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SHORT COMMUNICATION

Integrating visuospatial information across distinct experiences

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Abstract

In two experiments, we examined whether the presence of stable visual information and the confluence of the viewpoints would cause participants to integrate in a single memory representation spatial locations they encoded at different points in time. Participants studied from the same or from different viewpoints two layouts of objects within a common visually cluttered room. Then, they carried out a series of pointing trials that involved objects from either the same or different layouts. Results showed that participants were faster for within- than between-layout judgments when they had studied the two layouts from different viewpoints but were equally fast across the two types of judgment after studying the layouts from the same viewpoint (Experiment 1). This finding suggests that they integrated locations into a single representation only when encoding the layouts from the same viewpoint. However, when participants' memory for the layout studied first was refreshed prior to testing (Experiment 2), no difference in response time was found, suggesting that they had integrated all locations in a single representation before the beginning of testing.

Keywords Integration · Spatial cognition · Spatial memory · Visual encoding · Orientation

Introduction

Imagine visiting a shopping mall for the first time and memorizing the locations of stores you encounter along the route you take. Now, imagine going to the same mall again at a later date and taking another route that takes you by stores you have not seen during your first visit. Would you update your spatial representation to include the locations of all stores you have seen during your two visits or would you keep them in two separate representations linked to each visit?

The integration of information about separately learned spaces is considered an important distinct step in *spatial cognitive microgenesis*, i.e., the process of knowledge development over time when acquiring information about unfamiliar environments (Montello 1998; Siegel and White 1975). Thus, a growing literature in the field of spatial cognition has focused on investigating the circumstances under which people integrate into a single spatial representation information that is acquired at different points in time.

Most studies on spatial integration rely on the same general paradigm: Participants first experience two spatial layouts one after the other and then carry out a task that requires information from only one of the layouts (within-layout judgments) or from both layouts (between-layout judgments). The rationale of this paradigm is that if all information has been stored in a single integrated representation in memory, performance for within- and between-layout judgments should be similar. If, however, spatial information about the two layouts is maintained in distinct mental representations, performance should be inferior for between- than within-layout judgments, reflecting the cost of switching from one representation to the other.

In support of the distinct representations account, the overwhelming majority of studies that have used this paradigm report better performance for within- than between-layout judgments for vista-scale (e.g., Adamou et al. 2014; Giudice et al. 2009; Greenauer and Waller 2010; Greenauer et al. 2013; Meilinger et al. 2011) and for

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environmental-scale space (e.g., Ishikawa and Montello 2006; Montello and Pick 1993; Weisberg et al. 2013). For example, in a study Ishikawa and Montello (2006), participants were guided several times along two routes in a real environment before experiencing a connecting route between them. After each time they traversed the routes, they were asked to estimate directions and straight-line distances between landmarks located on the same or different routes. As results showed, although response accuracy and speed improved over the course of the experiment, participants remained faster and more accurate with within-route than between-route judgments. Similarly, Weisberg et al. (2013) had participants memorize the locations of buildings on two routes they navigated in a virtual university campus presented on a desktop. After navigating both routes, participants navigated two additional paths that connected the first two routes to each other. During testing, they pointed from one building location to all others using a virtual pointer. Results indicated that performance was more accurate for within- than between-route judgments, suggesting that participants did not integrate all locations into a single representation. Similar results are reported by studies using layouts of objects that can be viewed from a fixed perspective or by rotating one's body in place (Adamou et al. 2014; Giudice et al. 2009; Greenauer and Waller 2010; Greenauer et al. 2013). In addition to documenting superior performance for within- than between-layout judgments, these studies provided evidence that each layout was organized around its own reference frame. These findings add to the bulk of research supporting the presence of orientation-dependent spatial memories (e.g., Mou and McNamara 2002; Presson et al. 1987, 1989).

