



The spatial layout of doorways and environmental boundaries shape the content of event memories

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ABSTRACT

Physical boundaries in our environment have been observed to define separate events in episodic memory. To date, however, there is little evidence that the spatial properties of boundaries exert any control over event memories. To examine this possibility, we conducted four experiments that took manipulations involving boundaries that have been demonstrated to influence spatial representations, and adapted them for use in an episodic object memory paradigm. Here, participants were given 15 min to freely explore an environment that contained 36 objects, equally dispersed among six discriminable buildings. In a subsequent test of object-location binding, participants were required to indicate where they remembered encountering the objects. In Experiment 1 the spatial properties of the building boundaries were identical; however, in Experiment 2 the boundaries were differentiated by their geometric shape and the location of the doorways in the buildings. In the test phases of these experiments, we observed a shift from a bias towards remembering the positions of objects within a building but not the building itself (Experiment 1), to a bias towards remembering which building an object was in but not the location within the building (Experiment 2). In Experiment 3, the buildings shared the same geometry but were differentiated by the locations of doorways, and we observed no significant differences between response types. Finally, in Experiment 4, the buildings were uniquely shaped but shared the same doorway location, and we observed a bias towards remembering the positions of objects within a building. In addition, exploratory analyses of non-spatial interference revealed more correct recall for objects housed in the first building a participant visited during exploration, compared to all other buildings. Together, our data indicates that the location of doorways in boundaries and, to a lesser extent, boundary geometries influence event models, and that a primacy effect can be observed in the recall of multiple object-location bindings.

1. Introduction

As we live our daily lives, we receive a continuous stream of sensory information. By contrast, our memories of what happened in the past are of discrete events or episodes. That is, we have a conscious recollection of what happened at a particular point in time and space (Conway & Pleydell-Pearce, 2000; Tulving, 1983, 2002). To encode memories of separable events, the continuous stream of sensory information that we receive must be segmented into discrete episodes, a process that has been formally proposed by event cognition theories. According to these theories, we create event models that represent a series of experiences that we recollect as a connected whole. For instance, an event model for attending a meeting may be comprised of the sub-events of making

coffee at the beginning of the meeting, an introductory speech by the chair of the meeting, and the formal discussions of the meeting itself. As such, an event model can be seen as a representation of the spatio-temporal context of the current activity (Radvansky, 2017), and is conceptualised by both the Event Segmentation Theory (Kurby & Zacks, 2008; Zacks, Speer, Swallow, Braver, & Reynolds, 2007) and the Event Horizon Model (Radvansky, 2012; Radvansky & Zacks, 2011, 2017) as a schema that is held in working memory, which we use to process the stream of incoming sensory inputs. Importantly, this means the usefulness of an active event model is, to a large extent, limited to processing the sensory information pertaining to the current event. On perceiving an event boundary, such as leaving the meeting in the previous example, it is necessary to update the current event model to reflect whatever the

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next activity will be, and it is this updating process that serves to segment the continuous stream of sensory information into separable events in episodic memory.

Recently, there has been a growing empirical interest in understanding what cues in an environment allow for the detection of event boundaries and, therefore, the cues that elicit updating to a new event model. Within this literature, there is mounting evidence that physical boundaries in the world (i.e. the walls forming buildings and rooms) can serve as effective signals of event boundaries. In a series of experiments that have demonstrated the location updating effect, participants were required to walk through various rooms of a labyrinth, whilst picking up and setting down various objects along the way. Periodically, participants received a memory probe that asked about the object they are currently carrying. Across a number of studies conducted in virtual-worlds, it has been demonstrated that memory for a recently encountered object is worse when a participant has traversed through a doorway in between picking up an object and receiving the memory probe, compared to when they have travelled an equivalent distance within the same room (Radvansky & Copeland, 2006: see also Horner, Bisby, Wang, Bogus, & Burgess, 2016; Radvansky, Tamplin, & Krawietz, 2010; Radvansky, Krawietz, & Tamplin, 2011; Seel, Easton, McGregor, Buckley, & Eacott, 2019). Under the framework provided by event cognition models, these results can be interpreted as the boundaries of the rooms defining event boundaries (Radvansky et al., 2011, 2010). Here, probes administered after passing through a doorway require memory for an object that was encountered in an event model that is no longer active, whereas memory probes administered within the same room require memory for an object that was encountered in the currently active event model. Event cognition theories therefore provide an appealing explanation for location updating effects, as memories from a previously active event model are expected to be less accurate than memories from a currently active event model.

