only a segment at a time. The transition between viewpoints involved rotation of the array or participant movement around it. Rotation and participant movement were passively experienced or actively generated. The control condition presented the dollhouse as a series of static views. Across both experiments, participant movement significantly enhanced spatial memory relative to array rotation or static views. However, in Exp. 2, there was a further advantage for actively walking around the array compared to being passively pushed. These findings suggest that movement around a stable environment is key to spatial memory and flexible recall, with action providing an additional boost to the integration of temporally segmented spatial events. Thus, spatial memory may be more flexible than prior data indicate, when studied under more natural acquisition conditions.

1. Introduction

Like all mobile organisms, humans need to learn the spatial layout of their environments. To survive, we must remember the location of food sources and shelter, and avoid areas where we have experienced threats. In achieving these goals, it is vital to be able to flexibly recall a global configuration from various vantage points in and around the space. For familiar spaces, spatial memory is quite flexible (e.g., Easton & Sholl, 1995; Holmes & Sholl, 2005; for discussion, see Meilinger, Riecke, & Bülthoff, 2007). That is, we can easily recall the spatial configuration of our daily environment (e.g., the layout of our kitchen, home, and neighborhood) from multiple orientations (e.g., from the front or back). However, spatial memory for novel spaces seems to be more rigid, with arrays best recalled from a limited number of vantage points – typically the experienced ones (Didwadkar & McNamara, 1997; Mou, McNamara, Valiquette, & Rump, 2004; Shelton & McNamara, 1997, 2001), although there may be other preferred orientations including those aligned with the intrinsic axis of the spatial array (Mou & McNamara, 2002; Mou, Zhao, & McNamara, 2007) or the extrinsic axis of the surrounding area (Adamou, Avraamides, & Kelly, 2014). When participants experience multiple viewpoints, they appear to encode them relative to the frame of reference of the first one encountered (Kelly & McNamara, 2008, Exp. 1; Shelton & McNamara, 2001, Exp. 7; Tlauka & Nairn, 2004), or to encode each representation relative to a unique frame of reference (e.g., Avraamides, Adamou, Galati, & Kelly, 2012; Meilinger, Strickrodt, & Bülthoff, 2016; for discussion, see Meilinger, 2008).

These results pose a puzzle—given the survival value of spatial flexibility, why is spatial memory for novel spaces seemingly so fragmented and rigid? One possibility is that spatial flexibility is effortful, i.e., it requires mentally transforming stored representations to make inferences about spatial relationships from other perspectives (e.g., Fields & Shelton, 2006; King, Burgess, Hartley, Vargha-Khadem, & O'Keefe, 2002; Street & Wang, 2014; Waller, Montello, Richardson, & Hegarty, 2002). For instance, people might imagine rotating a stored spatial configuration (i.e., mental rotation, MR), or they might imagine moving around it (i.e., perspective taking, PT). Even more mental work might be required when there are separate views that present fragmented spatial information encoded with respect to different reference frames, so that mental alignment is required to form a unified

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representation (Meilinger, Berthoz, & Wiener, 2011; Meilinger et al., 2016). The need to transform spatial information and to make inferences would exact a cognitive cost in terms of accuracy and/or response latency, and these effects have been confirmed (Adamou et al., 2014; Avraamides et al., 2012; Marchette, Ryan, & Epstein, 2017; Meilinger & Watanabe, 2016; Meilinger et al., 2011; Pantelides, Kelly, & Avraamides, 2016). Inferences would also recruit additional brain regions associated with the spatial processing network, and this pattern too has been confirmed (Mellet et al., 2000; Shelton & Gabrieli, 2002).

An alternative approach to spatial flexibility is suggested by considering how flexibility emerges as environments become more familiar. Much prior work has been done under restricted viewing conditions. Experiencing natural transitions among multiple viewpoints during encoding, as occurs in everyday experiences of walking around and through our environments, might lead to integration and spatial flexibility with less need for inference. Indeed, this kind of experience at environmental scale is what theoretical accounts of spatial navigation and wayfinding have emphasized (e.g., Gallistel, 1990). Some research implies the integrated representation has metric properties, as implied by the term “cognitive map”, but other findings suggest a linked set of local spatial relations (e.g., Warren, Rothman, Schnapp, & Ericson, 2017).

In an initial study of viewing conditions, Holmes, Marchette, and Newcombe (2017) asked people to learn a tabletop environment viewed with continuous visual flow, with either active or passive movement of two kinds: the tabletop turned on its axis, or they circled the table. Relative to a control group given static snapshots, even passively-experienced visual flow enhanced spatial memory. No difference was observed between active or passive movement, between rotation (table turning) or perspective taking (movement around the table), or their interaction. Thus, these various modes of generating continuous visual flow apparently served similar functions, even though rotation and perspective change have proven to be distinct when they are imagined (e.g., Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001; Lambrey, Doeller, Berthoz, & Burgess, 2012; Wraga, Shephard, Church, Inati, & Kosslyn, 2005; Zacks, Vettel, & Michelon, 2003).

Although visual flow may indeed be sufficient to enhance spatial memory in some situations, there were three limitations to this initial look at how movement may be related to spatial memory and flexible recall. First, this study, and many before it, examined spatial memory for a spatial array that could be viewed in its entirety from a single vantage point, thus only considering the effect of experience over time with continuous visibility. Here, we not only studied situations in which all spatial locations could be viewed simultaneously (Experiment 1), but also added the more challenging situation in which the array was viewed piecemeal and thus had to be integrated across views (Experiment 2). The demand to integrate across views begins to address the concern that many of the paradigms used to investigate navigation focus on small – not large-scale spatial cognition (e.g., Wolbers & Wiener, 2014). The second limitation relates to the nature of the spatial array used in our 2017 study. The tabletop environment was an organized layout of wooded areas, buildings and so forth, whereas much prior research has concerned collections of unrelated and discrete objects. It is possible that the more unified organization made the array relatively easy to encode as a whole, hence the equivalent advantage detected for array rotation and observer movement. Here, we use a more discretized spatial array – a dollhouse with separate pieces of furniture located in four rooms. Finally, the third limitation was that *we did not examine spatial flexibility* in our initial investigation. The spatial measures only examined spatial memory from a single vantage point, thus the ability to recall a spatial array from multiple orientations was never empirically assessed. In the current set of experiments, we addressed this point by using multiple vantage points for testing rather than a single one, and once again examined if the type of transition used to generate continuous visual flow between views – i.e., array rotation versus perspective taking – differentially impacts spatial memory and flexible recall, and if active movement is better than passive viewing.

Why might the type of transition matter? When extended spaces are experienced over time, they are generally experienced by walking through and around them and thus perspective change from the vantage point of a moving observer is a more natural way of encoding environmental space than having the space move. In fact, rotation is only possible with tabletop models. Furthermore, we already know that changing one’s perspective at retrieval improves spatial performance compared to array rotation, whether it is accomplished by actual movement (e.g., Burgess, Spiers, & Paleologou, 2004; Simons & Wang, 1998; Wang & Simons, 1999; but see Motes, Finlay, & Kozhevnikov, 2006) or imagined movement (e.g., Creem, Wraga, & Proffitt, 2001; Kozhevnikov & Hegarty, 2001; Presson, 1982; Wraga, Creem, & Proffitt, 2000; Wraga, Creem-Regehr, & Proffitt, 2004; Wraga et al., 2005), and that as task difficulty increases, perspective taking is the preferred strategy for imaging a spatial array from alternate viewpoints (Kozhevnikov & Hegarty, 2001). Thus, one might expect that changing perspective during encoding would also be preferred.

Why might self-generated activity matter? The issue seemed worth probing again because the Holmes et al. (2017) studies stand in contrast with other work in this area. Several studies show that action provides an additional advantage over passive viewing, both when performed concurrently (e.g., Frick, Daum, Walser, & Mast, 2009; Gardony, Taylor, & Brunyé, 2014; Wexler & Van Boxtel, 2005) or when performed prior to imagined transformations (e.g., James, Humphrey, & Goodale, 2001; Wiedenbauer & Jansen-Osmann, 2008). These findings align with the idea that motor actions and mental operations are intrinsically intertwined (see Janczyk, Pfister, Crognale, & Kunde, 2012), and develop in tandem (e.g., Frick & Möhring, 2013). Neuroimaging studies provide support for the motor/mental connection, and show that mental transformations elicit activation in supplementary, pre-, and/or primary motor cortices (e.g., MR: Kosslyn, Thompson, Wraga, & Alpert, 2001; Vingerhoets, De Lange, Vandemaele, Deblaere, & Achten, 2002; see Zacks, 2008; PT: Creem et al., 2001; Vogeley et al., 2004; but see Wraga, Flynn, Boyle, & Evans, 2010; MR + PT: Wraga, Boyle, & Flynn, 2010; Wraga et al., 2005). Such findings imply that actively transitioning between viewpoints during learning may improve flexible recall and spatial integration. We hypothesized that active experience may be especially useful as the number of spatial locations increases (i.e., 20 locations versus the 8 used in Holmes et al., 2017; Exp. 1), or when the global configuration is viewed piecemeal and must be integrated across discrete experiences (Exp. 2).

2. Experiment 1

In Experiment 1, we examined the effect of viewpoint transitions on spatial learning and flexible recall when the global configuration of a complex scene could be viewed simultaneously. Participants viewed an array of dollhouse furniture from four viewpoints that presented the global configuration from multiple orientations in one of five between-subjects conditions. The control condition (Static Views, SV) presented the dollhouse as a series of temporally segmented views whereas in the remaining conditions, visual flow was continuous – participants viewed the natural transition from one room to the next. In the passive conditions, the experimenter generated the transition between rooms by rotating the dollhouse (Passive Array Rotation, PAR) or pushing the participant around it (Passive Perspective Taking, PPT). In the active conditions, participants generated each transition by manually rotating the dollhouse (Active Array Rotation, AAR) or walking around it (Active Perspective Taking, APT). Following encoding, participants completed a series of dependent measures to examine non-spatial and spatial memory. The spatial measures were of particular importance, and were designed to assess spatial memory from the preferred orientation and flexible recall from each of the four headings presented at encoding.

2.1. Methods

2.1.1. Participants

One hundred and twenty-five Temple University undergraduates participated in this study (M_{age} = 20.90 years, *SD* = 4.78, range: 18–65). Split by sex, the sample was composed of 29 males (M_{age} = 22.59 years, *SD* = 8.65, range: 18–65) and 96 females (M_{age} = 20.39 years, *SD* = 2.58, range: 18–33). Participants were recruited via Temple University's Undergraduate Research Participation Website (SONA Systems) and granted course credit for their participation.

2.1.2. Dollhouse stimulus

The dollhouse stimulus was composed of 20 pieces of furniture, randomly arranged. All furniture was labeled, with label names attached to toothpicks inserted in the center of each piece. The dollhouse contained four rooms, and each room contained five pieces of semantically relevant furniture composed of like colors (i.e., Living Room (navy blue/turquoise): TV, toy shelves, sofa, chair, coffee table; Bedroom (red/pink): vanity, closet, crib, bed, dresser; Kitchen (silver/white): fridge, counter, dining table, highchair, trash; and Bathroom (gold/tan): linen cabinet, shower, tub, sink, toilet; see Fig. 1). The furniture within each room was also randomly arranged, such that all layouts lacked a salient, geometric configuration.

All furniture was glued to a circular wooden base (diameter: 3 ft., area: 7.07 ft., circumference: 9.42 ft.) that rested on a metal swivel, permitting 360-degree rotation of the dollhouse in any direction. To facilitate rotation, eight wooden rods extended 6 inches from the dollhouse's base in 45-degree increments. The dollhouse rested on a circular table of identical measurements (height: 3.42 ft.) located in the center of a square enclosure (6 × 6 × 10 ft.), formed by four white curtains suspended from the ceiling of the encoding room (20 × 18 × 10 ft.).

2.1.3. Measures

All measures are described in the order they were administered; 1. Non-spatial measures; 2. Spatial measures; and 3. Psychometrics. This order minimized priming effects from one measure to the next, as well as created a delay between spatial learning and test, ensuring our spatial measures assessed long-term memory rather than working memory.

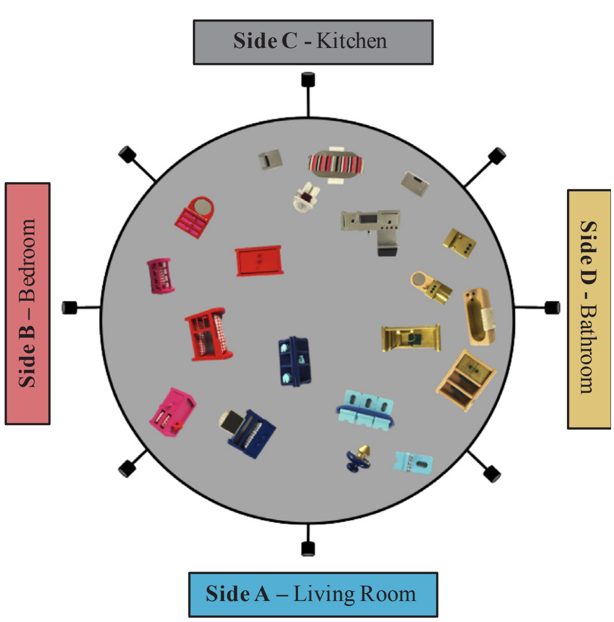

Fig. 1. Aerial view of the dollhouse stimulus in Experiment 1.

2.1.3.1. Non-spatial measures

Non-spatial measures assessed participants' associative memory and were presented in paper and pencil format. Performance was scored as the proportion of correct responses.

2.1.3.1.1. Furniture-name. The furniture-name task assessed object-verbal binding. A laminated sheet depicted all 20 pieces of furniture, and on a separate sheet, participants used a word bank to pair each name to its corresponding image.

2.1.3.1.2. Furniture-room. The furniture-room task assessed object-to-object binding. A laminated sheet displayed all 20 pieces of furniture with their corresponding labels, and on a separate sheet, participants listed the five pieces of furniture that belonged to each room.

2.1.3.2. Spatial measures

The spatial measures were designed to assess spatial memory from both preferred and non-preferred orientations. That is, the multiple-choice task required participants to recall the global layout from multiple headings, whereas the map-building task did not. For the map-building task, participants were free to recall the global layout from any perspective, and presumably chose that aligned with the reference frame perceived to most reliably preserve spatial location – that of the initial learning perspective (i.e., the preferred orientation; for greater discussion of perceived cue reliability, see Ratliff and Newcombe's (2008) adaptive-combination model). Thus the map-building task assessed the accuracy of the global representation (i.e., spatial memory), whereas the multiple-choice task assessed the ability to flexibility recall the global representation from multiple orientations (i.e., spatial flexibility).