Whereas it seems that by default spatial information acquired in different learning experiences is maintained in separate representations, some results indicate that under certain circumstances, people may integrate information into a single representation (e.g., Holding and Holding 1989; Moar and Carleton 1982). For example, in an experiment by Adamou et al. (2014), participants studied two four-object layouts presented in the same round room at different points in time and executed pointing judgments that involved pairs of objects from the same layout or from different layouts. Results from a first experiment showed that participants were faster and more accurate to point in within- compared to between-layout judgments. However, in a follow-up experiment that presented the same layouts within a square room, about half of the participants exhibited similar performance across the two types of judgments. Adamou et al. (2014) argued that the stable environmental reference frame provided by the square room had encouraged these participants to integrate the information about the two layouts in a single spatial representation prior to retrieval. This conclusion is in line with the findings from other studies showing that in some cases people encode a spatial layout using a salient allocentric reference frame that is transferred from a previous learning experience with another layout (e.g., Kelly and Avraamides 2011; Kelly et al. 2011; Kelly and McNamara 2010).

Overall, it seems that although spatial information encoded at different points in time is typically maintained in distinct representations, the details of certain situations, such as the presence of a stable and salient environmental reference frame, may prime the integration of information into a single representation during learning. In the present study, we further explore the circumstances under which integration in vista-scale environments may take place by investigating whether (1) the presence of the same stable visual information during two learning experiences, including the salient reference frame implied by the geometry of a square room, and (2) the observation from the same egocentric perspective may cause participants to integrate locations perceived in separate experiences into a single representation during learning.

To examine this possibility, we asked participants to study two spatial layouts presented within a cluttered square-shaped laboratory from the same versus different viewpoints and compared their performance across within- and between-layout judgments. If the geometry of the laboratory and the extraneous visual information that was visible during both encoding experiences encourage participants to integrate locations during learning, then similar performance is expected for within- and between-layout judgments, irrespective of whether the layouts were studied from the same or different viewpoints. If, however, egocentric experience overrides the environmental information in defining the reference frame from which spatial information is encoded in our particular setup, then participants should perform equally well across within- and between-layout judgments in the same viewpoint condition, in which integration is easier to achieve due to the common reference frame. In the case of egocentric encoding, learning from two different viewpoints could yield separate representations linked to each encoding experience as integration in this case would be more effortful to achieve.

It should be noted that to test our hypotheses we focus primarily on pointing latency data. This is because our conjecture is that inferior performance for between- than within-layout judgments can still be observed in pointing error, even if all locations are integrated into a single representation (see Pantelides et al. 2016). This may occur if the spatial relation between the two layouts is distorted in memory or if the intrinsic orientation of one or both layouts has been misperceived (i.e., all objects of the layout are shifted by the same extend). Thus, we consider pointing error as an index of the precision of spatial memory which could vary regardless of integration and response latency as an index of access to information in memory.[1] Under the assumption that switching from one spatial representation to another would entail additional time than activating a single representation, we assess integration based on response time. However, analyses are carried out and reported for both pointing error and response latency.

Experiment 1

In Experiment 1, participants studied six objects, presented as two layouts of three objects each, that were placed around them on the floor of a visually cluttered square laboratory. Half of the participants studied the two layouts from the same viewpoint, while the other half studied each layout from a different viewpoint. All participants were then tested in a different room with perspective taking trials that required pointing to objects from imagined perspectives. Each trial involved two objects: one to define the imagined perspective and the other to indicate the target. Trials could therefore be classified as involving within-layout or between-layout judgments depending on whether the two objects came from the same or different layouts. If participants kept the locations of each layout in distinct representations, their performance should be better for within- than between-layout judgments.

Participants

Twenty-eight students (ages 20–25, three males) from the University of Cyprus participated in this experiment in exchange of course credit. All participants signed an informed consent form before the experiment and were thoroughly debriefed afterward.

Design

The experiment followed a 2 (learning viewpoint; same vs. different) × 2 (judgment type; within-layout vs. between-layout) mixed-factorial design with learning viewpoint manipulated between participants and judgment type within.

[1] That accuracy and latency map to precision and retrieval access, respectively, have also been posited in research on attention (e.g., Prinzmetal et al. 2005) and working memory (e.g., Shimi et al. 2014).