Importantly, trivial interpretations of the location updating effect have been ruled out. The same pattern of data that is observed when conducting studies in a virtual environment has also been demonstrated in a real-world environment (Radvansky et al., 2011), suggesting that the effect is not simply an artefact of testing using a virtual world. It has also been demonstrated that the location updating effect is not amenable to explanations involving context-dependent memory (e.g. Godden & Baddeley, 1975), as memory remains poorer even under circumstances in which participants move to a new room, and then return to the room that contained the item that is questioned in the memory probe. Interestingly, though, performance when participants return to the original room is better than performance under circumstances in which participants move between a first, second, and third room (Radvansky et al., 2011). Here, in both circumstances, there are two event boundaries; however, there are two contexts when moving to a new room and returning to an original room, whereas there are three contexts when traversing through different three rooms. Poorer performance under the latter circumstances suggests that the location updating effect is a least partially caused by retrieval interference effects (Radvansky & Zacks, 2017). Similarly, recency judgements about items encountered in different spatial contexts have been observed to be more accurate when the shift between spatial contexts was distinct, as compared to shifts between spatial contexts with overlapping features, demonstrating greater interference effects when events are bounded by similar contexts (Gurguryan, Dutemple, & Sheldon, 2021).

The data reviewed above present coherent evidence that physical boundaries in the world can bound events within episodic memory (see Brunec, Moscovitch, & Barense, 2018 for a review). What is less known, though, is whether the spatial properties of physical boundaries exert any influence on event memories beyond being a barrier that can serve as a cue for event segmentation. In the spatial literature, manipulations to environmental boundaries have been shown to influence estimates of locations learned with respect to boundary walls (Hartley, Trinkler, & Burgess, 2004), and distances travelled between objects within a

bounded environment (Bellmund et al., 2020). Moreover, the category adjustment model (Huttenlocher, Hedges, & Duncan, 1991) proposes that we encode spatial locations according to fine metric detail, and also broader categorical information within a scene. Research examining this proposal using 2- (Huttenlocher et al., 1991) and 3-Dimensional scenes (Holden, Newcombe, & Shipley, 2013), as well as larger scale navigable environments (Uttal, Friedman, Hand, & Warren, 2010), has demonstrated that participant estimations of location can become biased towards the centre of a category prototype. Similar prototypical responses have been observed when participants are asked to recall the time at which an event occurred (e.g. Huttenlocher, Hedges, & Bradburn, 1990), and together these assessments of the category adjustment model seem to reflect schematic organisation of spatial locations (Tse et al., 2007; van Buuren et al., 2014) in a manner that is consistent with the schematic organisation of non-spatial memories (Bartlett, 1932).

Given the manner in which environmental boundaries have been observed to influence spatial memories, and empirical demonstrations of the schematic organisation of remembered spatial locations, it is possible that physical boundaries in an environment may exert some control over the recollection of event models - beyond serving as a cue for event segmentation. We are, however, only aware of tentative evidence that supports this proposal. In a series of experiments conducted by Marchette, Ryan, and Epstein (2017), participants freely explored a large park environment that contained four rectangle-shaped buildings that were visually discriminable. Within each building there were eight unique objects, and during an exploration period participants were instructed to view all 32 objects. In a test phase the objects were removed from the environment and, on each trial, participants were prompted to navigate to where in the environment they remembered a given object being located. When analysing the test trials on which participants navigated to an incorrect location, behaviour appeared to be driven by a memory of the positions of objects with respect to the geometry of the buildings, rather than the identity of the buildings themselves. That is, when participants gave an incorrect response, they were more likely to navigate to the correct position within the wrong building (a position-preserving error), than they were to navigate to the wrong position within the correct building (a building-preserving error). The same pattern of data was observed across a number of manipulations to the buildings, including changing the door participants used to enter the building between exploration and test phases, and changing the shape of two of the four buildings. Interestingly, though, the opposite pattern of results was obtained when the building walls were removed from the environment. When participants were required to learn the locations of objects that were placed in rectangle-shaped arrays within the larger park environment, behaviour appeared to be based on a memory for the identity of the array, rather than a memory for the position within the arrays. Consequently, under these conditions, participants giving incorrect responses at test were more likely to navigate to the correct array of objects, but to the wrong location within that array, than they were to navigate to the correct position within an array, but the wrong array. The removal of the physical boundaries, therefore, appeared to change what participants remembered about encountering the objects in the exploration phase of the experiment (i.e., object-location bindings).

