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Christina Adamou, Marios N. Avraamides & Jonathan W. Kelly

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BRIEF REPORT

Integration of visuospatial information encoded from different viewpoints

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Abstract Two experiments investigated whether separate sets of objects viewed in the same environment but from different views were encoded as a single integrated representation or maintained as distinct representations. Participants viewed two circular layouts of objects that were placed around them in a round (Experiment 1) or a square (Experiment 2) room and were later tested on perspective-taking trials requiring retrieval of either one layout (within-layout trials) or both layouts (between-layout trials). Results from Experiment 1 indicated that participants did not integrate the two layouts into a single representation. Imagined perspective taking was more efficient on within- than on between-layout trials. Furthermore, performance for within-layout trials was best from the perspective that each layout was studied. Results from Experiment 2 indicated that the stable environmental reference frame provided by the square room caused many, but not all, participants to integrate all locations within a common representation. Participants who integrated performed equally well for within-layout and between-layout judgments and also represented both layouts using a common reference frame. Overall, these findings highlight the flexibility of organizing information in spatial memory.

Keywords Spatial cognition · Spatial memory · Integration · Perspective taking

In the course of their everyday life, people move around in their environment and often experience the same space from different perspectives at different points in time (e.g., when entering a park from different entrances across different visits). In some cases, the spaces themselves change across experiences. For example, new buildings replace others in a neighborhood, new furniture are added to a room, and so on. A question that arises is whether people readily integrate new spatial locations into an existing representation at the time of encoding, or whether they store each unique episodic experience as a separate representation in memory, relating information across layouts only when needed at retrieval. The goal of the present study was to explore this question by investigating the retrieval of locations experienced in the same enclosing space but from different viewpoints and at different times.

Previous studies have investigated the integration of spatial information using the within- vs. between-layout paradigm (e.g., Maguire, Burke, Phillips, & Staunton, 1996; Montello & Pick, 1993). In these studies participants learn two layouts and then perform tasks that require using information from either one layout (within-layout judgments) or both layouts (between-layout judgments). If locations from the two layouts have been integrated into a single representation at the time of encoding, performance should be similar for within- and between-layout trials. In contrast, if two separate representations are maintained until retrieval, between-layout trials should result in inferior performance, as compared with within-layout trials, reflecting imprecision and a time cost to compute relations that are not directly represented in memory.

The majority of studies using this paradigm have shown better performance for within- than for between-layout

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C. Adamou · M. N. Avraamides (✉)
Department of Psychology, University of Cyprus, P.O Box 20537, Nicosia, Cyprus
e-mail: mariosav@ucy.ac.cy

M. N. Avraamides
Centre for Applied Neuroscience, Nicosia, Cyprus

J. W. Kelly
Department of Psychology, Iowa State University, Ames, IA, USA

judgments, suggesting that people keep distinct representations for each layout (e.g., Golledge, Ruggles, Pellegrino, & Gale, 1993; Maguire et al., 1996; Montello & Pick, 1993; but see Moar & Carleton, 1982). For example, in one study, Giudice, Klatzky, and Loomis (2009) had participants encode in memory six objects that were placed around them in a virtual environment. Three of the objects were encoded through vision, and the others through touch. In one experiment, visual and haptic objects were encoded separately. Results showed that error in pointing from imagined perspectives was greater for intermodal (between-layout) than for intramodal (within-layout) trials, which suggests that participants did not integrate the two layouts at encoding. Notably, a follow-up experiment in which the objects from the two modalities were learned in a mixed order revealed similar performance for intramodal and intermodal trials, indicating that the learning sequence can influence integration.

The study of Giudice et al. (2009) suggests that people do not typically integrate spatial information at the time of encoding when layouts are learned in separate blocks (see also Meilinger, Berthoz, & Wiener, 2011). Perhaps this is because chunking spatial information in separate representations supports cognitive economy. That is, if spatial memory relies on allocentric spatial representations (McNamara, 2003), an overall smaller number of object-to-object relations is maintained when objects are chunked in two representations than when they are integrated into a single representation. The drawback of chunking, however, is that if a task requires coordinating information across representations, spatial relations must be computed at the time of recall, rather than retrieved directly from memory. In the study of Giudice et al., such coordination was not particularly difficult, since visual and haptic layouts were experienced from the same starting orientation (i.e., participants started from a fixed facing orientation and rotated in place to view or touch objects). Research on spatial memory indicates that people maintain information on the basis of reference frames they establish during learning (Klatzky, 1998). According to one theory (Mou & McNamara, 2002), the reference frames used are allocentric but are stored from a preferred direction determined on the basis of various cues (e.g., layout symmetry, instructions, the geometric structure of the enclosing space). In the absence of any cues, egocentric experience plays an important role in determining the preferred direction. In the study of Giudice et al., it is highly likely that participants maintained both the visual and haptic objects from the same preferred direction (which was aligned with their initial orientation), making it easy to coordinate information across separate representations.