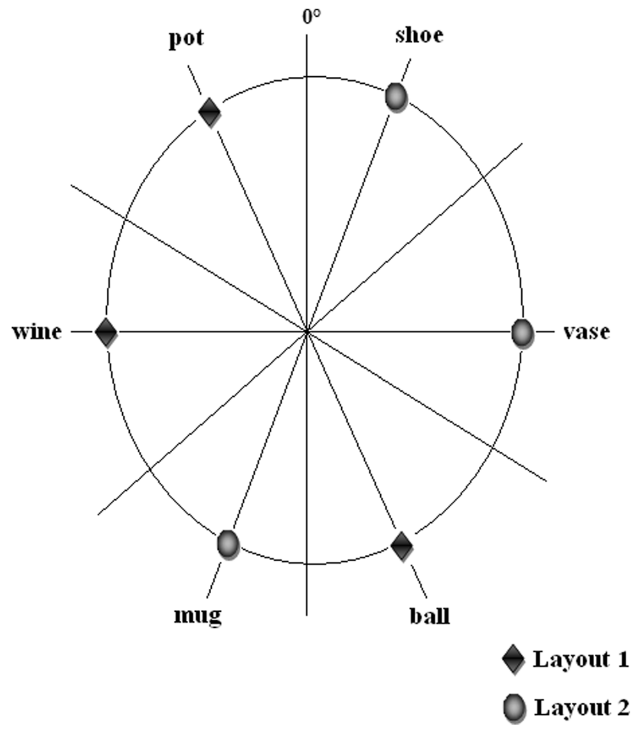

Fig. 1 Layout used in all experiments

Procedure

Practice phase

Before the beginning of experimental trials, participants completed a short practice phase using laboratory objects in order to become familiar with how to use the computerized pointer to point from imagined perspectives. For practice trials, participants received corrective feedback. Participants continued to the learning phase as soon as they pointed correctly, as judged visually by the experimenter, in 10 practice trials.

Learning phase

For this phase, two layouts of objects were learned in a common laboratory room. As each layout contained three objects, a total of six objects (ball, wine, pot, shoe, vase and mug; see Fig. 1) were learned. Participants stood in the center of the laboratory facing at 0°, and they were asked to view three objects that were placed around them and memorize their locations. They were only allowed to turn their heads to view objects locations. After memorizing the layout, participants were asked to point to each object with their eyes closed from the learning standpoint, after rotating 90° either to their right or left and after rotating 135° either to their right or left (i.e., right vs. left rotation was

Fig. 2 Pointer used for pointing responses in all experiments

counterbalanced between participants). This was done to ensure that participants had memorized objects in their correct locations and that they created a spatial image rather than remembering verbal information. After pointing correctly to all objects of each layout from the different perspectives, participants were guided to an adjacent laboratory and their memory was tested with *memory verification trials.* These trials required participants to point egocentrically, using the computerized pointer, to the remembered object locations as if they were at the learning standpoint. Participants continued pointing until they responded within ± 30° for all memorized objects and received verbal feedback for errors that exceeded the set threshold. Then participants were guided back to the learning room to learn the second layout, and the same procedure was followed. Half of the participants studied the two layouts from the same viewpoint (0° in Fig. 1), while the other half studied the two layouts from different viewpoints (i.e., 60° and 300°). Importantly, participants were not aware during learning about the nature of the upcoming testing trials.

Testing phase

Testing took place in an adjacent laboratory to decontextualize participants from the memorized layouts. In this phase, participants executed a series of perspective taking trials that asked them to point to objects from imagined perspectives from the center of the layout (e.g., "Imagine facing x point to y," where x and y are objects from the studied layouts). Each trial was presented as sentence on a computer screen and participants responded using the mouse on a computerized pointer that was presented below the sentence (Fig. 2). Pointing trials were controlled by a Python script running in the Panda 3D software. The experiment included a total of 120 trials (i.e., 4 blocks of 30 trials each) presented in a different randomized order for each participant. The order in which the two layouts were learned was counterbalanced across participants. Pointing error and response time were logged and used as the dependent measures. Participants were instructed to respond as fast as possible but without sacrificing accuracy for speed.

Following testing, participants were interviewed by the experimenter about the strategies they used to remember the layouts. They were specifically asked to report whether they visualized objects as two distinct layouts or whether they merged the objects into a single layout during encoding or at any other point in the experiment.