The data reported by Marchette et al. (2017) provide some evidence in support of the notion that physical boundaries exert some influence over event models; however, the comparison between boundaries versus no-boundaries is somewhat crude, and it is possible to provide alternative accounts for the effect described above. For instance, in the experiments Marchette et al. (2017) conducted with buildings present, there were more contexts in the environment, or least more well-defined contexts, compared to when the buildings were not present. In keeping with the retrieval interference effects noted earlier (Gurguryan et al., 2021; Radvansky et al., 2011; Radvansky & Zacks, 2017), this may have led to high levels of retrieval interference when the buildings were present, but much lower levels of retrieval interference when they were

not present. Due to these differing levels of retrieval interference, participants might be expected to mistake the building in which an object was encountered to a greater extent than they would confuse the array in which object was encountered when there were not buildings present. It is crucial to note here, though, that the purpose of Marchette et al.'s research was to examine whether we define spatial locations in a hierarchical global-to-local manner (i.e. remembering the building an object was in, and then location within that building), or whether global and local spatial representations are encoded separately. It is hardly surprising, therefore, that their experimental design does not adequately address our reinterpretation of their data in terms of physical boundaries exerting control over event memories.

In summary, there is now consistent evidence that physical boundaries provide effective event boundary cues for event segmentation (e.g. Radvansky et al., 2011; Radvansky & Copeland, 2006); however, it is yet to be determined whether the spatial properties of physical boundaries influence event memory beyond this segmentation process. The purpose of the present set of experiments, therefore, was to examine if manipulations to the spatial properties of the boundaries within an environment would lead to different biases in event memory. To achieve this, we employed an object-memory paradigm that has been used extensively in examining aspects of episodic memory (e.g., Horner et al., 2016; Hupbach, Gomez, & Nadel, 2011; Merriman, Ondřej, Roudaia, O'Sullivan, & Newell, 2016; Miller, Lazarus, Polyn, & Kahana, 2013; Pacheco, Sánchez-Fibla, Duff, & Verschure, 2017). Following Marchette et al. (2017), participants were required to visit buildings in a virtual environment that contained unique objects, before receiving memory probes in which they were required to navigate to the location where they remembered encountering a given object. Importantly, the environment in each experiment was ostensibly the same (e.g. the same number buildings, each containing the same number of objects); thus, any changes in the recollection of encountering objects across experiments would be due to our manipulation of the spatial properties of the building walls. In addition to assessing if our manipulations to the spatial properties of boundaries influenced recall of object-location bindings, we also explored possible sources of non-spatial interference when recalling this information (see Section 15). Here, we analysed recall of objects as a function of when they were encountered during exploration, with the expectation that objects that were contained within the first- and sixth-visited buildings might be least subject to interference during initial encoding. If this were the case, we would expect to observe better recall of objects contained in the first- and sixth-visited buildings, compared to the objects that were housed in the other four buildings.

2. Experiment 1

The purpose of Experiment 1 was two-fold. First, using different software and experimental cues, we wished to confirm that we could replicate the position-preserving bias in event memory that was consistently observed in the experiments reported by Marchette et al. (2017) where physical boundaries were present. Second, and of more theoretical interest, we wished to assess if this result would replicate when controlling for a potential confound in their experiments, in which 32 objects were split equally across four buildings in the environment. Under these circumstances, an object's position within a building was a relatively more valid signal of an object's location compared to the identity of the building. Following the literature examining the effects of relative validity on learning in the spatial domain (e.g. Kosaki, Austen, & McGregor, 2013), this preparation might have led to a bias for encoding the position of an object within a building over the identity of the building the object was in, which would explain any bias towards position-preserving errors during recall. In the present experiment, therefore, we split 36 objects equally among six buildings, such that the position of an object within a building and the identity of the building itself, both signalled six possible locations in which the object may have

been encountered.