2.1.3.2.1. Multiple-choice. The multiple-choice task was programmed using E-Prime 2.0 software (1412 × 1059 pixels) and was presented on a 17-inch Dell desktop computer running Windows 7 (Intel Core i7 CPU 860 @ 2.80 GH_Z). This task was a modified version of the JRD task (judgment of relative direction: see Shelton & McNamara, 2001) and assessed participants' ability to recall individual spatial locations from one of four headings aligned with each room of the dollhouse (i.e., Side A: living room; Side B: bedroom; Side C: kitchen; Side D: bathroom; see Fig. 1). Prior to the task, participants were instructed to, "Imagine you have a map that depicts the entire dollhouse from above." For each trial, participants viewed a blank map of the dollhouse (i.e., a grey circle) that depicted the location of one piece of furniture ("heading location"). This piece of furniture established the map's orientation and was always positioned at the bottom of the map, such that furniture from the living room, bedroom, kitchen, and bathroom established headings aligned with sides A, B, C, and D, respectively (see Fig. 2). From this perspective, participants chose the correct location of a second piece of furniture ("target location"). Participants used the keyboard to record their response, and selected the key associated with one of four possible locations presented on the map (see Fig. 3).

There were 40 total trials, randomly counterbalanced by heading (10 per heading). For each global judgment, heading and target locations occupied different rooms (e.g., heading: *toy shelves*; target: *sink*; see Fig. 3). To create the four possible locations, two furniture locations from the target room (i.e., one correct, one foil) were flipped along the map's horizontal and vertical axes, yielding the correct location and three foils – correct room/incorrect location, incorrect room/correct location, and incorrect room/incorrect location. This design created meaningful errors, such that *when* subjects erred we could gain insight into *how* they erred. For accuracy, performance was scored as the proportion of correct responses over 40 trials. For errors, we calculated the proportion of times participants chose the "correct room/incorrect location" foil when they made an error (correct room, incorrect location errors/total errors).

2.1.3.2.2. Map-building. The map-building task was presented in Power Point on a 17-inch Dell desktop computer running Windows 7 (Intel Core i7 CPU 860 @ 2.80 GH_Z). For this task, participants constructed a map of the dollhouse's global layout by placing the

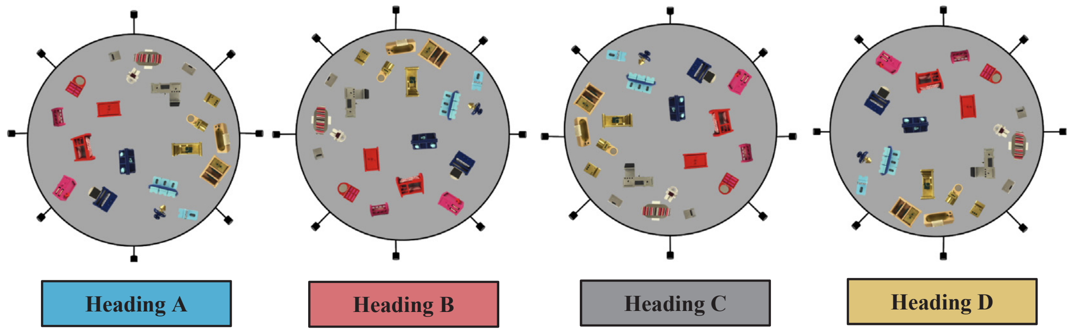

Fig. 2. Aerial views of the dollhouse aligned with each possible heading.

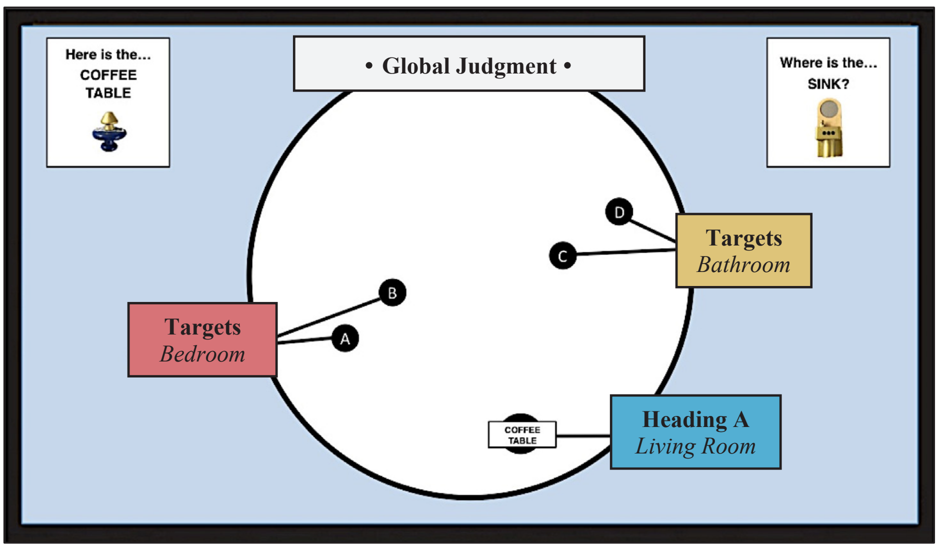

Fig. 3. The multiple-choice task. Depiction of a global spatial judgment aligned with heading A. Text boxes containing the labels "Global Judgment," "Targets, Bedroom," "Targets, Bathroom," and "Heading A, Living Room" were not present during the task; they are presented here for the reader's clarification.

furniture in its proper location. Labeled black circles, listed alphabetically to the left of the map, represented each piece of furniture. Uniform labeled symbols were selected in lieu of icons to increase variance, as well as mitigate the potential effects of relative furniture size and/or orientation on responses. Performance was scored using a bidimensional regression analysis (Friedman & Kohler, 2003; Tobler, 1994).

2.1.3.3. Psychometrics. All psychometrics were presented in paper and pencil format and administered last, in the order described below. The Spatial Orientation Test (SOT: Kozhevnikov & Hegarty, 2001; revised by Hegarty & Waller, 2004) and Mental Rotation Test (MRT: Vandenberg & Kuse, 1978) are two objective measures that assess spatial transformations – i.e., spatial perspective taking and mental rotation, respectively.

2.1.3.3.1. Spatial orientation test (SOT). The SOT assesses the ability to imagine various perspectives within a small-scale spatial array. Participants are shown an array of seven objects and must imagine standing at one object while facing another. From this perspective, participants draw an arrow to indicate the location of a third object. The spatial array is constant across 12 trials, with the imagined perspective and target location differing between trials. Performance was calculated as the mean angular distance between the correct and recorded response, yielding an overall error score.

2.1.3.3.2. Mental rotation test (MRT). The MRT assesses the ability to imagine 3-dimensional objects from various perspectives. Each trial presents a target object composed of small cubes and four alternative objects – two novel objects and two rotated versions of the target. Participants must discriminate between the alternatives by selecting the two objects that are rotated versions of the target. For each trial, participants could earn a maximum of 4 points (i.e., responses were quantified as follows: correct response = 2 points; incorrect response = -2 points; and no response = 0 points) and performance was calculated as the mean score across 24 trials.

2.1.4. Design

Using a counterbalanced between-subjects design, participants were assigned to one of five conditions[1]: 1. Static Views (SV: n = 25; 4 males/21 females; M_{age} = 20.84 years, *SD* = 3.10); 2. Passive Array Rotation (PAR: n = 25; 8 males/17 females; M_{age} = 22.72 years, *SD* = 9.33); 3. Active Array Rotation (AAR: n = 25; 4 males/21 females; M_{age} = 20.32 years, *SD* = 3.11); 4. Passive Perspective Taking (PPT: n = 25; 4 males/21 females; M_{age} = 20.32 years, *SD* = 1.57); or 5. Active Perspective Taking (APT: n = 25; 9 males/16 females; M_{age} = 20.28 years, *SD* = 2.19). Within each condition, the first room viewed at encoding was also counterbalanced (i.e., startview; see Procedure), yielding 20 between-subject cells.

2.1.5. Procedure

The experiment consisted of two phases: an encoding phase, in

[1] In Experiment 1, four participants were excluded from analyses due to experimenter error (SV), failure to complete the experiment (SV), prior knowledge of the experiment's aims (PPT), or rote clicking through the multiple-choice task (APT). Thus four additional participants were added to maintain even sample sizes across conditions.

which participants viewed the dollhouse stimulus, and a testing phase, in which participants completed the dependent measures detailed above. In the encoding phase, the manner in which participants viewed the dollhouse differed by condition; the testing phase was identical across all five conditions.

2.1.5.1. Encoding phase. Prior to entering the encoding room, the experimenter read an explanatory script according to condition assignment. Participants were informed that they would view a dollhouse and should try to remember as much as possible about the dollhouse, including the names of the furniture and how the furniture was arranged. Next, the participant put on noise-minimizing headphones and was led into the encoding room blindfolded (to control total encoding time). Once inside, the participant was placed in front of the dollhouse with the dollhouse positioned to one of four startviews (i.e., Side A: living room; Side B: bedroom; Side C: kitchen; Side D: bathroom; see Fig. 1).

The encoding phase began when the participant removed the blindfold and consisted of eight 15-s study sessions, yielding two study sessions per side. The first four study sessions presented the dollhouse in a clockwise sequence, whereas this sequence reversed for the last four sessions (for an animated depiction of the viewing sequence with startview set to side A, see the link in Fig. 2). This design yielded four viewing sequences according to startview (i.e., Side A: A, B, C, D, C, B, A, D; Side B: B, C, D, A, D, C, B, A; Side C: C, D, A, B, A, D, C, B; and Side D: D, A, B, C, B, A, D, C). Thus all participants viewed each side of the dollhouse twice, once from each direction. The conditions differed only by the manner in which one view transitioned to the next.

The control condition (Static Views, SV) presented the dollhouse as a series of segmented, static views. After each study session, participants replaced their blindfold and the experimenter rotated the dollhouse 90 degrees to yield the next static view. This process repeated for all eight study sessions. For the remaining four conditions, visual flow was continuous. Participants did not replace their blindfold after each study session and thus experienced the transition between views. However, two factors varied between the four conditions – the nature of the viewpoint transition (i.e., rotation of the dollhouse versus participant movement around it) as well as the agent that generated the transition (i.e., experimenter versus participant).

In the array rotation conditions, the dollhouse rotated during each transition. Participants watched as the experimenter rotated the dollhouse from one static view to the next (Passive Array Rotation, PAR) or, participants manually rotated the dollhouse in a direction specified by the experimenter (Active Array Rotation, AAR). The perspective taking conditions also contrasted passive versus active transitions, but differed in that the dollhouse remained stable while the participant moved around it. In the Passive Perspective Taking condition (PPT), participants were seated on a mobile stool and were pushed around the dollhouse, whereas in the Active Perspective Taking condition (APT), participants walked around the dollhouse and stopped when centrally aligned with the next view (see Fig. 4). It is important to note that for the active conditions (AAR, APT), the experimenter dictated the direction of rotation/movement using non-spatial language (e.g., “Rotate the dollhouse this way. Walk that way.”). Phrases such as “right/left” and “clockwise/counter clockwise” were never used, as these terms could prompt verbal coding of direction.

Observations from pilot work showed that on average, participants rotated the dollhouse (AAR) or walked around it (APT) at an approximate rate of 2 s per transition. To control total viewing time between the passive (PAR, PPT) and active (AAR, APT) conditions, this rate of rotation was applied to the passive conditions. For the control condition (SV), pilot work revealed a similar pattern; removal/replacement of the blindfold also averaged about 2 s. Thus total encoding time was relatively constant across all five conditions. All participants encoded the dollhouse for approximately 2.23 min (8 static views + 7 transitions; 15 s per view, 2 s per transition).

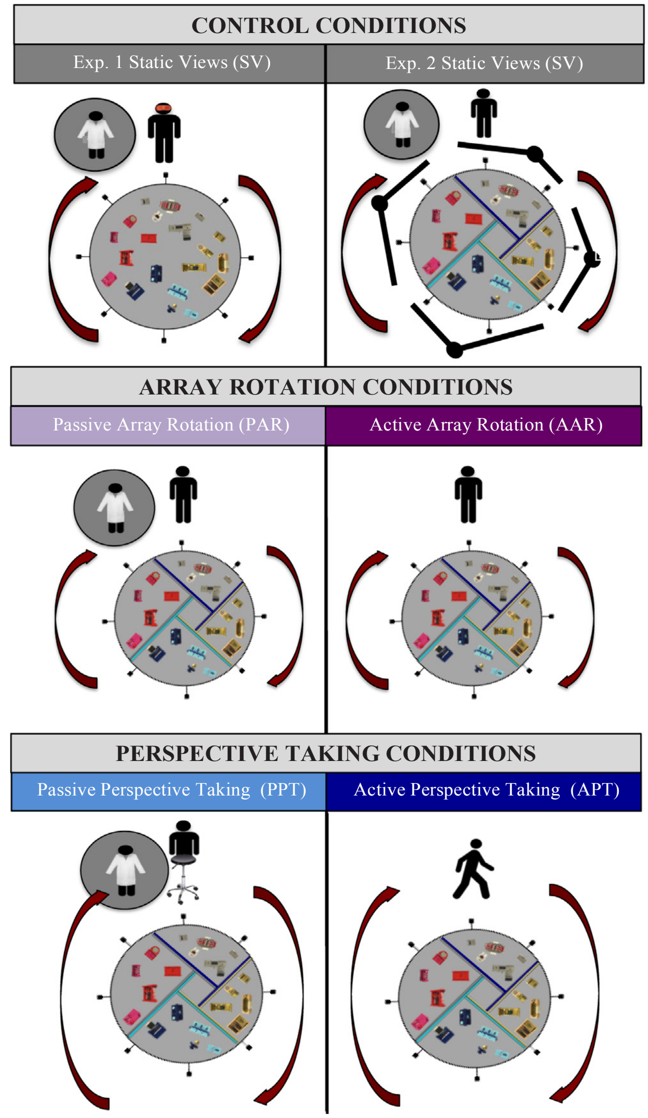

Fig. 4. Depiction of viewpoint transitions by condition. The control condition differed across experiments; the remaining conditions were identical (and are depicted using the dollhouse stimulus from Exp. 2). For an animated version, see: https://www.youtube.com/watch?v=63rsV-YppSk.