Results

For both measures of response time and accuracy, data were analyzed with repeated-measures ANOVAs with terms for learning perspective (same viewpoint vs. different viewpoint) and judgment type (within-layout vs. between-layout).

Response time and accuracy data deviating more than 2.5 standard deviations from the mean of each participant were considered as outliers and were discarded from all analyses. A total of 1.7% of the data were discarded based on this criterion.

Response time

For response time, the analysis revealed a significant main effect of judgment type, with participants being overall faster ($M = 12.13$ s, SD = .80 s) for within- compared to between-layout judgments ($M = 13.70$ s, SD = .76 s), $F(1. 26) = 27.83$, $p = .00$, $\eta^2 = .51$. The main effect of learning perspective was not significant, $F(1. 26) = .44$, $p = .51$, $\eta^2 = .01$. Importantly, a significant learning perspective x judgment type interaction was present, $F(1. 26) = 49.51$, $p = .00$, $\eta^2 = .60$ (Fig. 3). Participants were faster at within- compared to between-layout judgments when they studied the two layouts from different perspectives ($p < .001$), but they were similarly fast across the two types of judgments when they studied the two layouts from the same perspective, $p = .47$.

Accuracy

The analysis of accuracy revealed a significant main effect of judgment type, $F(1. 26) = 28.23$, $p < .001$, $\eta^2 = .52$. Participants were more accurate for within- ($M = 24.46°$, SD = 1.18°) than between-layout judgments ($M = 29.48°$, SD = 1.61°). Neither the main effect of learning perspective nor the learning perspective × judgment type interaction were significant, $F(1. 26) = 1.41$, $p = .24$, $\eta^2 = .05$ and $F(1. 26) = 3.38$, $p = .07$, $\eta^2 = .11$, respectively (Fig. 4).

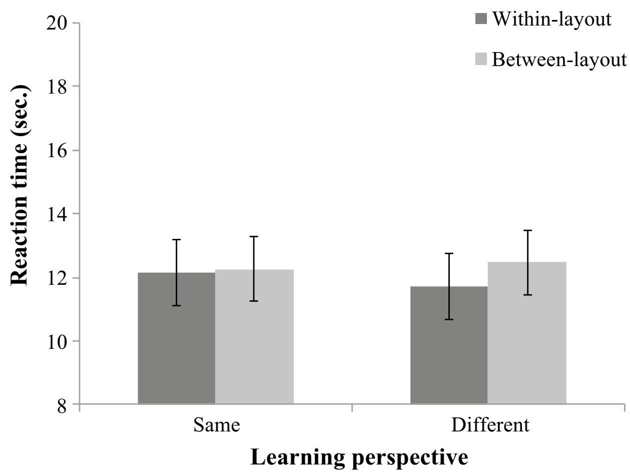

Fig. 3 Reaction time as a function of learning perspective and judgment type in Experiment 1. Error bars are standard errors from the ANOVA

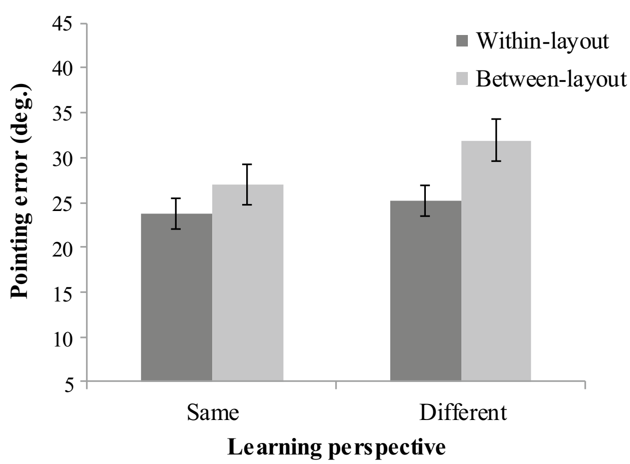

Fig. 4 Pointing error as a function of learning perspective and judgment type in Experiment 1. Error bars are standard errors from the ANOVA

Verbal reports

Data from participants' report questionnaires corroborated the findings from response latency. Specifically, in the same learning viewpoint condition 3 out of 14 participants reported integrating the targets from the two layouts in a single representation at the time of learning, while the remaining 11 reported doing so when they were guided to the neighboring room for testing but before testing began. In contrast, in the different learning viewpoint condition 13 out of 14 participants reported maintaining the locations from the two layouts in distinct representations during learning and only started to connect information from the two layouts during testing when they realized that the task required coordinating information across representations. The remaining participant reported merging the spatial information from the two layouts into a single representation at the time of learning. Notably, response latency results remain unchanged if this participant is excluded from the analysis.