2.1. Participants

G*Power 3.1.9.2 (Faul, Erdfelder, Lang, & Buchner, 2007) was used to determine the sample sizes that would be required to detect similar sized effects to those reported by Marchette et al. (2017), when using a two-tailed paired *t*-test, and power of 0.8. Taking only the effect size for Experiment 1 ($d_z = 0.83$) reported by Marchette et al. (2017), which most closely resembles the design of the current experiment, this calculation revealed a required sample size of 14. Using the mean average effect size ($d_z = 0.79$) from all experiments reported by Marchette et al. (2017), which included a null result, this calculation still only revealed a required sample size of 15. Consequently, both calculations indicated considerably smaller sample sizes than Marchette et al. recruited in their experiments ($N = 24$). To aid comparisons across our

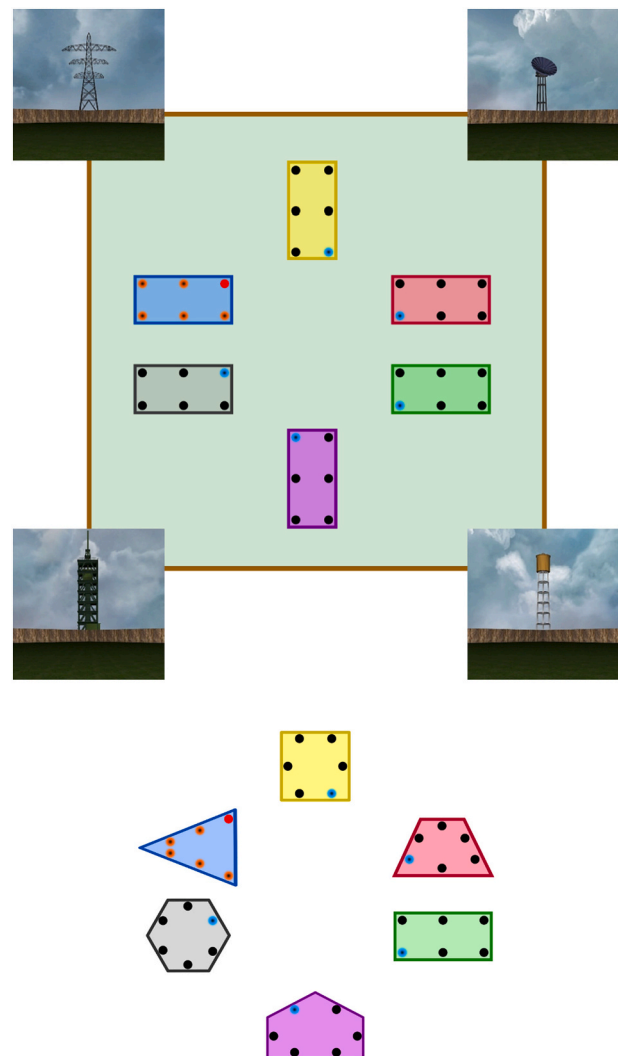


Fig. 1. Schematic representation of the environmental layout for Experiments 1–4. Panel A displays the six uniquely coloured rectangle-shaped buildings used in Experiment 1 and 3, and the distal cues that oriented the wider park environment. Panel B displays the uniquely coloured and different-shaped buildings used in Experiment 2 and 4, which were also situated in centre of the park environment. Filled circles represent the objects within the buildings, with an example of a target memory probe is represented by the red filled circle. A building-preserving error for that trial is indicated by circles with an orange outline, and a position-preserving error by circles with a blue outline. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

studies and theirs, therefore, we too recruited a total of 24 participants (20 female) aged 18–21 ($M = 19.21$, $SD = 0.93$), who took part in the experiment in return for course credit.