In the present study, we examined whether increasing the difficulty of between-layout coordination by having participants learn the two layouts from different perspectives would encourage participants to integrate the two representations at the time of encoding, thereby facilitating subsequent retrieval. Learning from different perspectives encourages the selection of unique reference frames for the two layouts, thereby increasing the difficulty of between-layout coordination. Participants studied two layouts consisting of four objects each and, as in Giudice et al. (2009), were then tested with pointing from imagined perspectives. In contrast to Giudice et al., both layouts were presented visually and were studied from unique viewpoints. Like previous studies on integration, we contrasted within- and between-layout judgments to determine the locus of integration (i.e., at encoding or at retrieval). Furthermore, we incorporated an additional test of integration by evaluating the preferred direction used to represent the two layouts in memory. When performance in pointing tasks is better from a specific direction, it is generally inferred that the reference frame selected to encode information during learning is aligned to that direction (Klatzky, 1998; Mou & McNamara, 2002). Therefore, if participants integrate spatial information from distinct experiences into a single representation, all locations should be organized around a common reference direction. In this case, of interest would be to determine whether participants assimilate new information into an existing reference frame established when encoding the first layout (Greenauer, Mello, Kelly, & Avraamides, 2013; Kelly & Avraamides, 2011) or whether they reorganize existing information using the reference frame primed by the second layout (Kelly & McNamara, 2010). If, instead, participants maintain information in separate representations until the time they are required to use them (Giudice et al., 2009; Meilinger et al., 2011), the two layouts should be organized around different preferred directions determined by egocentric experience.

Experiment 1

In the first experiment, participants studied objects in a virtual room where no geometric structure (or any other salient cue) was available, and thus, we expected participants to rely on egocentric experience to determine the preferred direction of their memories. If participants kept separate representations organized around different reference frames, we would expect (1) inferior performance for between-layout, as compared with within-layout, judgments and (2) superior performance on within-layout judgments when the imagined perspective was aligned with that layout's study view, as compared with other misaligned perspectives. If, on the other hand, participants integrated spatial information into a single representation, we would expect (1) equal performance for between- and within-layout judgments and (2) better performance from a single imagined perspective that could coincide with the study viewpoint of either the first or the second layout.

Method

Participants

Twenty-eight adults (20–32 years of age, 15 female) participated in the experiment in exchange for a small monetary compensation.

Materials and apparatus

Two layouts of four objects each (Fig. 1) were presented to participants visually, with the order of presentation counterbalanced across participants. One layout consisted of four objects: a chair, a grill, a coffee table, and a ball. The other layout consisted of a wrapped present, a basket, a flowerpot, and a library (Fig. 2).

A round learning room was used in order to preclude any influence of environmental geometry on reference frame selection. The objects were positioned in a circular arrangement, with the participant standing in the center of the circle, such that the objects themselves did not prime a particular direction. Both layouts contained objects located at the two learning orientations (labeled 0° or 210° in Fig. 1). Participants were not informed about the nature of the testing during learning of the two layouts. In the learning phase, participants viewed the layouts in an nVisor SX60 head-mounted display (HMD; NVIS, Reston, VA) with a 1,280 × 1,024 resolution and a 60-Hz refresh rate. The HMD had a 60° diagonal field of view and was outfitted with an InertiaCube3 (InterSense, Billerica, MA) tracker, which relayed orientation data to update graphics in real time. The virtual environment and the objects for the two layouts were created in Google Sketchup (Google Inc.) and were presented to participants in the HMD using the Panda 3D game engine (panda3d.net). The presentation of trials during testing was controlled by a Python script in Vizard™ (Worldviz Inc., Santa Barbara, CA).

Design and procedure

The experiment followed a within-participants factorial design with terms for the type of testing trials (within- vs. between-layout), the alignment of the studied layout to the physical space[1] (0° [aligned] vs. 210° [misaligned]), and the imagined perspective (0° vs. 210°).