Discussion

Results from Experiment 1 revealed longer latencies for between- compared to within-layout judgments, but only when participants studied the two layouts from different viewpoints. When they studied the layouts from the same viewpoint, latencies did not differ between within- and between-layout judgments. This finding suggests that participants kept the two layouts in distinct representations when they studied them from different viewpoints and integrated them into a single representation prior to testing when they studied them from the same viewpoint. This conclusion is corroborated by verbal reports, although those participants were able to pinpoint with accuracy when they had integrated information should be taken with caution. Indeed, most participants who studied the two layouts from different viewpoints reported that they maintained separate representations before testing. In contrast, most participants who studied the two layouts from the same viewpoint, reported integrating the locations from the two layouts in a single memory representation after encoding but before testing.

Overall, it seems that the presence of stable visual information during the two encoding phases did not on its own cause participants to integrate information into a single, potentially allocentric, representation. Instead, only when egocentric experience coincided during the two encoding phases did integration take place. Notably, based on the error data, it seems that participants maintained more precise spatial relations for the object locations they encoded together compared to those they encoded at distinct learning experiences, even when response latencies and verbal reports indicated that they integrated locations into a single representation. This discrepancy across error and latency results supports our conjecture that the two measures might be indexing different aspects of spatial performance, namely precision and access, respectively (Pantelides et al. 2016).

One possibility is that it is easier (or even automatic) to integrate information across the distinct experiences when encoding two layouts from the same rather than from a different viewpoint, due to the common egocentric reference frame. The fact that in our study the objects were placed around the participant might have encouraged the use of an egocentric reference frame over the stable allocentric frame implied by the geometry of the enclosing space. However, another possibility is that integration was hindered by memory decay. That is, it could be that the memory of the layout that was studied first has faded to some degree by the time the objects of the second layout were studied. Indeed, an analysis we conducted for within-layout judgments showed that response latencies were at least numerically longer for the layout that was studied first, suggesting the presence of some decay.[2] If the two layouts were encoded using distinct egocentric reference frames in the different viewpoint condition, perhaps it was more difficult to integrate locations when one of the representations had begun to fade. To examine this possibility, in Experiment 2 we modified slightly our procedure in order to counteract memory decay: We asked participants to point to the objects of the first layout again after they completed studying both layouts.

Experiment 2

Experiment 2 investigated whether refreshing the memory of the layout studied first would alter the findings of Experiment 1. Thus, everything was kept identical to Experiment 1 with the only exception that participants were asked, after they have completed learning both layouts and carrying out the memory verification trials, to return to the learning room and point to the objects of the first studied layout one more time. This memory refreshment could strengthen the memory for the first studied layout, making it easier for participants to integrate it with the memory of the second studied layout prior to testing. If participants carry out testing based on a single spatial representation, similar performance in response time across within- and between-layout judgments should be observed.

Method

Participants

Twenty-eight students (ages 20–25, three males) from the University of Cyprus participated in this experiment in exchange of either course credit or a small monetary compensation (€10). All participants signed an informed consent form before the beginning of the experiment.

Materials, design and procedure

Everything was identical to Experiment 1 with one exception; after executing memory verification trials, participants were guided back to the learning room when they were asked to point to the locations of the objects in the layout encoded first (in order to refresh their memory for that layout) from the viewpoint the layout was initially encoded (0°, 60° or 300° depending on the condition participants were assigned to). Pointing was carried out in the absence of any objects.

Results

Response time and accuracy data deviating more than 2.5 standard deviations from the mean of each participant (1.4% of all data) were considered as outliers and were discarded from all analyses. As in Experiment 1, data for response time and accuracy were analyzed using a repeated-measures ANOVA with learning perspective (same viewpoint vs. different viewpoints) as the between-subjects factor and judgment type (within-layout vs. between-layout) as the within-subjects factor.