2.2. Materials

All virtual environments were constructed using freely available MazeSuite software (Ayaz, Allen, Platek, & Onaral, 2008; www.mazesuite.com), and displayed on an Apple Macbook Pro 12,1 (13.3 in. screen) running on a windows 10 partition. Assuming a walking speed of 2 m/s, the outside environment comprised a 95 m × 95 m square park that had a grass texture applied to the floor, panel fencing around the outside, and a cloudy skybox wrapping the entire world. A unique landmark was placed beyond each corner of the surrounding fence of the square park: an electricity pylon, a water tower, a radio satellite dish (all sourced from turbosquid.com), and a space shuttle launch gantry (sourced from nasa.gov). These landmarks oriented the park such that each building held a unique position within the environment (broadly, North, North-East, South-East, South, South-West, and North-West). Set within the park were blue (RGB: 0, 25, 51), grey (RGB: 25, 25, 25), purple (RGB: 51, 25, 51), green (RGB: 25, 51, 25), red (RGB: 51, 0, 0), and yellow (RGB: 102, 76, 25) buildings (see Fig. 1).

In Experiment 1, all buildings were rectangle-shaped (8 m × 24 m) and orientated such that a short wall was facing the centre of the park. The entrance to each building was indicated by a white door, which was located in the middle of the short wall that faced the centre of the park (see Fig. 2). In addition to the colour of the walls, the six buildings were differentiated by unique textures that were applied to the inside floors

(see Fig. 3). Atop these floors, in each building, there were six identical dark grey (RGB: 20, 20, 20) plinths (1.33 m × 1.33 m). Two plinths were placed either side of the doorway of the building, equidistant from the doorframe and long wall of the buildings. These positions were mirrored for a further two plinths located on the other short wall of the building. Finally, the remaining two plinths were positioned opposite each other, in the centre of the long walls of the building. During the exploration phase of the experiment, resting on each plinth was 1 of 36 unique, nameable objects (e.g. football, laptop, chair). To position the objects within an environment, each plinth and each object was assigned an integer between 1 and 36, and plinth-object pairings were made by randomly drawing without replacement a number from each set.

2.3. Procedure

Prior to beginning the exploration phase of the experiment, participants were instructed that they would freely explore the environment for 15 min (900 s), in which time they should make sure to view all 36 objects contained within the environment. During the exploration phase, a counter in the bottom right of the displayed the time elapsed, in seconds. Participants began in the centre of the park, facing in a random direction between 0 and 359 degrees, and navigated using the arrow keys on the keyboard. Pressing on the “up” and “down” cursor keys permitted the participant to move forward and backward within the arena, respectively, and pressing on the “left” and “right” cursor keys permitted the participant to rotate counter-clockwise and clockwise within the arena, respectively. The doors to each building in the environment were initially closed, but opened when a participant