Learning phase The learning phase began by having participants face in the direction of a virtual arrow presented on the floor (hereafter referred to as 0°). This arrow provided participants with a perceptual marker for their orientation in the virtual room. When they were ready to begin, the arrow disappeared, and the objects of the first layout became visible. Participants were allowed to turn their head in the virtual environment to view the objects without changing their body orientation. They were given unlimited time to memorize the objects and their locations. Participants informed the experimenter when they felt confident that they had memorized the layout. The objects were then removed, and the 0° arrow appeared on the floor along with an additional arrow pointing to 210°. Participants were instructed to turn toward the direction indicated by the 210° arrow. At this point, the arrows disappeared, the second set of objects appeared, and participants followed the same learning procedure as before. Participants informed the experimenter when they felt confident that they had memorized the layout, at which time the objects were removed. Participants removed the HMD while facing a random orientation to continue with the testing phase. At no point during learning were

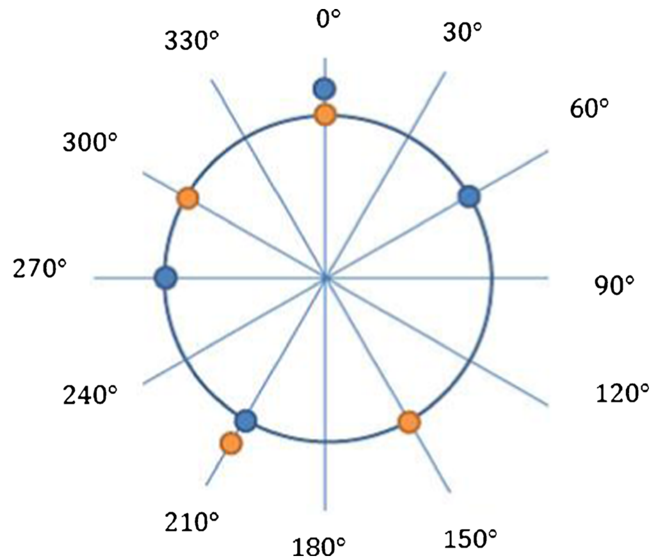

Fig. 1 Schematic representation of the two spatial layouts. Arrows indicate the two learning viewpoints

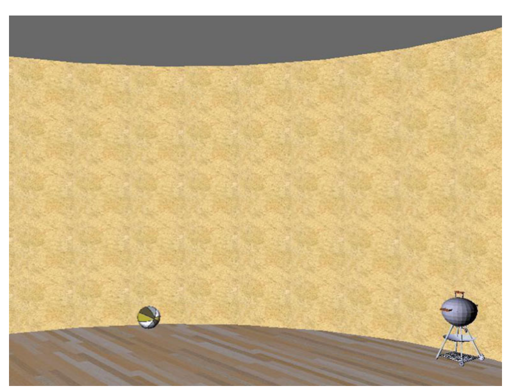

Fig. 2 Example view of objects in the virtual environment used in Experiment 1

[1] Participants were not aware of the alignment of their study view in the virtual room with the geometric structure of the physical room. We use the arbitrary labels 0° and 210° to differentiate between the two study views.

participants informed of the nature of the upcoming testing phase.[2]

Testing phase In the testing phase, participants carried out a series of pointing trials on a desktop computer located in the same laboratory. They were instructed to imagine standing in the center of the room facing one object (the orienting object) and then point to another object (the target object) from that perspective. Trials involved pairs of objects from one layout or both layouts (within- vs. between-layout trials). There were 52 pointing trials in total, consisting of 24 within-layout trials (12 for each layout) and 28 between-layout trials (14 with the orienting object from the one or the other layout). Trials were presented in a different random order for each participant.

An on-screen dial (Fig. 3), operated by moving the mouse, was used to execute pointing responses. The dial was made up of a circle with an index line. The name of the orienting object appeared above the circle, while the target object was presented below it. Participants were asked to indicate their response by rotating the index line and clicking the mouse to enter their response. Both pointing error (i.e., the angular difference between the actual and correct pointing angles) and pointing latency were recorded.