Response time

In contrast to Experiment 1, neither the main effect of judgment type nor the learning perspective x judgment type interaction were significant, $F(1.\ 26) = 1.10$, $p = .30$, $\eta^2 = .04$ and $F(1.\ 26) = .30$, $p = .58$, $\eta^2 = .01$, respectively (Fig. 5). The effect of learning perspective was also not significant, $F(1.\ 26) = .15$, $p = .69$, $\eta^2 = .00$.

Accuracy

The analysis for accuracy revealed a significant main effect of judgment type, with participants being more accurate with within- compared to between-layout judgments, $F(1.\ 26) = 24.34$, $p < .001$, $\eta^2 = .48$. Neither the main effect of learning perspective nor the learning perspective x judgment type interaction were significant, $F(1.\ 26) = .51$, $p = .47$, $\eta^2 = .02$ and $F(1.\ 26) = .22$, $p = .63$, $\eta^2 = .00$, respectively (Fig. 6).

Verbal reports

According to the information collected through the questionnaire, 13 out of 14 participants in the same learning viewpoint condition reported that they integrated the locations from the two layouts in a single representation during learning. The remaining participant reported that she kept two layouts in distinct representations. In the different learning viewpoint

[2] $t\ (26) = 1.83$, $p = .08$ ($M = 13.53$, $SD = 4.54$ for the layout studied first, $M = 10.74$, $SD = 3.44$ for the layout studied second).

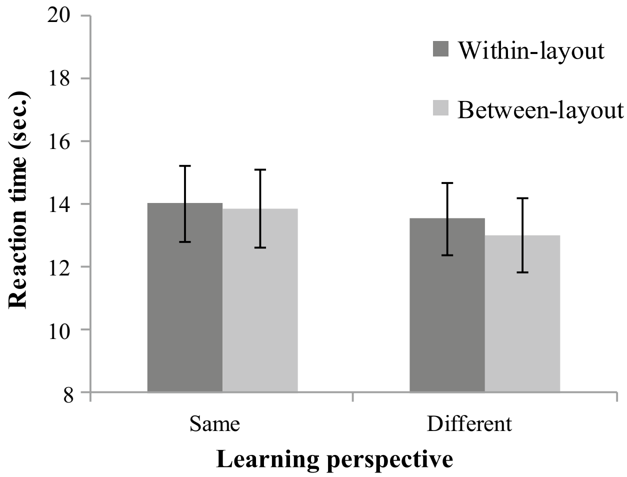

Fig. 5 Reaction time as a function of learning perspective and judgment type in Experiment 2. Error bars are standard errors from the ANOVA

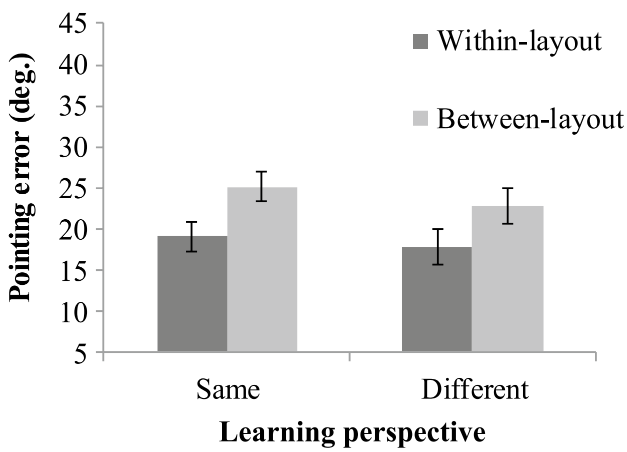

Fig. 6 Pointing error as a function of learning perspective and judgment type in Experiment 2. Error bars are standard errors from the ANOVA

condition, 12 out of 14 participants reported that they maintained the locations from the two layouts in distinct representations during learning, but they merged them together once they were guided to the adjacent room for the testing, but before testing began. The remaining two participants reported that they kept the targets from the two layouts in distinct representations.