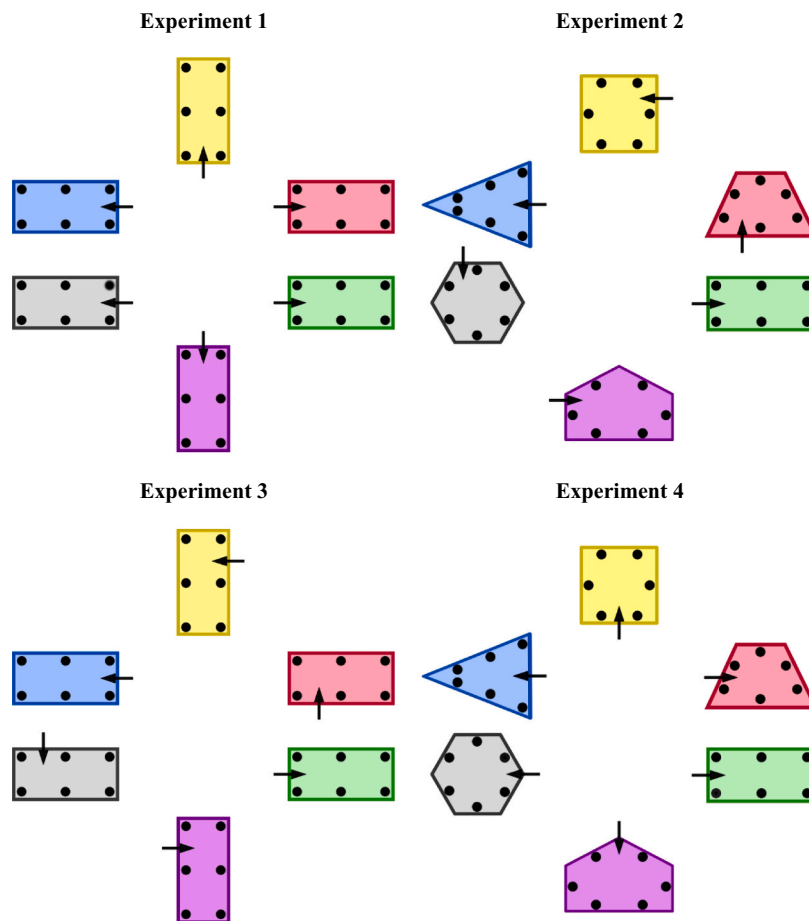


Fig. 2. Schematic representations of the building geometries and doorways used in Experiments 1–4. Arrows represent the location of the doorways in the boundaries of the buildings, and filled circles represent objects within the environment.

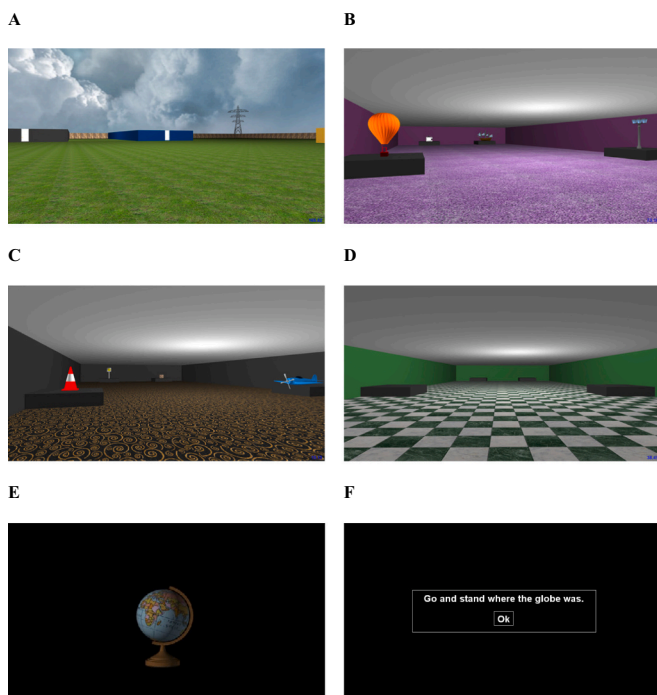


Fig. 3. Screenshots of the experimental task. Panel A) The park environment that contained 6 buildings, oriented by distal cues. Panels B and C) Examples of the inside of the buildings during the exploration phase of the experiment. Panel D) An example of the inside of a building during the memory probes of the experiment. Panels E and F) An example of the picture and text instructions given to participants at the beginning of each memory probe.

approached them. Upon entering a given building, all six objects within that building could be viewed. Following 15 min of free exploration, participants completed a series of memory probes, during which they navigated in the same environment as the exploration phase, but with none of the 36 objects present. On each memory probe, participants were shown a picture of one of the objects in the environment (e.g. a laptop) against a black background screen for 3 s, after which a text instruction (e.g. go and stand where the laptop was) was displayed on screen until participants pressed enter on the keyboard. On pressing enter, participants were placed back at the centre of the park environment facing in a randomised direction between 0 and 359 degrees, and were required to navigate to the plinth on which they remembered the object being located. There was no time limit on any memory probes, with each trial being terminated when participants pressed ‘E’ on the keyboard. Each participant received 36 memory probes, one for each object that was present in the environment during exploration. The order in which object-location bindings were probed was pseudo-randomised for each participant, such that objects from the same building were not probed more than twice consecutively.