2.1.5.2. Testing phase. Following the encoding phase, the experimenter explained that the participant would complete a series of tests pertaining to the dollhouse and should think about the dollhouse while walking to the testing room. Walk time from the encoding room to the testing room was recorded. In the testing room, participants sat at a large desk facing a centrally located desktop computer and completed the dependent measures in the following order: 1. Furniture-Name (4 min.); 2. Furniture-Room (3 min.); 3. Multiple-Choice; 4. Map-Building; 5. Spatial Orientation Test (5 min.); and 6. Mental Rotation Test (6 min.).

2.2. Results

2.2.1. Non-spatial measures

All measures are analyzed in the order presented at test. For non-spatial measures, performance was analyzed using 5 (condition) × 4 (startview) factorial ANOVAs. However, it is important to note that performance on both non-spatial measures was quite high and basically at ceiling across conditions.

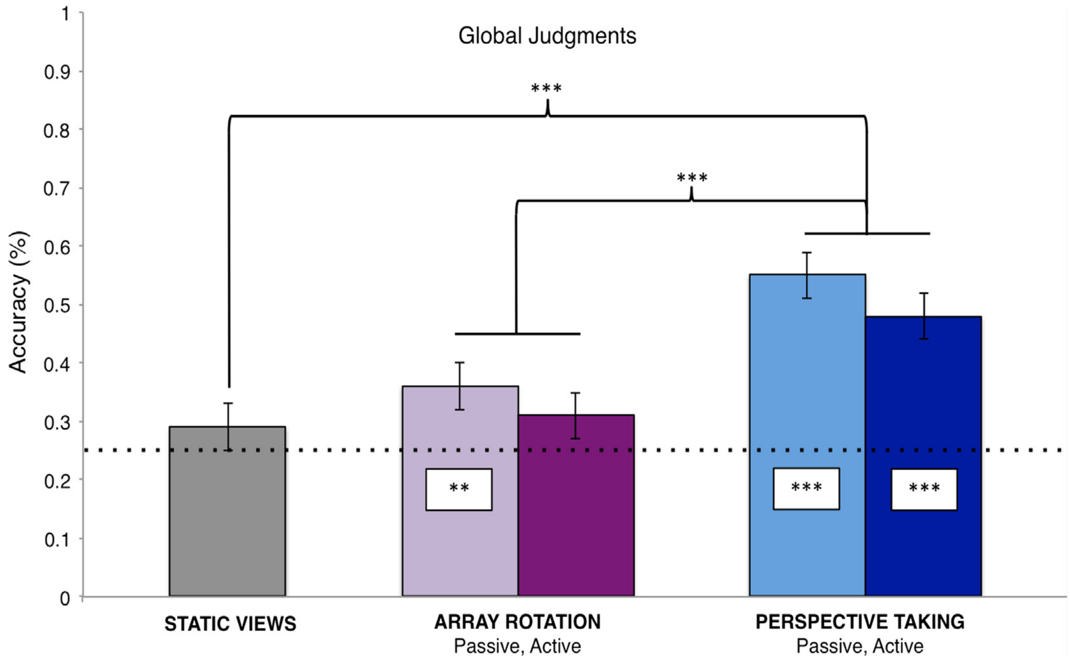

Fig. 5. The multiple-choice task. Experiment 1 spatial performance by condition (± SEM). $^{***}p < .001$, $^{**}p < .01$.

2.2.1.1. Furniture-name. Performance on the furniture-name task did not significantly differ by condition, $F_{(4, 105)} = 1.24$, $p = .30$, $\omega_p^2 = .007$, or startview, $F_{(3, 105)} = 0.25$, $p = .86$, $\omega_p^2 = .00$, and the condition ∗ startview interaction was not significant, $F_{(12, 105)} = 0.78$, $p = .67$, $\omega_p^2 = .00$.

2.2.1.2. Furniture-room. Performance on the furniture-room task was similar to that detected on the furniture-name task. Performance did not significantly differ by condition, $F_{(4, 105)} = 0.61$, $p = .66$, $\omega_p^2 = .00$, or startview, $F_{(3, 105)} = 1.04$, $p = .38$, $\omega_p^2 = .00$, and the condition ∗ startview interaction was not significant, $F_{(12, 105)} = 0.65$, $p = .80$, $\omega_p^2 = .00$.

2.2.2. Spatial measures

For the multiple-choice and map-building tasks, spatial performance was analyzed in three steps. First, we ran 5 (condition) × 4 (startview) factorial ANOVAs to examine if spatial performance differed by condition, and if this effect varied by the first viewpoint presented at encoding. Next, having detected significant main effects of condition only, we ran three complex contrasts to further examine the nature of this effect. Specifically, we compared the SV condition to the AR and PT conditions (i.e., collapsed across passive/active conditions) to examine if continuous visual flow enhanced spatial performance and if this effect differed by the type of transition used to generate it. Then, we compared the AR and PT conditions to examine the effect of transition type with visual flow held constant. Seeing that continuous visual flow was advantageous only when paired with movement around a stable array (i.e., in the perspective taking conditions), we ran one final pairwise contrast to examine if active perspective taking (APT) provided an additional advantage over passive movement (PPT).

2.2.2.1. Multiple-choice. For the multiple-choice task, the 5 (condition) × 4 (startview) factorial ANOVA yielded a significant main effect of condition only, $F_{(4, 105)} = 10.68$, $p < .001$, $\omega_p^2 = .24$. The main effect of startview, $F_{(3, 105)} = 0.59$, $p = .62$, $\omega_p^2 = .00$, and the condition ∗ startview interaction, $F_{(12, 105)} = 1.51$, $p = .13$, $\omega_p^2 = .05$, were not significant. Collapsed across active and passive conditions, complex contrasts showed that continuous visual flow generated by array rotation ($M = .34$, $SD = .16$) provided no advantage over static viewing in the SV condition ($M = .30$, $SD = .12$), $t_{(120)} = 0.96$, $p = .34$, $d = 0.28$. But, when generated by movement around a stable array in the PT conditions ($M = .51$, $SD = .21$), continuous visual flow significantly improved spatial performance compared to the SV, $t_{(120)} = 5.10$, $p < .001$, $d = 1.23$, and array rotation conditions, $t_{(120)} = 5.08$, $p < .001$, $d = 0.91$. Last, a pairwise contrast showed that the perspective taking advantage did not significantly differ between passive ($M = .55$, $SD = .22$) and active conditions ($M = .48$, $SD = .20$), $t_{(120)} = 1.52$, $p = .13$, $d = 0.33$. Comparisons to chance (25 percent) revealed a similar pattern, with one exception. Performance in the SV, $t_{(24)} = 1.89$, $p = .07$, and AAR conditions, $t_{(24)} = 1.96$, $p = .06$, did not significantly differ from chance. However, performance in the PAR condition was significantly greater than chance, $t_{(24)} = 3.36$, $p = .003$, as was performance in both the passive and active PT conditions (PPT: $t_{(24)} = 6.86$, $p < .001$; APT: $t_{(24)} = 5.54$, $p < .001$; see Fig. 5).

Importantly, although a one-way ANOVA showed that mean response times (in seconds) significantly differed by condition, $F_{(4, 120)} = 4.66$, $p = .002$, $\omega^2 = .02$, Bonferroni-corrected contrasts ($\alpha = .005$) showed that only participants in the passive PT condition took significantly longer than those in the active AR and SV conditions ($ps \leq .002$). The remaining eight contrasts were not significant ($ps \geq .01$), suggesting that the PT advantage as a whole likely did not stem from a speed/accuracy tradeoff.

Next, we calculated the proportion of correct room errors (i.e., correct room, incorrect location errors/total errors) to examine if error-type differed between the SV, AR, and PT conditions. Because perspective taking provided a significant advantage in terms of accuracy, we were particularly interested to see if this advantage extended to errors. That is, when participants in the PT conditions erred, were they more likely to choose an incorrect location within the correct room? As expected, complex contrasts showed that those in the PT conditions ($M = .53$, $SD = .24$) made significantly more correct room errors than those in the SV ($M = .33$, $SD = .15$), $t_{(120)} = 4.13$, $p < .001$, $d = 1.00$, and AR conditions ($M = .35$, $SD = .15$), $t_{(120)} = 4.67$, $p < .001$, $d = 0.90$; there was no difference between the SV and AR conditions, $t_{(120)} = 0.32$, $p = .75$, $d = 0.13$. Last, a pairwise contrast showed no difference between passive ($M = .56$, $SD = .25$) and active PT ($M = .49$, $SD = .24$), $t_{(120)} = 1.38$, $p = .17$, $d = 0.29$. Comparisons to

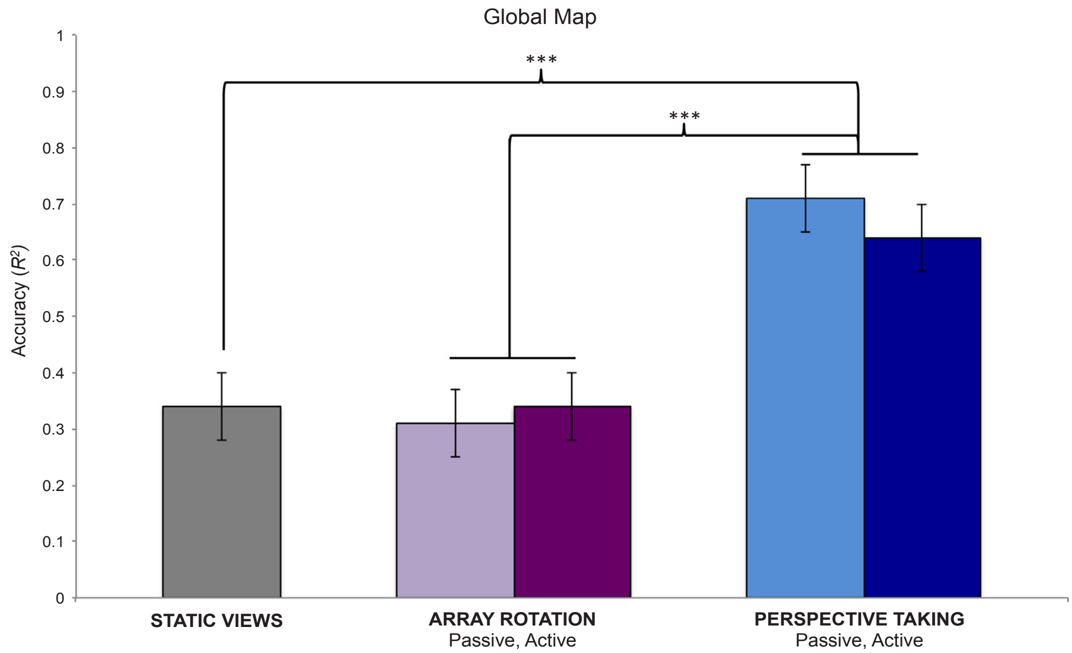

Fig. 6. The map-building task. Experiment 1 spatial performance by condition (± SEM). $^{***}p < .001$.

chance (33 percent) showed that only those in the PT conditions made correct room errors significantly greater than chance level (PPT: $t_{(24)} = 4.73$, $p < .001$; APT: $t_{(24)} = 3.35$, $p = .003$). In the remaining conditions, the proportion of correct room errors did not significantly differ from chance.

Last, when participants selected a location within the correct room, we examined if perspective taking enhanced their ability to recall the fine grain spatial location (i.e., correct location/total correct room selections). Complex contrasts showed an advantage for the PT conditions ($M = .68$, $SD = .15$) over the SV ($M = .57$, $SD = .12$), $t_{(120)} = 3.12$, $p = .002$, $d = 0.81$, and AR conditions ($M = .59$, $SD = .16$), $t_{(120)} = 3.04$, $p = .003$, $d = 0.58$. There was no difference between the SV and AR, $t_{(120)} = 0.64$, $p = .52$, $d = 0.15$, nor between the passive ($M = .70$, $SD = .15$) and active PT conditions ($M = .66$, $SD = .15$), $t_{(120)} = 0.96$, $p = .34$, $d = 0.26$.

2.2.2.2. Map-building. Performance on the map-building task was similar to that detected on the multiple-choice task. The 5 (condition) × 4 (startview) factorial ANOVA yielded a significant main effect of condition only, $F_{(4,\ 105)} = 9.84$, $p < .001$, $\omega_p^2 = .22$; the main effect of startview, $F_{(3,\ 105)} = 0.82$, $p = .48$, $\omega_p^2 = .00$, and the condition ∗ startview interaction, $F_{(12,\ 105)} = 0.95$, $p = .50$, $\omega_p^2 = .00$, were not significant. Because map-building performance violated the normality assumption (Kolmogorov-Smirnov: $ps \leq .003$; Shapiro-Wilk: $ps \leq .001$), the Kruskal-Wallis test for non-parametric data was used to confirm the significant effect of condition, χ^2 (4, N = 125) = 28.01, $p < .001$. Collapsed across passive and active conditions, Mann-Whitney U contrasts showed that those in the perspective taking conditions ($M = .66$, $SD = .30$) significantly outperformed those in the SV ($M = .34$, $SD = .27$), $U = 267.00$, $p < .001$, $r = .46$, and AR conditions ($M = .32$, $SD = .31$), $U = 584.00$, $p < .001$, $r = .46$; there was no difference between the SV and AR conditions, $U = 570.00$, $p = .54$, $r = .07$. Last, a pairwise contrast showed that performance did not differ between the passive ($M = .71$, $SD = .28$) and active PT conditions ($M = .64$, $SD = .33$), $U = 263.00$, $p = .34$, $r = .14$ (see Fig. 6). Importantly, a one-way ANOVA showed that the PT advantage did not stem from a speed/accuracy tradeoff, $F_{(4,\ 120)} = 0.61$, $p = .66$, $\omega^2 = .00$.

2.2.3. Preferred orientation

Because participants could construct their maps from any viewpoint, the map-building task was used to assess the preferred orientation of the spatial representation (i.e., map heading; see Fig. 2). The map heading could relate to any of the four startviews presented at encoding (i.e., living room, bedroom, kitchen, or bathroom), thus we used a 4 (startview) × 4 (map heading) chi-square to examine if participants aligned their maps with the first viewpoint experienced collapsed across conditions. The chi-square confirmed our prediction, and showed that participants were significantly more likely to align their maps with the first viewpoint compared to any other (n = 77/125; 62 percent), $\chi^2(9) = 93.97$, $p < .001$, Cramér's $V = .50$ (see Fig. 7), suggesting that in the absence of salient geometric cues (as in the current study), the first viewpoint served as the preferred orientation. This is, the first viewpoint served as the principal vector used to anchor relative inter-object spatial location (i.e., the spatial reference frame).