Fig. 3 The on-screen dial used for pointing responses

Results

Pointing latency and error data deviating more than 3 standard deviations from the mean of each participant were considered outliers and were discarded from the analyses. Initial analyses indicated no speed–accuracy trade-off. The within-participants correlation between pointing latency and pointing error was .03 (SD = .13), not significantly different from zero, $t(27) = 0.99$, p = .33. For the sake of brevity, we report only analyses using error data, but the same analyses conducted with latency data resulted in identical conclusions. Graphs from latency analyses are included as Supplemental Material.

Given that no practice was included in the experiment to avoid biasing the selection of reference frames, pointing errors were quite large. Overall, participants were more accurate on within-layout trials ($M = 58.02$, $SD = 22.57$) than on between-layout trials ($M = 71.99$, $SD = 29.45$), $t(27) = 2.83$, $p = .009$, which suggests that the two layouts were kept in separate representations in memory.

To examine the reference directions used to represent the two individual layouts, we analyzed pointing error for the within-layout trials. Specifically, we carried out a repeated measures analysis of variance (ANOVA) with terms for study alignment (0° or 210°) and imagined perspective (0° or 210°). We should note that we only compared the two imagined perspectives that were common to the two layouts. Numerically, performance for the remaining perspectives was never at par with the preferred direction of the layout.

The error analysis showed that neither the main effect of imagined perspective nor that of alignment was significant, $F(1, 27) = 1.36$, $p = .25$, and $F(1, 27) = 1.41$, $p = .25$, respectively. However, a significant interaction was present, $F(1, 27) = 8.66$, $p = .007$, $\eta^2 = .24$ (Fig. 4). When participants learned the layout from the 0° view, they pointed more accurately from the 0° than from the 210° imagined perspective, $p = .005$. On the other hand, when they learned from the 210° view, they were more accurate when the imagined perspective was aligned with 210° than with 0°, although this difference was marginally significant, $p = .07$.[3]

Discussion

The results of Experiment 1 showed that participants performed better on trials that required retrieval of information from a single layout than on those that entailed coordinating information across layouts. Furthermore, individual-layout retrieval was better from the imagined perspective that coincided with the learning viewpoint. These results indicate that participants kept the spatial information from the two layouts in separate representations in memory and related information at the time of retrieval. Thus, the difficulty of relating information across layouts maintained from different preferred directions did not encourage participants to integrate the two sets of spatial information prior to retrieval. However, the absence of geometric structure in Experiment 1 might have

[2] Studies typically test participants with egocentric pointing to ensure that they have memorized locations after learning. Doing so, however, may prime the direction from which pointing takes place. For this reason, we relied on participants' verbal assurance for adequate learning.

[3] This difference was statistically significant in the latency analysis, $p < .01$.

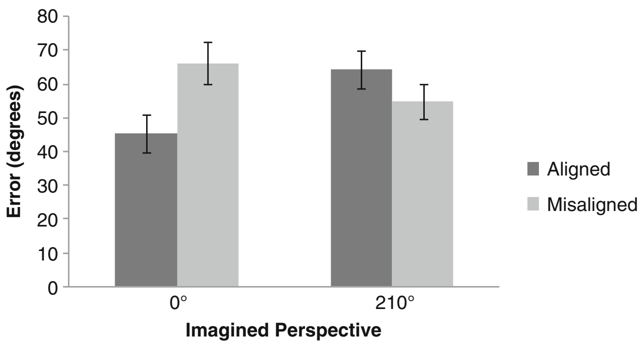

Fig. 4 Pointing error as a function of study alignment and imagined perspective and learning view for within trials, Experiment 1. Error bars are standard errors from the ANOVA

made it too difficult for participants to integrate information from the two layouts during learning. Perhaps, adding information that would allow using a stable environmental reference to organize their memory for the two layouts would encourage them to integrate the information acquired from the two viewpoints. To examine this, in Experiment 2, we presented objects within a square room and added external cues on the walls of the room to make the allocentric relationship between layouts more salient.

Experiment 2

Method

Participants

Thirty six adults (18–37 years of age, 19 females) participated in the experiment in exchange for monetary compensation.

Design and procedure

The procedure differed from that in Experiment 1 in two important ways. First, the surrounding virtual room was square, and external cues (a door and wall paintings) were added (Fig. 5). The 0° learning view was aligned with the geometric structure of the room, while the 210° learning view was misaligned. Second, the order in which participants experienced the two views was counterbalanced: Half of the participants studied one layout from 0° and then the other from 210°, and the other half studied in the reverse order. The assignment of layout identity to learning viewpoint was also randomized across participants.