2.4. Data analysis

For each memory probe, we classified responses as either correct, a position-preserving error (navigating to the correct position within a building, but to the wrong building), a building-preserving error (navigating to the correct building, but the wrong position within the building), or a non-systematic error (navigating to neither the correct building, nor the correct position within a building). To give a general overview of behavioural performance on memory probes, we compare mean percent correct responses to chance (1 in 36) using a one-sample *t*-test. Although the outcomes of these analyses were not crucial in relation to the aims of our study, they are informative in allowing comparisons of general performance across our experiments.

In keeping with the analysis performed by Marchette et al. (2017), we then expressed, for each participant, the number of position- and building-preserving errors as a proportion of the total number of incorrect responses given in the memory probes (participants that made no incorrect choices were omitted from this analysis). As this calculation included non-systematic errors, the values contributed by each participant to the analysis did not necessarily sum to 100; thus, it was permissible to treat these data with a paired-samples *t*-test. It is, however, possible that this analysis strategy could exaggerate the number of building- and position-preserving errors that a single participant committed. For instance, if a participant committed one non-systematic and one position-preserving error during the memory probes, then they would contribute a value of 50% position-preserving errors to the analysis described above. However, when expressed as a function of all 36 memory probes that were administered, this value would be 2.78%. Given this, we also present a more conservative analysis in which we expressed building- and position-preserving errors as proportions of all 36 memory probes (participants who made no errors at test contributed values of 0 to this analysis). Again, as the values contributed by each participant to this analysis did not necessarily sum to 100%, these data were treated with paired-samples *t*-tests.

To rule out the possibility that biases in performance during the memory probes simply reflected biased exploration in the first phase of the experiment, we compared both the time spent exploring each building and the number of visits made to each building during exploration using a repeated-measures analysis of variance (ANOVA). Alongside statistical analyses, we report measures of effect size (Cohen’s *d* for paired-samples *t*-tests, and partial eta-squared for ANOVAs), as well as appropriate confidence intervals around these effect sizes.

3. Results

3.1. Behaviour during exploration

Each participant visited every building during exploration, and in general participants tended to visit the buildings in a clockwise or anticlockwise order from the first building they entered (21 out of 24 participants demonstrated this pattern of exploration). As shown in the leftmost bars of Panels A and B in Fig. 4, participants spent roughly the same amount of time exploring objects inside each of the six buildings, and also visited each building equally. One-way repeated measures ANOVAs, with a factor of building (North, North-East, South East, South, South-West, North-West), revealed no significant differences in the time participants spent inside of each building, $F(5, 115) = 0.92, p = .47, \eta_p^2 = 0.04[0.00-0.07]$, or the number of visits they made to each building, $F(5, 115) = 0.94, p = .46, \eta_p^2 = 0.04[0.00-0.07]$.

3.2. Overall behavioural performance

As shown in the leftmost bar of Panel A of Fig. 5, the mean percentage of trials in which participants successfully navigated to the correct location of the environment ($M = 64.93, SD = 29.32$) far exceeded what would be expected by chance, $t(23) = 10.38, p < .001, d = 2.12$.

3.3. Building-preserving and position-preserving errors

Two participants made no errors during the memory probes and were, therefore, omitted from our analysis of position- and building-preserving errors that were expressed as a function of only incorrect responses. As shown in the leftmost two bars of Panel B of Fig. 5, the percentage of incorrect trials in which participants committed a position-preserving error ($M = 64.79, SD = 28.30$) was more than the percentage of incorrect trials in which participants made a building-preserving error ($M = 15.92, SD = 24.62$). A paired-samples *t*-test revealed this difference was significant, $t(21) = 4.85, p < .001, d = 1.84$.