2.2.3.1. Map-building. Because the majority of participants chose to align their maps with the first viewpoint, we examined if map-building performance differed for startview-aligned and misaligned maps. Indeed, a one-way ANOVA showed that participants who aligned their maps with the first viewpoint ($M = .56$, $SD = .34$) significantly outperformed those who did not ($M = .32$, $SD = .29$), $F_{(1,\ 123)} = 16.44$, $p < .001$, $\omega^2 = .04$ (effect confirmed by the Kruskal-Wallis test: χ^2 (1, N = 125) = 14.88, $p < .001$). The significant effect of startview alignment on map-building performance warranted further investigation of the perspective taking advantage. Specifically, we examined if the PT advantage differed for startview-aligned and misaligned maps. To examine this question, we added condition to the one-way ANOVA above.

As expected, a 5 (condition) × 2 (alignment: startview-aligned vs. startview-misaligned) ANOVA yielded significant main effects of condition, $F_{(4,\ 115)} = 4.97$, $p = .001$, $\omega_p^2 = .11$, and alignment, $F_{(1,\ 115)} = 6.85$, $p = .01$, $\omega_p^2 = .04$. Interestingly, the condition ∗ alignment interaction was also significant, $F_{(4,\ 115)} = 2.52$, $p = .05$, $\omega_p^2 = .05$. Kruskal-Wallis tests showed that performance significantly differed by condition for startview-aligned maps only, χ^2 (4, N = 77) = 16.17, $p = .003$. When maps were not oriented to the first viewpoint, performance was equally poor across conditions, χ^2 (4, N = 48) = 8.14,

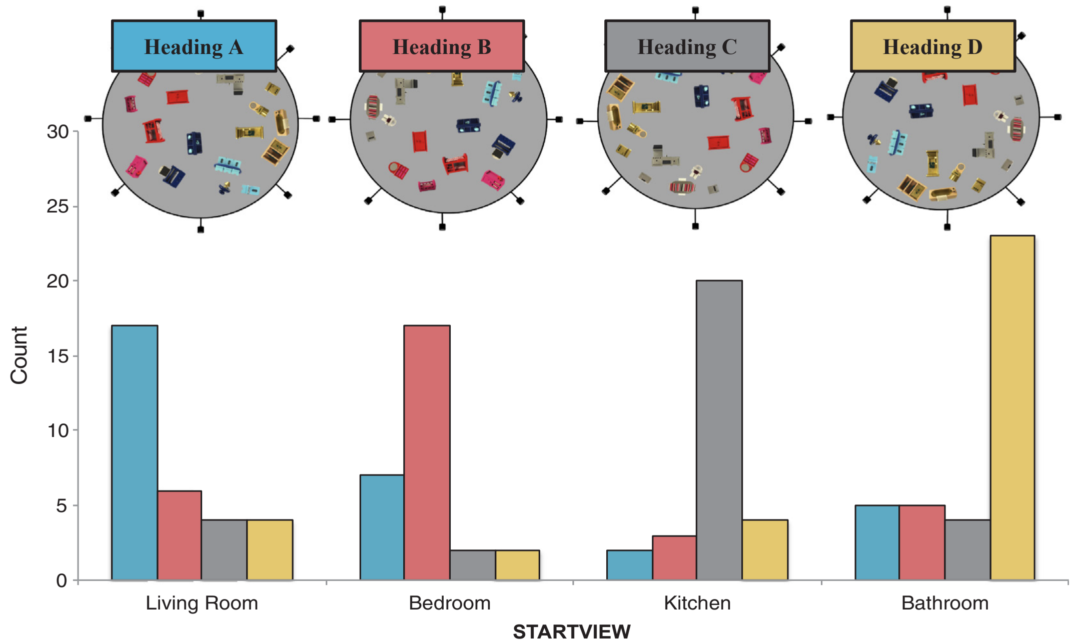

Fig. 7. The map-building task. Experiment 1 distribution of global headings by startview.

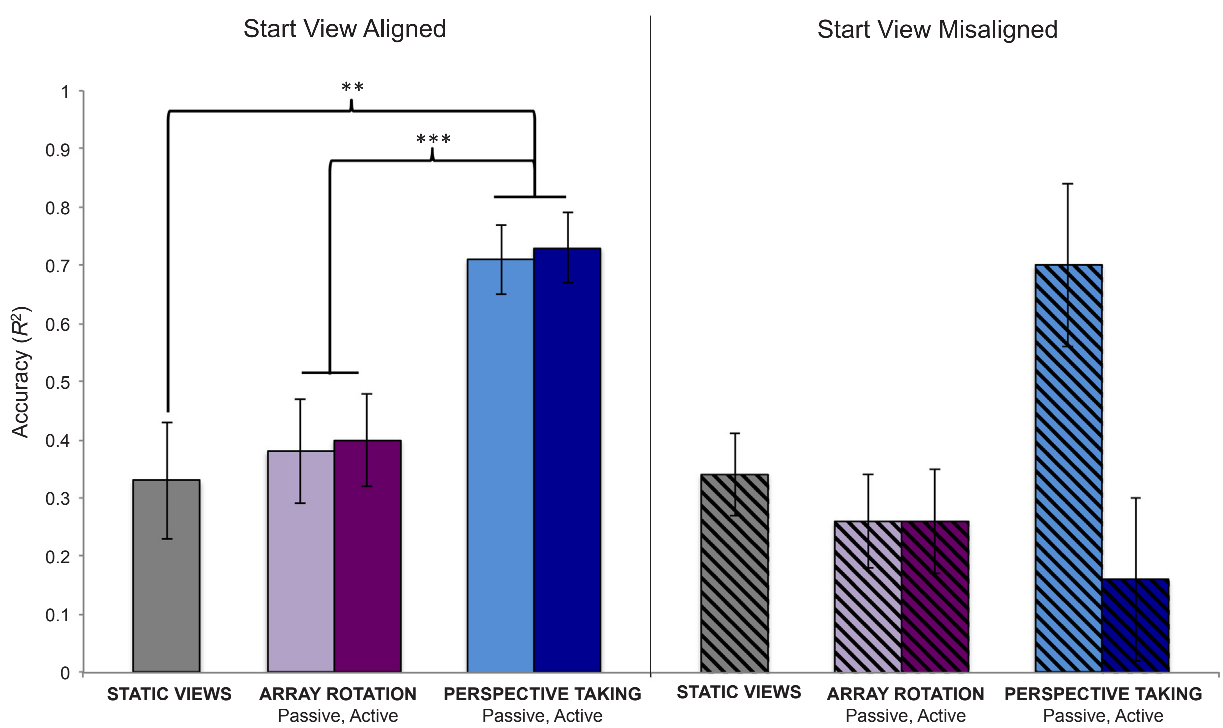

Fig. 8. The map-building task. Experiment 1 spatial performance for startview-aligned and startview misaligned global maps by condition (± SEM). $^{***}p = .001$, $^{**}p < .01$.

$p = .09$ (Note: high performance in the PPT condition likely reflects the small number of participants in this group, $n = 4$). Investigation into the effect of condition for startview-aligned maps revealed a similar pattern to that detected above – that is, the effect was driven by the PT conditions. Mann-Whitney U contrasts showed that those in the PT conditions ($M = .72$, $SD = .27$) significantly outperformed those in the SV ($M = .33$, $SD = .27$), $U = 68.00$, $p = .002$, $r = .42$, and AR conditions ($M = .38$, $SD = .34$), $U = 276.00$, $p = .001$, $r = .41$. There was no difference between the SV and AR conditions, $U = 114.00$, $p = .93$, $r = .02$, nor between the passive ($M = .71$, $SD = .28$) and active PT conditions ($M = .73$, $SD = .27$), $U = 220.00$, $p = .99$, $r = .002$ (see Fig. 8).

2.2.3.2. Multiple-choice. The significant effect of startview alignment on map-building performance warranted further investigation of multiple-choice performance. Specifically, we reanalyzed multiple-choice performance using a 5 (condition, *between-subjects*) × 4 (startview, *between-subjects*) × 4 (trial heading, *within-subjects*) mixed-model ANOVA to examine if performance for startview-aligned trials was superior to that for misaligned trials, and if this effect differed by

Table 1
Experiment 1 correlations, sample sizes, means, and standard deviations for dependent measures.

Measure	1	2	3	4	5	6	N	Mean	SD
1. Furniture-Name	–						125	.92	.13
2. Furniture-Room	.40**	–					125	.97	.07
3. Multiple-Choice	.28**	.20*	–				125	.40	.20
4. Map-Building (R^2)	.27**	.17	.75**	–			125	.47	.34
5. SOT (Error)	-.36**	-.33**	-.39**	-.18	–		116	46.64	27.35
6. MRT	.22*	.04	.43**	.32**	-.38**	–	107	.98	.87

Note. Bivariate correlations, means, and standard deviations are collapsed across conditions. All measures are entered into table in the order in which they were presented at test; horizontal numbered entries refer to vertical numbered entries of dependent measures. Spatial measure/psychometric correlations are boxed. For mean and standard deviation columns – save for SOT – higher values indicate better performance.
SOT = Spatial Orientation Test; MRT = Mental Rotation Test.

condition, as detected for the map-building task. As expected, the main effect of condition was significant, $F_{(4,\ 105)} = 10.68$, $p < .001$, $\eta_p^2 = .29$. Importantly, however, the startview ∗ heading, $F_{(9,\ 105)} = 1.51$, $p = .14$, $\eta_p^2 = .04$, and condition ∗ startview ∗ heading interactions, $F_{(36,\ 105)} = 0.68$, $p = .92$, $\eta_p^2 = .07$, were not significant, suggesting that performance did not significantly differ between startview-aligned and misaligned trials, with PT providing a universal advantage.

2.2.4. Psychometrics

The SOT and MRT[2] significantly correlated with performance on the multiple-choice and map-building tasks, with one exception – SOT/map-building, $r_{(114)} = -.18$, $p = .06$ (see Table 1). Given the significant spatial correlations, we wanted to check if spatial ability was evenly distributed by our counterbalanced assignment. An exploratory factor analysis of psychometric performance generated one factor that explained 83 percent of the variance, thus ensuring that the SOT and MRT loaded onto the same cognitive construct – i.e., the ability to perform mental transformations. Next, a one-way ANOVA showed that the distribution of Factor 1 scores (i.e., spatial ability) did not significantly differ by condition, $F_{(4,\ 102)} = 1.59$, $p = .18$, $\omega^2 = .00$, confirming the success of our counterbalanced assignment. Last, we examined if spatial ability moderated the effect of condition on spatial performance. To investigate this question, we added spatial ability as a covariate to the initial 5 (condition) × 4 (startview) factorial ANOVAs and reexamined spatial performance on the multiple-choice and map-building tasks. For both tasks, the ANCOVA yielded significant main effects of condition (*ps* < .001) and spatial ability (*ps* ≤ .004). Importantly, spatial ability did not significantly interact with any other factor (*ps* ≥ .16), suggesting this construct did not moderate any previously detected effects.

2.3. Discussion

In Experiment 1, non-spatial performance was, as expected, quite high and did not differ by condition. Spatial performance, however, revealed a consistent advantage for moving around the array. Participants who circled the dollhouse (either passively or actively) showed significantly enhanced spatial memory from the preferred orientation and flexible recall from multiple orientations. However, although participants viewed the array from multiple viewpoints, the first viewpoint served as the preferred orientation of the stored representation. Together, these findings suggest that array stability is key to spatial memory and flexible recall of a spatial configuration.

The data contrast with Holmes et al. (2017), who found a general advantage for continuous visual flow, no matter the movement used to generate it. These conflicting findings may be explained by Holmes' much simpler (8 spatial locations) and interwoven spatial array (i.e., a "landscape", where part of the "oak forest" overlapped the "monument," the "sand dunes" wrapped around the "evergreen forest," etc.; see Holmes et al., 2017, Fig. 1a). Because these structures were intertwined, the landscape array may have been perceived as a singular multi-component object, versus a multi-object scene, as in the current study. Visual and/or haptic feedback can facilitate spatial updating following rotation or translation of an object, often to a level comparable to observer movement (Creem-Regehr, 2003, Exp. 3; Creem-Regehr, 2004; Wraga et al., 2000, Exp. 3). However, when applied to multi-object scenes, such visual and/or haptic feedback does not provide an advantage equivalent to that of observer movement (Wang & Simons, 1999; see Creem-Regehr, 2004). Perhaps the larger and less unified array in the current study taxed the spatial system so that continuous visual flow was no longer sufficient to track such a large quantity of locations (20 pieces of furniture) across viewpoint changes generated by array rotation. Although some studies show no effect of set-size on spatial updating (e.g., Harrison, 2007; Hodgson & Waller, 2006; but see Wang et al., 2006), all have examined the effect of set-size at test, after learning specific spatial arrays, of various complexity, and often to criterion.

In Experiment 1, the entire spatial configuration could be viewed from a single vantage point. However, in the real world, complex displays or environments are often learned piecemeal in a series of partial views, e.g., as we move from room to room or along sections of crowded city streets. Because we often move within and around spatial environments that need to be integrated, we may be better adapted to learn spatial information via observer movement. In fact, given enhanced cognitive load, active movement might create more benefits than passive movement.

[2] Due to experimental time restraints, not all participants completed the psychometrics, as the SOT (n = 116/125, 93 percent) and MRT (n = 107/125, 86 percent) were administered last, in that order.

3. Experiment 2

In Experiment 2, we examined the effect of viewpoint transitions when spatial information must be integrated to acquire global spatial knowledge. Participants viewed the layout of dollhouse furniture from four viewpoints that presented small chunks of the global configuration. Each viewpoint presented one room of a dollhouse (i.e., living room, bedroom, kitchen, and bathroom) that contained five pieces of furniture. Thus for global spatial judgments, participants had to integrate spatial locations across discrete learning experiences.

3.1. Methods

3.1.1. Participants

One hundred and twenty-five Temple University undergraduates participated in Experiment 2 (M_{age} = 21.09 years, SD = 4.38, range: 18–48). Split by sex, the sample was composed of 35 males (M_{age} = 21.26 years, SD = 4.28, range: 18–42) and 90 females (M_{age} = 21.02 years, SD = 4.44, range: 18–48). As in Experiment 1, participants were recruited via Temple University's Undergraduate Research Participation Website (SONA Systems) and granted course credit for their participation.