As in Experiment 1, two arrows appeared on the floor before the objects became visible. One arrow, pointing to 0°, was aligned with the structure of the room, and the other, pointing to 210°, was misaligned. All participants initially faced the 0° arrow to emphasize the shape of the room before

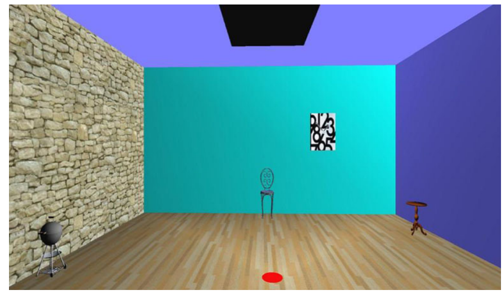

Fig. 5 Example view of objects in the virtual environment used in Experiment 2

learning. If the first learning view was 0°, participants stayed at this orientation and viewed the objects of the first layout. If the first learning view was 210°, participants were instructed to rotate into alignment with the 210° arrow and study the layout from that view. Once the first layout was memorized, the procedure was repeated such that participants studied the second layout from the other view. After participants indicated that they had memorized the objects and their locations, they were guided to a different laboratory to carry out the testing phase as in Experiment 1.

Results

As in Experiment 1, there was no speed–accuracy trade-off. The correlation between pointing latency and pointing error averaged −.05, (SD = .5) and was not significantly different from zero, $t(35) = 0.63$, $p = .53$.

Pointing error was somewhat lower in this experiment, as compared with Experiment 1. Performance for between-layout trials (M = 65.47, SD = 41.86) was less accurate than for within-layout trials (M = 49.91, SD = 36.03), $t(35) = 2.01$, $p = .05$. Within-layout judgments were analyzed by an ANOVA with terms for order (aligned-first, misaligned-first), study alignment (0°, 210°), and imagined perspective (0°, 210°) to determine the reference frames used to represent the individual layouts.

The analysis revealed that neither the main effect of order nor that of alignment was significant, $F(1, 34) = 0.63$, $p = .43$, and $F(1, 34) = 0.58$, $p = .45$, respectively. However, there was a significant effect of imagined perspective, with participants performing better from the imagined perspective that was aligned to the environment (0°), than from the one that was not (210°), $F(1, 34) = 6.66$, $p = .014$, $\eta^2 = .16$. There was also a significant interaction between alignment and imagined perspective, $F(1, 33) = 6.09$, $p = .0019$,$\eta^2 = .15$. When the learning view was aligned with the environment (0°), participants were more accurate when the imagined perspective was also from 0° than when it was from 210°, $p = .001$ (Fig. 6). When the learning view was misaligned with the environment (210°), participants performed similarly

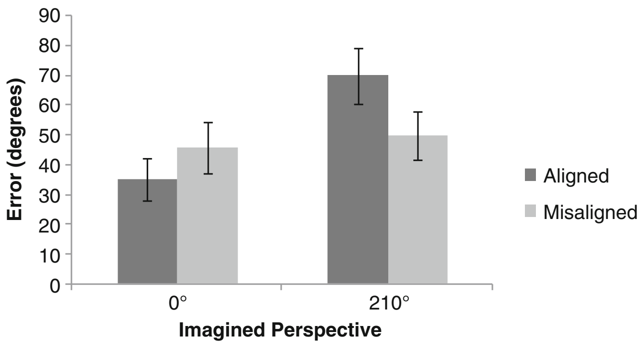

Fig. 6 Pointing error as a function of study alignment and imagined perspective and learning view for within trials, Experiment 2. Error bars are standard errors from the ANOVA

from both imagined perspectives, $p = .66$ (Fig. 6). None of the interactions involving order approached significance.

Individual differences

The lack of a difference between the two imagined perspectives in the misaligned layout of Experiment 2 is compatible with the possibility that individual participants used different strategies to organize their memories, with some using the environmental reference frame and others the study viewpoint. To examine this, we divided participants into two groups on the basis of whether their pointing error was lower for the 0° or the 210° perspective. Out of 36 participants, 21 were in group 1 (lower error for 0°) and 15 in group 2 (lower error for 210°). If participants in group 1 had integrated locations into a single representation, they should exhibit no within- versus between-judgment difference in performance. This hypothesis was corroborated by statistical analysis, $t(20) = 0.55$, $p = .59$. In contrast, participants in group 2 were significantly less accurate for between- than for within-layout judgments, $t(14) = 2.33$, $p = .036$ (Fig. 9, Supplemental Material). Additional analyses using only participants of group 1 indicated no effect of learning order (or trend in that direction).