Discussion

The findings from Experiment 2 differed markedly from those of Experiment 1. While in Experiment 1 participants were faster for within- than between-layout judgments when studying the two layouts from different viewpoints, in Experiment 2 this was not the case. In both the same and the different learning conditions, participants were equally fast to respond in within- and between-layout trials. Notably, in terms of pointing error, participants were still more accurate with within- than between-layout judgments.

Overall, these findings suggest that participants integrated spatial information into a single representation prior to testing, but these relations were represented less precisely than in the individual representations for each layout, which were presumably used for within-layout judgments. That integration took place before testing is corroborated by the verbal reports of the participants. For both perspective conditions of this experiment, almost all participants reported integrating spatial information at some point before the beginning of testing. This might have occurred because refreshing the memory created first counteracted decay and allowed participants to maintain more vivid representations in memory. Alternatively, going back to the layout studied first simply provided participants with another chance to integrate information into a single representation prior to testing or even encouraged them to do so. Although our results do not allow pinpointing how exactly revisiting the first layout eliminated the latency difference across within- and between-layout judgments, they provide evidence that integration is possible under these circumstances.

Notably, according to verbal reports, most participants in the same learning viewpoint integrated locations into a single representation during learning, while those in the different learning viewpoint did so after learning was concluded but before testing. This difference across conditions is in line with the idea that integration takes place rather effortlessly (or even automatically) when studying locations from the same viewpoint but not when studying them from different viewpoints. In the latter case, integration might have resulted from the deliberate visualization of all locations in the interval between learning and testing, which is more in line with the idea that refreshing led to stronger memory representations.

General discussion

In the present study, we explored whether integration of spatial information across two learning experiences would take place during learning when (1) visual information during encoding, including the environmental reference frame of the laboratory, was available during both learning experiences and (2) the two learning experiences occurred from the same egocentric perspective. Results from Experiment 1 indicated that participants were faster to point to memorized locations from imagined perspectives when the information—the object to be faced and the target—came from the same spatial layout (within-layout trials) than from different layouts (between-layout trials) but only when the two layouts were studied from different viewpoints. When they studied the two layouts from the same viewpoint, participants responded equally fast to within- and between-layout trials. Together with the verbal reports, this pattern of results indicates that participants integrated information across layouts during learning when they observed them from the same viewpoint but not when they observed them from a different viewpoint.

In Experiment 2, we refreshed participants' memory for the layout studied first before testing their memory with the within- versus between-layout paradigm. Results were strikingly different than those of Experiment 1. Importantly, participants were equally fast to respond in within- and between-layout trials regardless of whether they studied the layouts from the same or different viewpoints. Furthermore, verbal reports revealed that in the different viewpoint condition, unlike Experiment 1 in which participants reported maintaining separate representations and integrated them as testing unfolded, in Experiment 2 they indicated that they had integrated all locations into a single representation in the interval between learning and testing. Thus, verbal reports and pointing latencies converge in that, in both same viewpoint and different viewpoint conditions, participants carried out the test trials using an integrated representation.

Taken together, the findings from the two experiments converge with those from other studies (e.g., Adamou et al. 2014; Holding and Holding 1989; Moar and Carleton 1982) suggesting that integration during learning is possible under certain circumstances. For example, when they studied the two spatial layouts from the same viewpoint, participants in our experiments integrated the locations into a single representation before learning. Our conjecture is that when integration is easy, as in the case of observing spatial layouts with a small number of objects from the same viewpoint, participants will engage in it even if they do not know whether the upcoming task would require coordinating information across layouts. However, when integration is not as easy, as in the case of observing two layouts from different viewpoints, people will integrate during learning only when they have a good reason to do it.

This conjecture is in line with the finding of many previous studies using the within- versus between-layout paradigm documenting that, when encoding spatial information from different viewpoints, participants maintain by default a separate spatial representation for each layout (e.g., Ishikawa and Montello 2006; Meilinger et al. 2011). Keeping separate representations supports cognitive economy as a fewer number of object-to-object locations are maintained in memory. It is also in line with accounts of spatial memory arguing for hierarchical organization of information with multiple connected representations (Hirtle and Jonides 1985; McNamara et al. 1989) and with spatial cognitive microgenesis accounts positing that the integration of spatial information across learning experiences is a rather sophisticate step in the development of spatial knowledge over time and one that may require extensive experience (Montello 1998; Siegel and White 1975).