3.1.2. Dollhouse stimulus

The dollhouse stimulus was identical to that in Experiment 1, save for one modification – the global layout was split into four rooms by 2-foot foam boards attached to the dollhouse's circular base (see Fig. 9). Thus participants could only view one room per study session (i.e., five pieces of furniture per local layout). The use of a circular base paired with a square, featureless enclosure helped eliminate allocentric cues (i.e., landmarks/geometric cues) that may have prompted spatial integration at encoding via automatic spatial updating (e.g., local layouts coded along a single frame of reference). This design helped ensure that all participants – independent of condition – coded each local layout separately, and thus stored the dollhouse's global layout as multiple, discrete spatial representations in memory (i.e., one representation per room).

3.1.3. Measures

All measures were identical across experiments, save for two additions. First, the multiple-choice and map-building tasks included local spatial measures that assessed spatial memory for furniture locations that belonged to the same room. These additions permitted direct comparison of local versus global spatial memory; that is, memory for locations viewed simultaneously versus sequentially (i.e., memory for furniture locations within and between rooms, respectively). Second, we added a serial recall task to assess participants' sequential memory for the order in which they viewed the rooms during encoding.

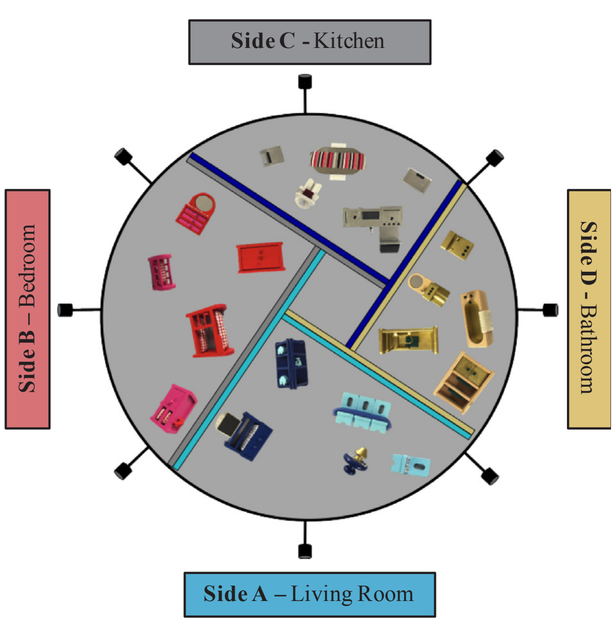

Fig. 9. Aerial view of the dollhouse stimulus in Experiment 2.

3.1.3.1. Spatial measures. The spatial measures were designed to assess local and global spatial memory. Both tasks assessed local spatial memory from preferred orientations only (i.e., from headings aligned with each room). However, the tasks assessed global spatial memory from both preferred and non-preferred orientations. As in Experiment 1, the multiple-choice task required participants to recall the global layout from multiple headings (i.e., global trials), whereas the map-building task did not (i.e., global map task). Thus, in Experiment 2, the map-building task assessed the accuracy of the integrated global representation, whereas the multiple-choice task assessed the ability to flexibly recall the integrated representation from multiple orientations. Importantly, although the dollhouse stimulus in Experiment 2 included walls, these borders were not presented in the local/global trials for the multiple-choice task, nor the global map for the map-building task; however, they were presented in the four local maps (see description of map-building task below).

3.1.3.1.1. Multiple-choice. The multiple-choice task was identical to that in Experiment 1 save for the addition of 40 local spatial judgments, yielding 80 total trials, randomly counterbalanced by heading (20 per heading). Within each heading, participants performed 10 global and 10 local judgments, yielding 40 trials per judgment type. Global judgments were identical across experiments and as in Experiment 1, heading and target locations always occupied different rooms (e.g., heading: *toy shelves*; target: *sink*). For local judgments, however, both locations occupied the same room (e.g., heading: *crib*; target: *dresser*; see Fig. 10). To create the four possible locations for local trials, two furniture locations (one correct, one foil) were flipped along the map's vertical axis only, as a horizontal flip would yield locations outside the room's spatial boundaries. Thus, all foils for local trials occupied the correct room but not the correct location, and were as follows – foil, inverse correct, and inverse foil.

3.1.3.1.2. Map-building. The map-building task was identical to that in Experiment 1 save for the addition of four local maps, one per room. The map-building task was administered in two parts – the global map, presented first, and four local maps, presented second. As in Experiment 1, participants constructed the global map from any heading (this task was screen recorded using Rylstim Screen Recorder to examine spatial integration strategy). For local maps, participants again constructed maps of the dollhouse, but did so one room at time. Each local map was labeled by room, and showed the walls of the room to-be-completed. The first map presented ("start map") never matched the first room viewed ("startview") and was counterbalanced by condition. In addition, the local maps' order of presentation never matched that at encoding to control priming effects between the local maps task and serial recall.

3.1.3.2. Sequential measures. Sequential measures assessed participants' memory for the learning sequence presented at encoding. The serial recall task assessed linear memory for the rooms' temporal order. The map-building task (specifically, the final layout of participants' global maps) was used to assess memory for the rooms' spatiotemporal sequence – that is, memory for the rooms' temporal order and position in space.

3.1.3.2.1. Serial recall. The serial recall task was presented in paper and pencil format. Participants were reminded that they viewed each room of the dollhouse twice, yielding eight total learning sessions, and then used a word bank containing all four rooms to list the rooms in the order viewed at encoding. The instructions read: *"Now, I want you to*

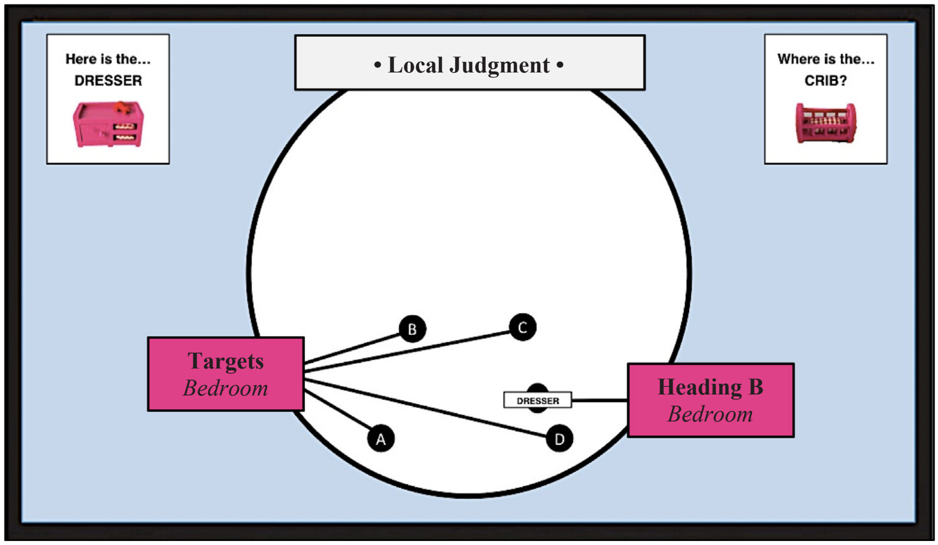

Fig. 10. The multiple-choice task. Depiction of a local spatial judgment aligned with heading B. Text boxes containing explanatory labels were not present during the task.

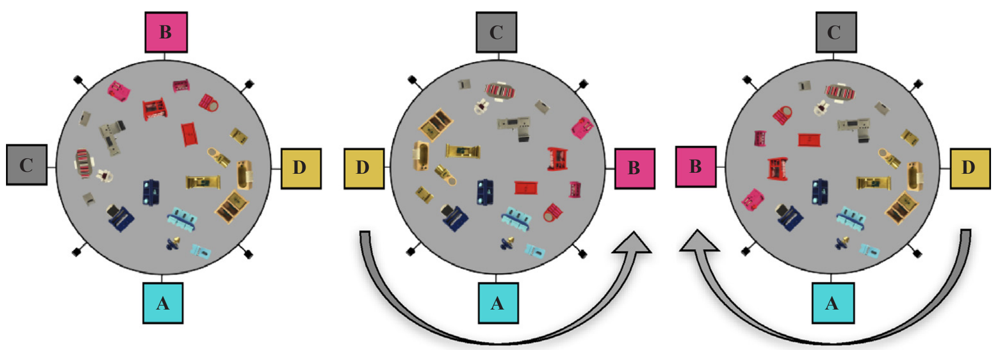

Fig. 11. Global maps. Depiction of sequential classifications.

think back to when you viewed each room of the dollhouse. You were shown each room twice. In the numbered spaces below, please list the rooms in the order you viewed them." Performance was scored as the proportion of correct responses for the first four learning sessions, the last four learning sessions, and overall.

3.1.3.2.2. Map-building. To assess memory for time and space, participants' global maps were categorized as one of three sequence-types: Incorrect, temporal sequence correct, or spatiotemporal sequence correct. Maps coded as "incorrect" ordered the rooms incorrectly along the temporal dimension (e.g., A. Living room; C. Kitchen; B. Bedroom; D. Bathroom). Maps coded as "temporal sequence correct" ordered the rooms correctly along the temporal dimension (A. Living Room; B. Bedroom; C. Kitchen; D. Bathroom), but the sequence was incorrect with respect to the rooms' spatial position (counterclockwise layout). Maps coded as "spatiotemporal correct" ordered the rooms correctly along both the temporal and spatial dimensions (A. Living Room; B. Bedroom; C. Kitchen; D. Bathroom – clockwise layout; see Fig. 11).

3.1.4. Design

As in Experiment 1, participants were assigned to one of five between-subjects conditions: 1. Static Views (SV: n = 25; 7 males/18 females; M_{age} = 19.89 years, *SD* = 1.51); 2. Passive Array Rotation (PAR: n = 25; 5 males/20 females; M_{age} = 21.52 years, *SD* = 5.16); 3. Active Array Rotation (AAR: n = 25; 9 males/16 females; M_{age} = 20.04 years, *SD* = 1.72); 4. Passive Perspective Taking (PPT: n = 25; 8 males/17 females; M_{age} = 23.32 years, *SD* = 7.16); or 5. Active Perspective Taking (APT: n = 25; 6 males/19 females; M_{age} = 20.68 years, *SD* = 2.81). Within each condition, two additional factors were counterbalanced: "startview" – the first room viewed at encoding, and "start map" – the first local map presented in the map-building task.

3.1.5. Procedure

The procedure for Experiment 2 was identical to that of Experiment 1 except for one modification. For the SV condition, visual occluders were used in lieu of a blindfold (see Fig. 4). Four opaque screens were placed in front of each room, and for each study session, the experimenter removed the occluder for 15 s, then replaced the occluder and rotated the dollhouse until the next room was aligned with the participant. This process repeated for all eight study sessions. As in Experiment 1, the use of occluders blocked the natural visual flow from one room to the next; however, and importantly, participants could now view the direction of each rotation. This was a necessary modification. Without directional knowledge, participants would be unable to accurately integrate partial spatial locations into a unified global representation. Finally, observations from pilot work revealed that removal/replacement of the occluders averaged about 2 s, similar to the time needed to remove/replace the blindfold in the SV condition for Experiment 1. Thus total encoding time was relatively constant across

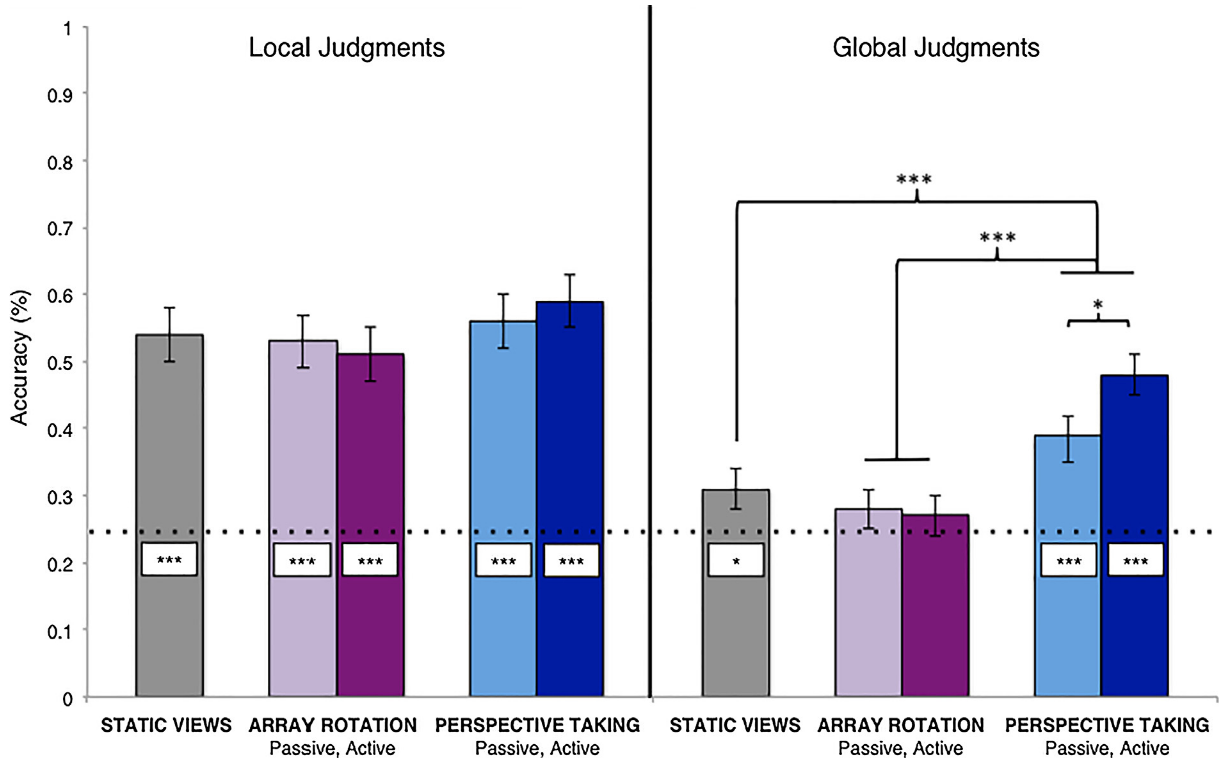

Fig. 12. The multiple-choice task. Experiment 2 spatial performance by condition (± SEM). $^{***}p \leq .001$, $^{*}p < .05$.

both experiments for all five conditions; All participants encoded the dollhouse for approximately 2.23 min (8 static views + 7 transitions; 15 s per view, 2 s per transition).