Discussion

The overall performance in Experiment 2 was better than that in Experiment 1, which indicates that the environmental structure facilitated the encoding of spatial information to memory. Moreover, the results of Experiment 2 suggest that some participants integrated locations from the two layouts in a single representation at the time of learning. These participants performed equally well for within- and between-layout judgments and organized both layouts with a preferred direction determined by the salient environmental reference frame. In contrast, other participants organized the two layouts on the basis of distinct preferred directions coinciding with their learning experience. As was expected, these participants had worse performance for trials relating information across than within layouts.

General discussion

Previous studies have compared within- versus between-layout judgments (Giudice et al., 2009; Golledge et al., 1993; Maguire et al., 1996; Meilinger et al., 2011; Moar & Carleton, 1982; Montello & Pick, 1993) or evaluated the transfer of reference frames (Greenauer et al., 2013; Kelly & Avraamides, 2011) to investigate whether spatial information from different experiences is integrated into a single spatial representation in memory. In the present study, we have combined the two approaches to examine spatial integration in a situation where people encode visual information in memory by viewing, from different perspectives, two distinct layouts separated in time.

Results indicated that in the absence of a structured environment (Experiment 1), distinct representations were maintained. Participants performed better for within- than for between-layout trials and from the study perspective of each layout. This result is in line with those from previous studies showing that participants do not integrate separately learned layouts at the time of encoding (e.g., Giudice et al., 2009; Golledge et al., 1993; Maguire et al., 1996; Montello & Pick, 1993).

Introducing environmental cues in Experiment 2 resulted in integration of the two layouts at the time of learning, but only for a subgroup of participants. Participants who represented both layouts using a reference frame aligned with environmental cues also demonstrated equal performance for within- and between-layout judgments. In contrast, participants who represented each layout using a reference frame selected from that layout's study view performed better for within- than for between-layout trials, suggesting that they kept distinct representations in memory.

Overall, our findings are compatible with the theory proposed by McNamara and colleagues (e.g., Mou & McNamara, 2002; Shelton & McNamara, 2001) that in the absence of salient environmental cues, egocentric experience determines the preferred direction for spatial layouts. The geometric structure in Experiment 2 clearly influenced the choice of reference frame to encode spatial information in memory: More than half of the participants used the salient environmental reference frame provided by the geometric structure of the room to integrate spatial information into a single representation. Furthermore, the absence of an order effect suggests that both assimilation of information into an existing reference frame (Greenauer et al., 2013) and reorganization of existing information on the basis of a new reference frame (Kelly & McNamara, 2010; Meilinger et al., 2011) took place.

A possible explanation for our results is that people by default maintain spatial information acquired from distinct perceptual experiences in separate representations. Although doing so may cause difficulties in computing spatial relations across experiences at retrieval, it makes the maintenance of information easier. In our case, maintaining two representations with four locations each results in 12 (6 in each layout) unique object-to-object relations, whereas maintaining eight locations in a single representation results in 28 unique relations. Therefore, people may create separate information chunks from each layout and coordinate information across representations only when necessary for the task (e.g., Meilinger et al., 2011). However, our findings from Experiment 2 show that the presence of an environmental reference frame encourages some people to opt for storing more relations in memory. Doing so facilitates performance across layouts, since it relies on the direct retrieval of information from memory rather than from the ad hoc computation of novel relations.

Overall, our findings are compatible with the hypothesis that selecting a reference frame to organize a spatial memory is a flexible process, with people weighing probabilistically the available cues in order to make a choice (Galati & Avraamides, in press). The fact that not all participants integrated information at the time of learning in Experiment 2 could also mean that people flexibly choose whether to integrate at encoding or not. Further studies may focus on identifying the situations in which people prefer to integrate during learning. One possibility is that informing participants before learning about the nature of the upcoming task (so that they know that it will entail coordinating information across experiences) may cause them to integrate the layouts into a single representation. An alternative possibility is that whether one integrates or not at the time of encoding is influenced by cognitive limitations such as working memory capacity. While these interesting questions remain, our findings extend those of previous studies to support that maintaining separate representations is the default when environmental cues are lacking. At the same time, they provide one example situation in which at least some participants integrate prior to retrieval.

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