If our conjecture that integration during learning takes a place only when it is easy or when people have a reason to do it, a question that arises is why participants in Experiment 2, but not in Experiment 1, integrated locations prior to testing when they had studied them as separate. One possibility is that refreshing participants' memories in Experiment 2 had strengthened the memory trace for the location of the layout studied first, making integration more easy. It could also be that revisiting the locations of the first layout in memory had taken away temporal cues that could distinguish the episodic memories of the two encoding experiences. If following refreshing participants regarded the two learning phases as a single experience, perhaps they were also more likely to merge all locations into a single spatial representation. In line with the latter possibility are findings from Giudice et al. (2009) showing that participants kept in separate representations locations they had encoded from vision and touch as separate episodes (i.e., first the visual and then the haptic locations and vice versa) but integrated them in a single representation when they learned locations from the two modalities in mixed order (i.e., switching from studying a visual location to a haptic and back). Verbal reports from Experiment 2 though indicated that most participants who studied the layouts from different viewpoints integrated them not during studying but after it was concluded. This is more in line with the idea that refreshing made the representation of the layout studied first more vivid compared to Experiment 1, allowing integration to take place retrospectively. Finally, it is also possible that revisiting the locations of the first layout introduced some demand characteristics. That is, participants could have thought that they were asked to point again to the locations of the first layout because the experimenters wanted them to integrate all locations into a single representation. Regardless of the underlying cause, our results provide evidence that integration can take place even if encoding takes place from different perspectives. This is in line with the findings of Adamou et al. (2014) who showed that, in the presence of a stable allocentric reference frame, many participants integrate spatial information learned from different perspectives.

Notably, our results also suggest that on its own, stable visual information including the salient environmental reference frame implied by the geometry of the testing room does not suffice for integration to occur during learning. Perhaps that information had interacted with refreshing in Experiment 2 to promote integration, but in Experiment 1 it did not cause participants studying the layouts from different viewpoints to integrate. A possible explanation for this is that participants relied on egocentric encoding to remember the locations. Perhaps the fact that locations were placed around participants than in front of them had encouraged this kind of encoding.

A note to be made is that pointing error in both Experiments 1 and 2 showed that participants maintained more precise spatial memories for the spatial relations between locations encoded at the same learning experience compared to those encoded at different learning experiences, regardless of whether latencies and verbal reports indicated that integration occurred during encoding or later. These findings are in line with the idea that pointing error is an index of the precision with which people represent spatial information in memory, while latency an index of the speed with which they the access such information from memory (Pantelides et al. 2016). Perhaps participants were more accurate with within-layout judgments because they observed directly the spatial relations among objects, whereas they could only infer these relations for objects across layouts.

Overall, the current findings are compatible with theories arguing for hierarchical representations of space that organize distinct clusters of locations within spatial memory (e.g., Hirtle and Jonides 1985). While each cluster is organized around its own distinct microreference frame, the relations among clusters are organized by a macroreference frame (see Kelly et al. 2018 for recent evidence).

In closing, we should point out some important limitations of the current research. First, the layouts we used are not typical of everyday life in that we kept all objects at the same distance from the observer and that angular deviations among them were in multiples of 30°. This was done to avoid taxing working memory resources and to be allow comparisons with past studies using such set ups in vista-scale spaces (e.g., Giudice et al. 2009). Still, it is possible that less regular layouts could give rise to different results (e.g., if they are more demanding in working memory resources they could be less likely to be kept separate in memory). Second, the vast majority of our participants (50 out of 56) were female. Although inspecting the data of the six male participants did not yield any obvious deviations from the overall patterns observed, there is still a possibility that our findings cannot generalize to both genders.

While these and other questions (e.g., how familiarity influences integration) remain open, the findings from the present study still contribute to the growing spatial cognition literature. In particular, the findings extend what is currently known about spatial integration of information across learning experiences by showing that the learning viewpoint and memory refreshment are both important factors influencing when integration takes place. At the same time, our findings suggest that a stable environmental reference frame and other visual information available during encoding are not on their own sufficient to promote integration.

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Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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