The testing phase was identical to that of Experiment 1 – save for the additions described above – and all participants completed the dependent measures in the following order: 1. Furniture-Name (4 min); 2. Furniture-Room (3 min); 3. Multiple-Choice (RT recorded); 4. Map-Building, *global map first* (RT recorded), *local maps second* (RTs recorded for each map); 5. Serial Recall (2 min); 6. SOT (5 min); and 7. MRT (6 min).

3.2. Results

3.2.1. Non-spatial measures

As in Experiment 1, all measures are analyzed in the order presented at test. For non-spatial measures, performance was analyzed using 5 (condition) × 4 (startview) ANOVAs.

3.2.1.1. Furniture-name. Performance on the furniture-name task did not significantly differ by condition, $F_{(4,\ 105)} = 1.67, p = .16, \omega_p^2 = .03$, or startview, $F_{(3,\ 105)} = 1.30$, $p = .28$, $\omega_p^2 = .007$, and the interaction was non-significant, $F_{(12,\ 105)} = 0.43$, $p = .95$, $\omega_p^2 = .00$.

3.2.1.2. Furniture-room. Furniture-room performance significantly differed by condition only, $F_{(4,\ 105)} = 3.53$, $p = .01$, $\omega_p^2 = .08$; the main effect of startview, $F_{(3,\ 105)} = 1.60$, $p = .19$, $\omega_p^2 = .02$, and the condition ∗ startview interaction were not significant, $F_{(12,\ 105)} = 1.03$, $p = .43$, $\omega_p^2 = .00$. However, because furniture-room performance was basically at ceiling across conditions (95–100 percent accuracy), the main effect of condition was not examined further.

3.2.2. Spatial measures

Spatial performance on the multiple-choice and map-building tasks was analyzed in four steps. First, we ran 5 (condition, *between-subjects*) × 2 (judgment-type: local vs. global spatial judgments, *within-subjects*) mixed-model ANOVAs to examine the effect of condition on spatial memory. Second, because the interaction was significant for both spatial measures, we ran two one-way ANOVAs to separately examine the effect of condition on local and global spatial memory (i.e., memory for locations within and between rooms, respectively). Third, having detected a significant effect of condition for global performance only, we ran three complex contrasts to further examine the nature of this effect. As in Experiment 1, we compared the SV condition to the AR and PT conditions (i.e., collapsed across passive/active conditions) to examine if continuous visual flow enhanced global performance and then contrasted the AR and PT conditions to examine global performance with visual flow held constant. As detected in Experiment 1, continuous visual flow enhanced global performance in the PT conditions only, thus we ran one final pairwise contrast to examine if active PT provided an additional advantage over passive movement.

3.2.2.1. Multiple-choice. For the multiple-choice task,[3] the mixed-model ANOVA yielded significant main effects of condition, $F_{(4,\ 118)} = 4.30$, $p = .003$, $\eta_p^2 = .21$, and judgment-type, $F_{(1,\ 118)} = 189.39$, $p < .001$, $\eta_p^2 = .65$, with performance on local trials ($M = .55$, $SD = .18$) significantly greater than that for global trials ($M = .34$, $SD = .16$). The condition ∗ judgment-type interaction was also significant, $F_{(4,\ 118)} = 3.14$, $p = .02$, $\eta_p^2 = .18$. One-way ANOVAs used to examine the effect of condition within judgment-type showed no effect of condition on local trials, $F_{(4,\ 118)} = 0.69$, $p = .60$, $\omega^2 = .001$. Across all conditions, local performance was relatively high and significantly greater than chance (25 percent; all $ps < .001$; see Fig. 12).

For global trials, however, performance significantly differed by condition, $F_{(4,\ 118)} = 9.27$, $p < .001$, $\omega^2 = .04$. Collapsed across active and passive conditions, complex contrasts showed that continuous visual flow generated by array rotation ($M = .27$, $SD = .08$) provided no

[3] Due to experimenter error, multiple-choice data missing from two participants in the PAR condition.

advantage over static viewing in the SV condition ($M = .31$, $SD = .13$), $t_{(118)} = 0.94$, $p = .35$, $d = 0.37$. But, when generated by movement around a stable array in the PT conditions ($M = .43$, $SD = .19$), continuous visual flow significantly improved global performance compared to the SV, $t_{(118)} = 3.59$, $p < .001$, $d = 0.74$, and array rotation conditions, $t_{(118)} = 5.49$, $p < .001$, $d = 1.15$. Last, a pairwise contrast showed that active perspective taking ($M = .48$, $SD = .19$) provided an additional boost over passive observer movement ($M = .38$, $SD = .19$), $t_{(118)} = 2.14$, $p = .04$, $d = 0.53$ (see Fig. 12).

Comparisons to chance (25 percent) revealed a similar pattern in that performance in the PT conditions was significantly greater than chance (PPT: $t_{(24)} = 3.86$, $p = .001$; APT: $t_{(24)} = 5.91$, $p < .001$). However, performance in the SV condition was also significantly greater than chance, $t_{(24)} = 2.13$, $p = .04$. Performance in the array rotation conditions did not significantly differ from chance (PAR: $t_{(24)} = 1.77$, $p = .09$; AAR: $t_{(24)} = 1.18$, $p = .25$; see Fig. 12).

In addition to accuracy, we also used the 5 (condition, *between-subjects*) × 2 (judgment-type, *within-subjects*) mixed-model ANOVA to examine response time data (in seconds). The omnibus yielded a significant main effect of judgment-type, $F_{(1,\ 118)} = 101.14$, $p < .001$, $\eta_p^2 = .46$, and a significant condition ∗ judgment-type interaction, $F_{(4,\ 118)} = 2.89$, $p = .02$, $\eta_p^2 = .09$; the main effect of condition was not significant, $F_{(4,\ 118)} = 0.81$, $p = .52$, $\eta_p^2 = .03$. Importantly, further investigation into the simple main effect of condition within judgment-type revealed that response times did not significantly differ by condition for local trials, $F_{(4,\ 118)} = 0.16$, $p = .96$, $\omega_p^2 = .00$, nor global trials, $F_{(4,\ 118)} = 1.62$, $p = .17$, $\omega_p^2 = .003$, suggesting that the PT advantage detected for global trials did not stem from a speed/accuracy tradeoff. The significant interaction was likely driven by inconsistent significant simple main effects of judgment-type within condition, which were of no particular interest, but did trend as expected – that is, with spatial judgments on global trials taking longer than those on local trials across all conditions.

Next, we examined the proportion of correct room errors for global trials. As expected, complex contrasts showed that those in the PT conditions ($M = .46$, $SD = .22$) made significantly more correct room errors than those in the SV ($M = .37$, $SD = .15$), $t_{(118)} = 2.15$, $p = .03$, $d = 0.48$, and AR conditions ($M = .31$, $SD = .08$), $t_{(118)} = 4.35$, $p < .001$, $d = 0.91$, and there was no difference between the SV and AR conditions, $t_{(118)} = 1.43$, $p = .16$, $d = 0.50$. Although those in the active PT condition ($M = .50$, $SD = .22$) made marginally more correct room errors than those in the passive PT condition ($M = .41$, $SD = .22$), this effect did not reach statistical significance, $t_{(118)} = 1.75$, $p = .08$, $d = 0.41$. In addition, comparisons to chance (33 percent) showed that only those in the active PT condition made correct room errors significantly greater than chance level, $t_{(24)} = 3.72$, $p = .001$.

Last, when participants selected a location within the correct room, complex contrasts showed a fine-grain advantage for the PT conditions ($M = .63$, $SD = .14$) over the SV ($M = .54$, $SD = .17$), $t_{(118)} = 2.60$, $p = .01$, $d = 0.58$, and AR conditions ($M = .55$, $SD = .13$), $t_{(118)} = 3.07$, $p = .003$, $d = 0.59$. No difference was detected between the SV and AR conditions, $t_{(118)} = 0.07$, $p = .95$, $d = 0.07$, nor the passive ($M = .62$, $SD = .12$) and active PT conditions ($M = .65$, $SD = .15$), $t_{(118)} = 0.84$, $p = .40$, $d = 0.22$. Comparisons to chance (50 percent) showed that only those in the PT conditions performed above chance (PPT: $t_{(24)} = 4.70$, $p < .001$; APT: $t_{(24)} = 5.01$, $p < .001$).

3.2.2.2. Map-building. Analyses of map-building performance revealed a similar pattern to that detected on the multiple-choice task. Again, the mixed-model ANOVA yielded significant main effects of condition, $F_{(4,\ 120)} = 7.03$, $p < .001$, $\eta_p^2 = .30$, judgment-type, $F_{(1,\ 120)} = 106.47$, $p < .001$, $\eta_p^2 = .41$ – with performance on local maps ($M = .66$, $SD = .23$) significantly greater than that for global maps ($M = .39$, $SD = .34$) – and a significant condition ∗ judgment-type interaction, $F_{(4,\ 120)} = 5.53$, $p < .001$, $\eta_p^2 = .26$. One-way ANOVAs showed a significant effect of condition for global map performance only, $F_{(4,\ 120)} = 9.27$, $p < .001$, $\omega^2 = .09$ (local map performance: $F_{(4,\ 120)} = 1.33$, $p = .26$, $\omega^2 = .001$). As in Experiment 1, global map performance violated the normality assumption (Kolmogorov-Smirnov: $ps \le .01$; Shapiro-Wilk: $ps \le .001$), thus the Kruskal-Wallis test for non-parametric data was used to confirm the significant effect of condition, χ^2 (4, N = 125) = 20.60, $p < .001$. As expected, Mann-Whitney U contrasts showed that continuous visual flow generated by array rotation ($M = .26$, $SD = .03$) provided no advantage over static viewing ($M = .25$, $SD = .05$), $U = 592.00$, $p = .71$, $r = .04$. Conversely, continuous visual flow generated by perspective taking ($M = .58$, $SD = .05$) significantly improved global performance compared to the SV, $U = 358.00$, $p = .003$, $r = .35$, and AR conditions, $U = 690.00$, $p < .001$, $r = .55$. However, unlike global performance on the multiple-choice task, active PT ($M = .65$, $SD = .07$) did not provide a significant advantage over passive movement for the global maps task ($M = .50$, $SD = .08$), $U = 241.00$, $p = .17$, $r = .20$ (see Fig. 13).

As for the multiple-choice task, we used the 5 (condition, *between-subjects*) × 2 (judgment-type, *within-subjects*) mixed-model ANOVA to examine response time data on the map-building task (in seconds).[4] The omnibus yielded a significant main effect of judgment-type only, $F_{(4,\ 119)} = 265.09$, $p < .001$, $\eta_p^2 = .69$, with global maps ($M = 218.96$, $SD = 100.45$) taking significantly longer than local maps ($M = 85.19$, $SD = 41.73$). Importantly, the main effect of condition, $F_{(4,\ 119)} = 0.87$, $p = .49$, $\eta_p^2 = .03$, and the condition ∗ judgment-type interaction, $F_{(4,\ 119)} = 1.82$, $p = .13$, $\eta_p^2 = .06$, were not significant, suggesting the PT advantage detected for global maps did not stem from a speed/accuracy tradeoff.

3.2.3. Global reference frame

Next, we examined the frame of reference used to integrate partial spatial information into a unified global representation. Specifically, when spatial information is viewed piecemeal, we were curious if new spatial locations are assimilated into that of the first viewpoint (i.e., startview), or, if locations are accommodated to fit the reference frame most recently experienced (i.e., that of the last viewpoint; see Greenauer, Mello, Kelly, & Avraamides, 2013). As in Experiment 1, participants' global maps were used to assess the preferred orientation of the integrated representation (i.e., global heading). Collapsed across conditions, a 4 (startview: living room, bedroom, kitchen, bathroom) × 4 (global map heading: living room, bedroom, kitchen, bathroom) chi-square showed that participants were significantly more likely to align their global maps with the first viewpoint compared to any other (n = 74/125; 59 percent), $\chi^2(9) = 87.10$, $p < .001$, Cramér's $V = .48$, suggesting that assimilation was the dominant approach (see Fig. 14). For maps misaligned with the first viewpoint, there was no evidence that the last viewpoint took precedence (n = 18/51; 35 percent), thus providing little support for accommodation (see Meilinger & Watanabe, 2016).

3.2.3.1. Map-building. Next, we examined the effect of assimilation on spatial integration – that is, when participants chose to integrate spatial locations viewed sequentially into the reference frame of the first viewpoint experienced. A one-way ANOVA showed that participants who aligned their maps with the first viewpoint ($M = .49$, $SD = .35$) significantly outperformed those who did not ($M = .24$, $SD = .26$), $F_{(1,\ 123)} = 17.98$, $p < .001$, $\omega^2 = .05$ (effect confirmed by the Kruskal-Wallis test: χ^2 (1, N = 125) = 16.00, $p < .001$). As in Experiment 1, the significant effect of startview alignment on global performance warranted further investigation of the perspective taking advantage. To examine this question, we added condition to the one-way ANOVA above.

[4] Local maps RT data missing from one participant in the PAR condition.

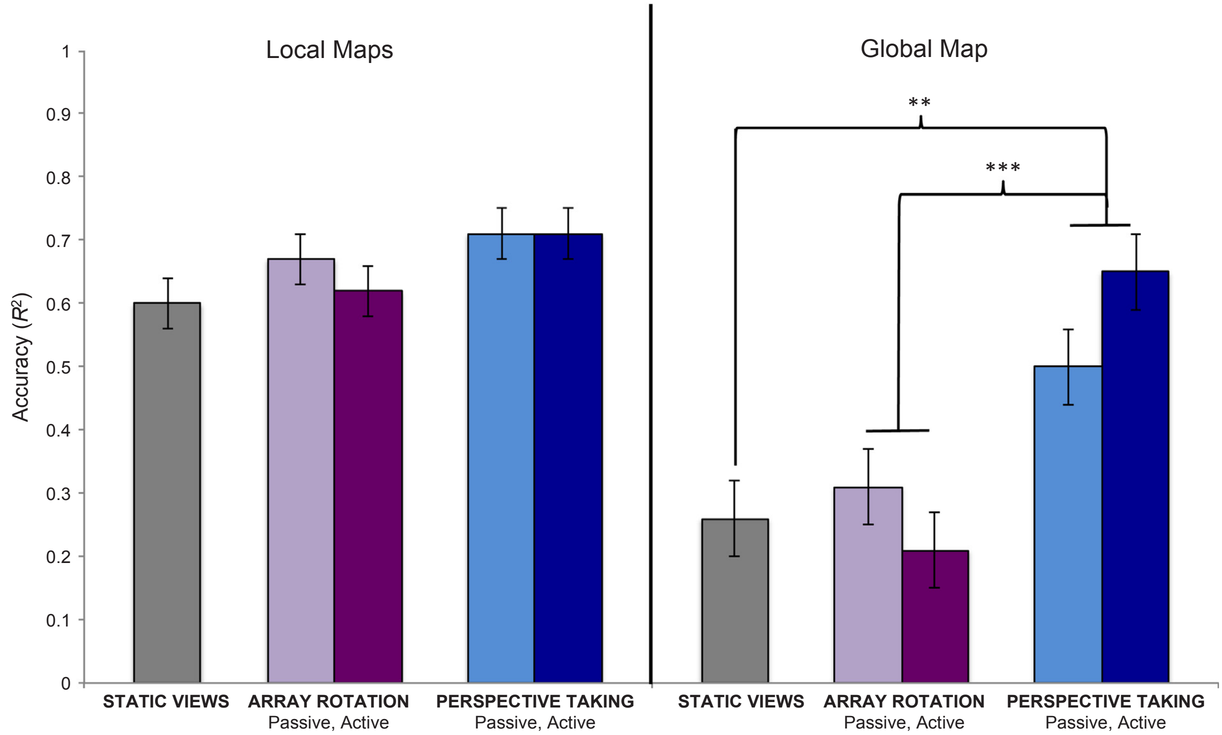

Fig. 13. The map-building task. Experiment 2 spatial performance by condition (± SEM). $^{***}p < .001$, $^{**}p < .01$.

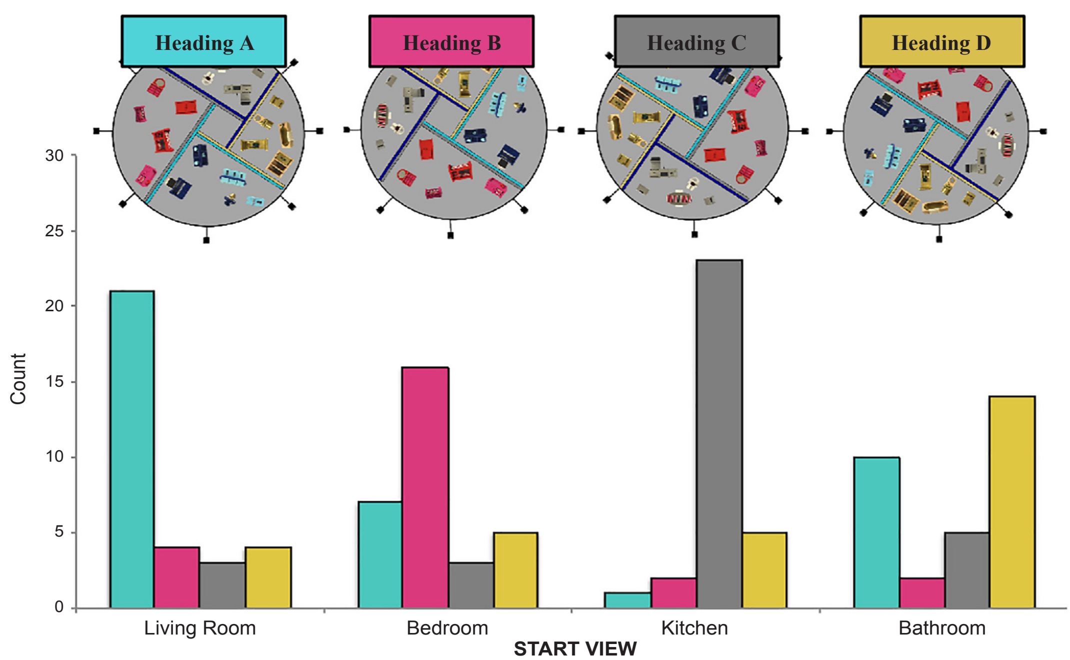

Fig. 14. The map-building task. Experiment 2 distribution of global headings by startview.

As expected, a 5 (condition) × 2 (alignment: startview-aligned vs. startview-misaligned) ANOVA yielded significant main effects of condition, $F_{(4, 115)} = 7.19$, $p < .001$, $\omega_p^2 = .12$, alignment, $F_{(1, 115)} = 17.76$, $p < .001$, $\omega_p^2 = .16$, and a significant condition ∗ alignment interaction, $F_{(4, 115)} = 2.53$, $p = .04$, $\omega_p^2 = .05$. Kruskal-Wallis tests showed that performance significantly differed by condition for startview-aligned maps only, χ^2 (4, N = 74) = 23.11, $p < .001$ (misaligned maps: χ^2 (4, N = 51) = 1.99, $p = .74$). Mann-Whitney U contrasts revealed a similar pattern to that initially detected; those in the PT conditions (i.e., active + passive: $M = .69$, $SD = .34$) significantly outperformed those in the SV ($M = .27$, $SD = .27$), $U = 116.00$, $p = .002$, $r = .45$, and AR conditions ($M = .35$, $SD = .27$), $U = 182.00$, $p < .001$, $r = .48$, and there was no difference between the SV and AR conditions, $U = 169.00$, $p = .41$, $r = .14$. However, the pattern differed in that active PT ($M = .83$, $SD = .19$) now provided a significant boost over passive movement ($M = .56$, $SD = .39$), $U = 81.00$, $p = .04$, $r = .35$ (see Fig. 15). Importantly, a 5 (condition) by 2 (alignment) chi-square showed that the number of startview-aligned versus startview-misaligned maps was evenly distributed across conditions, $\chi^2(4) = 3.78$, $p = .44$, Cramér's $V = .17$, suggesting that the PT

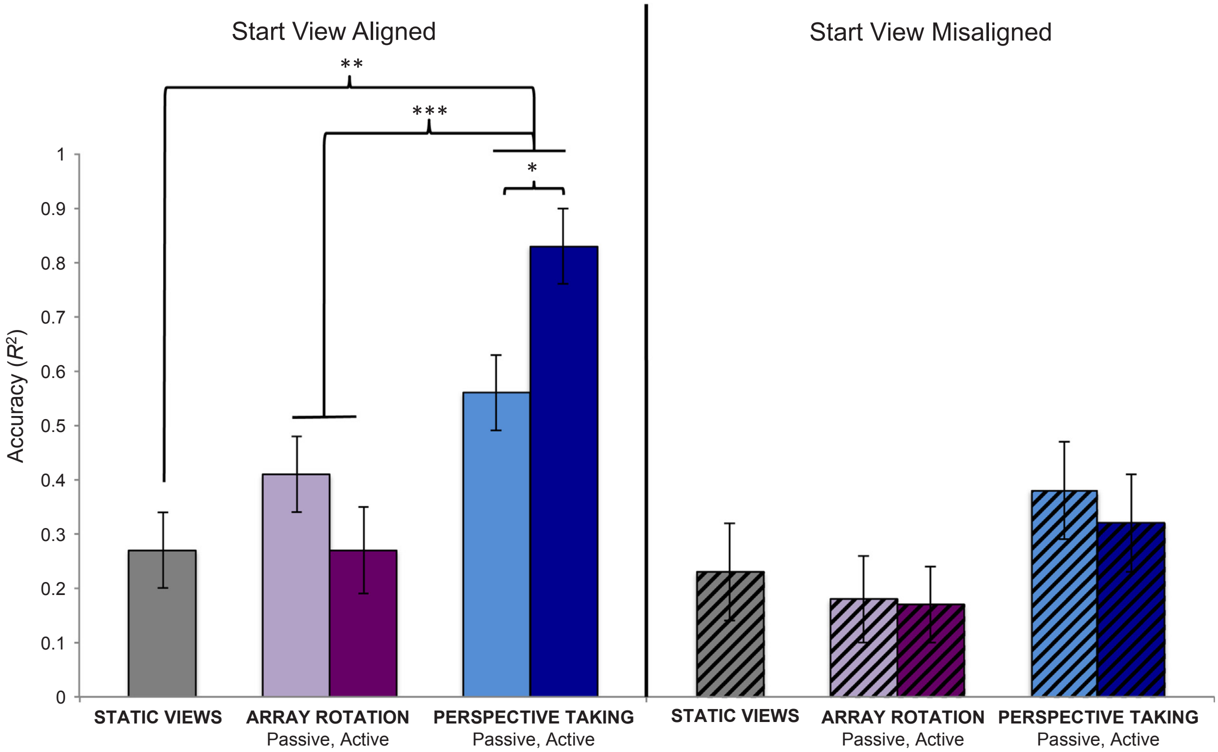

Fig. 15. The map-building task. Experiment 2 spatial performance for startview-aligned and startview-misaligned global maps by condition (± SEM). $^{***}p < .001$, $^{**}p < .01$, $^{*}p < .05$.

advantage did not stem from prompting assimilation; rather, perspective taking enhanced the process of integration via assimilation. To foreshadow, PT enhanced spatiotemporal memory (results presented below), thus enhancing the accuracy of the step-wise reconstruction of spatial locations into the reference frame of the first viewpoint.

3.2.3.2. Multiple-choice. As in Experiment 1, the significant effect of startview alignment on global map performance warranted further investigation of multiple-choice performance. Specifically, we reanalyzed performance on global trials using a 5 (condition, *between-subjects*) × 4 (startview, *between-subjects*) × 4 (global trial heading, *within-subjects*) mixed-model ANOVA to examine if performance for startview-aligned trials was superior to that for misaligned trials, and if this effect differed by condition (as detected on the map-building task, across both experiments). As detected in Experiment 1, the main effect of condition was significant, $F_{(4,\ 103)} = 9.41$, $p < .001$, $\eta_p^2 = .27$, but importantly, the startview ∗ heading, $F_{(9,\ 103)} = 0.99$, $p = .45$, $\eta_p^2 = .03$, and condition ∗ startview ∗ heading interactions, $F_{(36,\ 103)} = 0.87$, $p = .69$, $\eta_p^2 = .09$, were not significant, suggesting that startview-aligned and misaligned trials were equally difficult, with PT providing a universal advantage. A lack of an alignment effect likely reflects the increased difficulty of the task, compared to that of the map-building task. Because the trials were randomly counterbalanced by heading (see Experiment 1 Methods), participants had to constantly update the heading from trial to trial, thus requiring substantial cognitive effort to infer between-room locations, even for trials aligned with the initial viewing perspective, as these trials were preceded by startview-misaligned headings.

3.2.4. Integration strategy

The global map task was used to examine spatial integration strategy – that is, *how* participants integrated local layouts into a unified global representation. Observations from screen recordings revealed that integration strategy varied by two factors, 1. Room placement: sequential-room vs. random-room; and 2. Map anchor: anchor/heading congruent vs. anchor/heading incongruent. Within room placement, participants who used a sequential-room strategy completed the map one room at a time (i.e., placed 3 or more pieces of within-room furniture on the map before switching to another room; n = 106/125, 85 percent), whereas those using a random-room strategy placed furniture from different rooms on the map in no specific order (n = 19/125, 15 percent). In addition to room placement, participants also differed by how they initially anchored the global map (i.e., the first piece of furniture used to establish relative spatial location). Some participants selected furniture from the room used to orient the map (i.e., that positioned at the bottom – anchor/heading congruent; n = 94/125, 75 percent), while others did not (anchor/heading incongruent; n = 31/125, 25 percent). To examine the effect of strategy on integration accuracy, we ran a 5 (condition) × 2 (strategy) ANOVAs on global performance.

3.2.4.1. Room placement. For room placement strategy, the omnibus yielded a significant main effect of condition only, $F_{(4,\ 115)} = 3.35$, $p = .01$, $\omega_p^2 = .07$. Interestingly, the main effect of placement strategy was not significant, $F_{(1,\ 115)} = 0.003$, $p < .95$, $\omega_p^2 = .00$ (condition ∗ room placement interaction, $F_{(4,\ 115)} = 0.53$, $p = .71$, $\omega_p^2 = .00$). Although sequential-room was the predominant strategy, constructing the map room-by-room ($M = .40$, $SD = .35$) was no more advantageous than randomly switching between rooms ($M = .32$, $SD = .28$). In addition, a 5 (condition) by 2 (room placement strategy) chi-square showed that sequential- and random-room strategies were evenly distributed across conditions, $\chi^2(4) = 7.70$, $p = .10$, Cramér's $V = .25$.

3.2.4.2. Map anchor. For map anchor strategy, the omnibus yielded significant main effects of condition, $F_{(4,\ 115)} = 3.06$, $p = .02$, $\omega_p^2 = .06$, and map anchor, $F_{(1,\ 115)} = 8.81$, $p = .004$, $\omega_p^2 = .06$ (main effect of map anchor confirmed by the Kruskal-Wallis test: χ^2 (1, N = 125) = 4.91, $p = .03$). Participants who anchored their maps with the preferred heading ($M = .43$, $SD = .36$) significantly

Table 2
Hierarchical regression evaluating predictive power of condition and serial recall performance.

DV	Factor	*R*	R^2	ΔR^2	ΔF	*Sig.*	*df*	*β*	*Sig.*
Multiple-Choice	1. Condition	.32	.10	.10	13.76	**.000**	1,121	.02	**.03**
	2. Serial Recall	.56	.32	.21	37.40	**.000**	1,120	.25	**.000**
Map-Building	1. Condition	.35	.12	.12	17.26	**.000**	1,123	.04	**.02**
	2. Serial Recall	.70	.49	.36	86.22	**.000**	1,122	.69	**.000**

Note. Betas reported are those at which the variable was entered into the equation.

outperformed those who did not ($M = .24$, $SD = .24$). Finally, the condition ∗ map anchor interaction was not significant, $F_{(4,\ 115)} = 1.98$, $p = .10$, $\omega_p^2 = .03$. Participants in the PT conditions significantly outperformed all others, independent of how they initially anchored their maps. Last, a 5 (condition) by 2 (map anchor strategy) chi-square showed that anchor/heading congruent and incongruent strategies were evenly distributed across conditions, $\chi^2(4) = 3.17$, $p = .53$, Cramér's $V = .16$.

3.2.5. Sequential measures

The serial recall and map-building tasks were used to assess temporal and spatiotemporal sequential memory, respectively (i.e., memory for temporal order and position in space; see Methods section).

3.2.5.1. Serial recall. Similar to spatial performance, a one-way ANOVA showed a significant effect of condition on serial recall, $F_{(4,\ 120)} = 6.92$, $p < .001$, $\omega_p^2 = .16$. Because performance violated the normality assumption (Kolmogorov-Smirnov: *ps* ≤ .05; Shapiro-Wilk: *ps* ≤ .02), the Kruskal-Wallis test was used to confirm the significant effect of condition, χ^2 (4, N = 125) = 22.10, $p < .001$. Similar to spatial performance, Mann-Whitney U contrasts showed that those in the PT conditions ($M = .74$, $SD = .29$) significantly outperformed those in the SV ($M = .53$, $SD = .32$), $U = 389.00$, $p = .005$, $r = .32$, and AR conditions ($M = .46$, $SD = .26$), $U = 631.00$, $p < .001$, $r = .45$; there was no difference between the SV and AR conditions, $U = 572.50$, $p = .54$, $r = .07$. Last, a pairwise contrast examining the effect of active ($M = .80$, $SD = .28$) versus passive PT ($M = .68$, $SD = .28$) was not significant, $U = 242.50$, $p = .13$, $r = .21$.

Because serial recall performance mimicked the pattern detected for spatial performance, we examined if memory for temporal order was integral to spatial integration. Hierarchical multiple regression analyses were used to examine the predictive power of temporal memory on global spatial performance with condition held constant. Entered first, condition accounted for 10 percent of the variance for the multiple-choice task (adjusted $R^2 = .095$), which significantly differed from zero, $F_{(1,121)} = 13.76$, $p < .001$. Entered next, serial recall performance accounted for an additional 21 percent of variance, a significant increase from that predicted by condition alone, $F_{(1,120)} = 27.65$, $p < .001$. The same pattern was detected for the map-building task. Condition accounted for 12 percent of the variance (adjusted $R^2 = .116$, $F_{(1,123)} = 17.26$, $p < .001$), but when entered next, serial recall performance accounted for an additional 36 percent of variance ($F_{(1,122)} = 57.71$, $p < .001$; see Table 2).

3.2.5.2. Map-building. We used the final layout of participants' global maps to assess spatiotemporal sequential memory. Global maps were categorized as incorrect (incorrect temporal sequence, counterclockwise layout), temporal sequence correct (correct temporal order, counterclockwise layout), or spatiotemporal sequence correct (correct temporal order, clockwise layout; see Fig. 12 in Methods section). Not surprisingly, when collapsed across correct categories, those in the PT conditions (n = 35/50 participants, 70 percent) were significantly more likely to arrange the rooms in the correct temporal order, $\chi^2(1) = 18.66$, $p < .001$, Cramér's $V = .39$ (remaining conditions: n = 23/75 participants, 31 percent; see Fig. 12). Interestingly, for those who accurately recalled the rooms' temporal order (n = 58/125, 46 percent), participants in the PT conditions were also significantly more likely to arrange the rooms in the correct spatiotemporal sequence (n = 30/35 participants, 86 percent) compared to all other conditions (n = 13/23 participants, 57 percent). That is, they were more likely to accurately recall the *direction* of the temporal sequence, $\chi^2(1) = 6.17$, $p = .01$, Cramér's $V = .33$ (see Fig. 16).

3.2.6. Psychometrics

As expected, the SOT and MRT[5] significantly correlated with local and global spatial performance, with two exceptions – SOT/local maps, $r_{(118)} = -.17$, $p = .05$, and MRT/global maps, $r_{(111)} = .11$, $p = .24$ (see Table 3). An exploratory factor analysis of psychometric performance generated one factor that explained 87 percent of the variance and a one-way ANOVA showed that the distribution of Factor 1 scores (i.e., spatial ability) did not significantly differ by condition, $F_{(4,\ 108)} = 0.45$, $p = .77$, $\omega^2 = .01$, confirming the success of our counterbalanced assignment. Last, we added spatial ability as a covariate to the initial 5 (condition: *between-subjects*) × 2 (judgment-type: local vs. global spatial judgments, *within-subjects*) ANOVAs and reexamined spatial performance on the multiple-choice and map-building tasks. For both tasks, the mixed-model ANCOVA yielded significant main effects of condition (*ps* ≤ .009), judgment-type (*ps* < .001), spatial ability (*ps* ≤ .002), and significant condition ∗ judgment-type interactions (*ps* ≤ .027). As in Experiment 1, spatial ability did not significantly interact with any other factor (*ps* ≥ .165), suggesting this construct did not moderate any previously detected effects.

3.3. Discussion

In Experiment 2, participants were significantly more accurate (and were generally faster) when recalling local versus global configurations. This finding was consistent across all conditions, providing further evidence that spatial integration across multiple orientations is a difficult cognitive process (as in, e.g., Adamou et al., 2014; Avraamides et al., 2012). However, movement around the dollhouse significantly enhanced spatial integration from the preferred orientation, as well as flexible integration from multiple orientations (in terms of both accuracy and correct room errors). The advantage of moving around the array was found for both passive and active movement, but importantly, action provided an additional advantage over passive experience on both spatial measures.

It seems likely that the active perspective taking advantage for certain key measures depended on the fact that array stability coupled with active walking enhances spatiotemporal memory – that is, memory for the rooms' temporal order at encoding, as well as memory for the direction of each viewpoint transition. Participants who moved around the array experienced each temporal event (i.e., local layout) at separate locations in space, whereas when the array rotated, all events

[5] Due to experimental time restraints, not all participants completed the psychometrics, as the SOT (n = 120/125, 96 percent) and MRT (n = 113/125, 90 percent) were administered last, in that order.

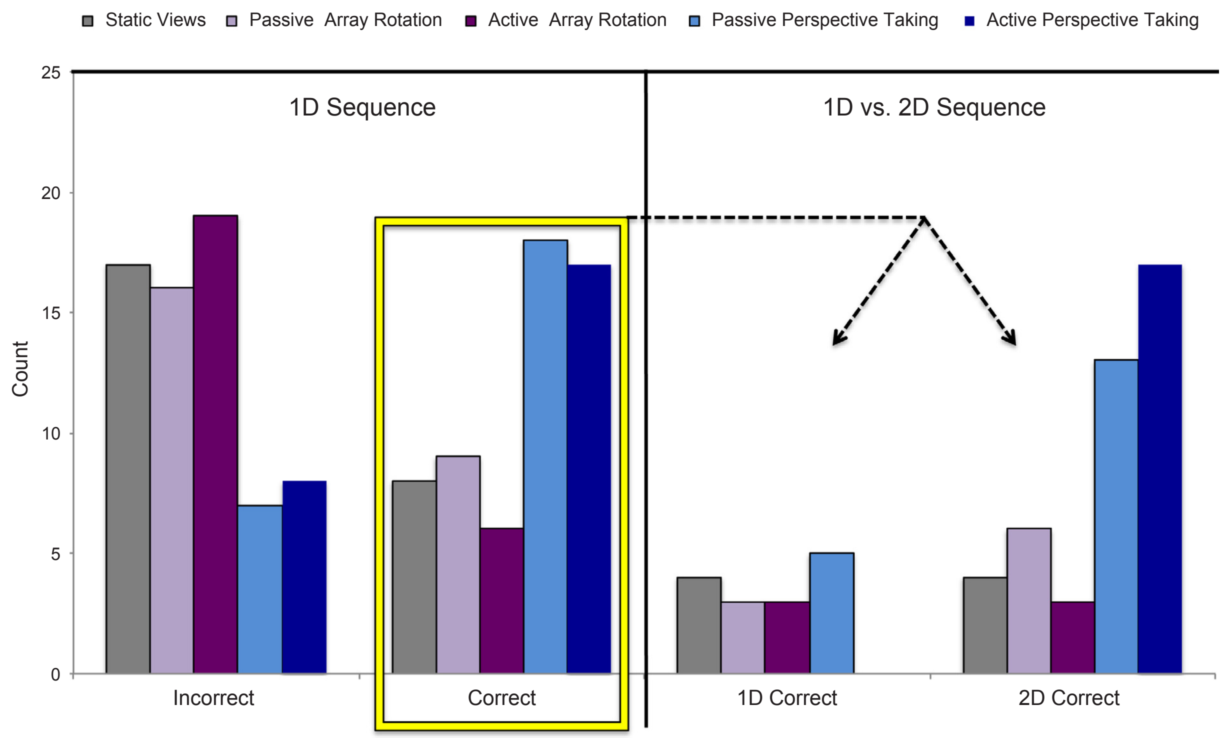

Fig. 16. Experiment 2 distribution of global map sequence by condition.

overlapped onto a single spatial location, likely blurring memory for temporal order. Furthermore, when events overlap in space, directional information is not preserved by the temporal sequence. The global configuration in Experiment 2 could have been reconstructed in a step-wise manner by mentally re-traveling the path between discrete events. In this view, the process of spatial integration is similar to episodic memory. To generate inferences across discrete events – either spatial or episodic – one must mentally re-travel the temporal sequence linking one event to the next (see Buzsáki & Moser, 2013; Buzsáki, Peyrache, & Kubie, 2014; Friston & Buzsáki, 2016).

This approach is supported by research on the neural correlates of space and time, as both are represented as sequential firing patterns across populations of pyramidal neurons in the hippocampal formation – specifically, in regions CA1 and CA3 (see Eichenbaum, 2013; Salz et al., 2016). It is also supported by research on the role of spatial stability in both allocentric and egocentric coding. External cues, such as stable landmarks (Knierim, Kudrimoti, & McNaughton, 1995) and environmental boundaries (boundary cells: Bjerknes, Moser, & Moser, 2014; Solstad, Boccara, Kropff, Moser, & Moser, 2008) are used to establish relative spatial position, but self-motion is especially important to place field precision, and is often more heavily weighted than visual input (e.g., conflict paradigms that contrast visual and idiothetic cues show a significant proportion of hippocampal neurons preferentially respond to idiothetic, self-motion cues; Chen, King, Burgess, & O'Keefe, 2013; for a review, see Bush, Barry, & Burgess, 2014). In its absence, pure visual information not only recruits fewer hippocampal neurons, but also generates larger firing fields, yielding a significantly less precise map (i.e., see Terrazas et al., 2005).

4. General discussion

Together, these experiments show that the nature of our spatial experience matters. Compared to array rotation, participants who moved around the array formed more accurate and flexible spatial memories. However, although perspective taking provided a significant and reliable spatial advantage in both studies, the nature of the effect was somewhat different. In Experiment 1, when participants could view the global configuration from all vantage points, observer movement enhanced spatial updating across viewpoint changes, enhancing spatial learning from multiple spatial orientations. In Experiment 2, when participants had to integrate locations across discrete experiences, observer movement enhanced global spatial memory for the unified layout but there was no effect of condition on local spatial memory. Participants remembered the local layouts for all rooms quite well, no matter how they experienced the transition from one room to the next. It was only when they had to combine spatial information into a unified representation that movement around the array significantly enhanced their ability to integrate the rooms. This fact suggests not all temporal transitions are the same for developing an integrated spatial representation.

One mechanism at work in these situations may be the effect of array stability on spatial coding. Movement around the array preserves the allocentric connection with the world; the spatial reference frame remains aligned with the initial viewing location and is not disrupted. Although observers must still update their position as they move, this process is substantially easier and more efficient than updating each of the array's locations, sequentially or holistically, as needed for array rotation. In addition, an egocentric representation automatically re-sets as the observer moves (e.g., as shown in movement-ignore paradigms: Farrell & Robertson, 1998; Farrell & Thomson, 1998; May & Klatzky, 2000; see Creem-Regehr, 2004), perhaps through the addition of vestibular feedback or optic flow (equivalent scene recognition across passive and active observer movement: Wang & Simons, 1999, Exp. 3; see Simons, Wang, & Roddenberry, 2002; for greater discussion of multisensory feedback, see Vidal, Lehmann, & Bülthoff, 2009).

An additional mechanism may come into play in Experiment 2. Movement around the array may enhance spatiotemporal memory – that is, memory for the encoding sequence and the direction of each viewpoint transition. The additional advantage detected for active over passive observer movement in Experiment 2 may be due to a more reliable memory for the spatiotemporal sequence. Because the dollhouse, furniture array, and surrounding environment were designed to discourage integration during encoding, spatiotemporal memory for the transition between partial views could provide an excellent support for

Table 3
Experiment 2 correlations, sample sizes, means, and standard deviations for dependent measures.

Measure	1	2	3	4	5	6	7	8	9	n	Mean	SD
1. Furniture-Name	–									125	.91	.13
2. Furniture-Room	.45**	–								125	.97	.06
3. MC Global Trials	.32**	.28**	–							123	.34	.16
4. MC Local Trials	.24**	.36**	.51**	–						123	.55	.18
5. Global Map (R^2)	.22*	.27**	.67**	.44**	–					125	.39	.34
6. Local Maps (R^2)	.33**	.24**	.45**	.69**	.41**	–				125	.66	.22
7. Serial Recall	.24**	.31**	.54**	.31**	.68**	.40**	–			125	.59	.31
8. SOT (Error)	-.33**	-.23*	-.36**	-.29**	-.24**	-.17	-.33**	–		120	49.83	28.99
9. MRT	.26**	.18	.25**	.31**	.11	.24**	.16	-.50**	–	113	.89	.79

Note. Bivariate correlations, means, and standard deviations are collapsed across conditions. All measures are entered into table in the order in which they were presented at test; horizontal numbered entries refer to vertical numbered entries of dependent measures. Spatial measure/psychometric correlations are boxed. For mean and standard deviation columns – save for SOT – higher values indicate better performance.
MC = Multiple-Choice Task; SOT = Spatial Orientation Test; MRT = Mental Rotation Test.

accurate spatial integration. When the global configuration could be viewed simultaneously in Experiment 1, spatiotemporal memory for each transition was unnecessary.

5. In sum

In Experiment 1, we show that movement around a stable array enhances our ability to learn and flexibly recall the spatial layout from multiple perspectives. In Experiment 2, when the array was viewed piecemeal and had to be integrated across discrete episodes, we found that active movement provides an additional advantage on key measures above passive experience. These findings suggest that array stability is key to flexible spatial memory, with action providing an additional boost to spatial integration. Furthermore, results from our second experiment show that when spatial information is experienced as discrete episodes, this information is stored and mentally reconstructed in a similar manner, highlighting the potential importance of memory for serial order to spatial integration. Notably, across both experiments, spatial information is preferentially stored at an orientation aligned with the first viewpoint experienced, allowing us to reconcile these findings on flexibility with prior work on the primacy of the initial viewpoint. Overall, these experiments suggest that there is a mode of spatial learning adapted to create flexible representations of the large-scale spatial environment. Driven in part by evolutionary forces (Gallistel, 1990), but also subject to individual variation (Weisberg & Newcombe, 2016), humans are able to create representations of their spatial world that support functional spatial behavior.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2018.05.003.

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