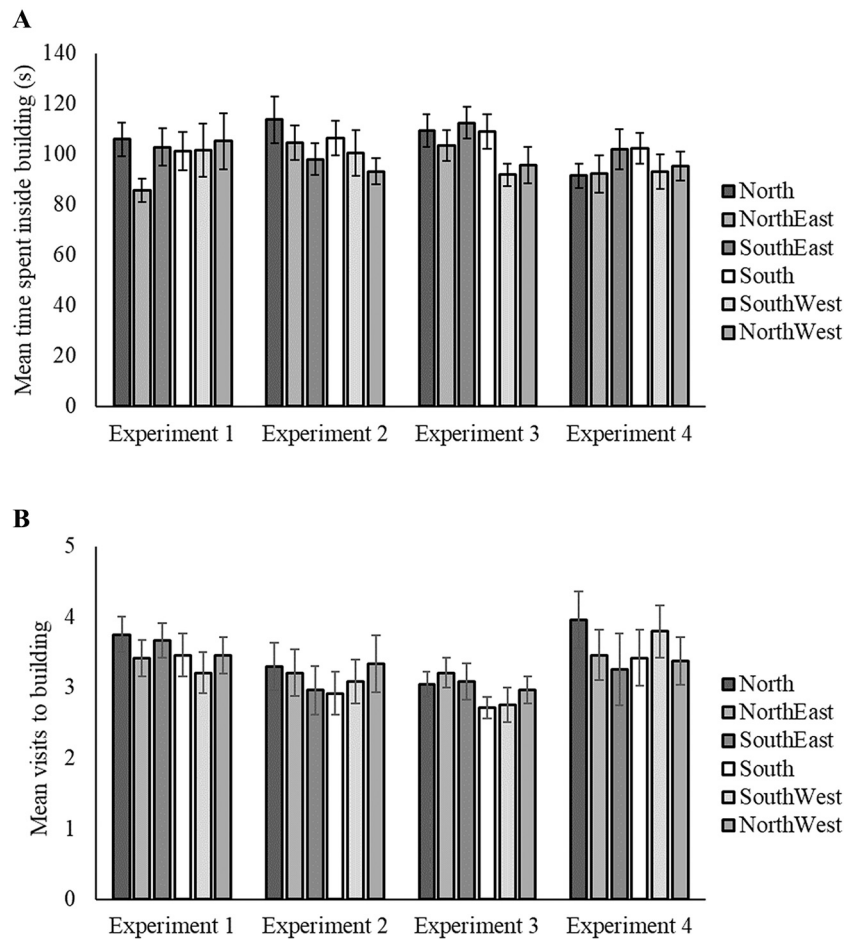


Fig. 4. Patterns of behaviour during exploration. Panel A) Mean time spent in each building by participants during the exploration phase of all experiments. Panel B) Mean number of visits to each building during the exploration phase of all experiments. Error bars represent ± 1 SEM.

[0.90–2.76].

In keeping with this result, the leftmost two bars of Panel C of Fig. 5 show that the percentage of all memory probes in which participants committed a position-preserving error ($M = 22.34$, $SD = 21.38$) was more than the percentage of all memory probes in which participants made a building-preserving error ($M = 5.09$, $SD = 8.73$). A paired-samples t-test revealed this difference was significant, $t(23) = 3.44$, $p = .002$, $d = 1.06$ [0.37–1.72].

4. Discussion

Having freely explored an environment that contained 36 objects distributed equally among six rectangular buildings, participants received memory probes that assessed their memory for encountering the objects in the environment. During these memory probes, participants demonstrated correct recall on over 60% of trials; however, in keeping with the results reported by Marchette et al. (2017), on trials with incorrect recall it was observed that participants were more likely to remember an object's position within a building (position-preserving error) than the building in which an object was located (building-preserving error).

The data reported in the current experiment replicate the effects reported by Marchette et al. (2017), whilst controlling for a potential confound in their design in which 32 objects were split equally among four buildings. As we have mentioned previously, this creates a situation where the position of an object within a building is a relatively more valid cue for memories of encountering objects in an environment, compared to the building in which an object is located. It is important to

note that Marchette et al. (2017) normalised error data in their experiments relative to the overall chances of making a position- or building-preserving error; however, this analysis technique can only equate the position- and building-cues after participant recall. That is, the difference in the relative validity of the cues was still present during encoding which, based on previous spatial memory literature (Kosaki et al., 2013), might have been expected to bias memories for encountering objects towards encoding objects with respect to the relatively more valid position-cue (see also Wagner, Logan, Haberlandt, & Price, 1968). In the current experiment, however, the relative validities of the position- and building-cues were equated, and this did not influence participants' subsequent recall of encountering the objects.

Having replicated the position-preserving bias observed by Marchette et al. (2017) using different experimental software and cues, and whilst also controlling for relative validity, we performed Experiment 2 to explore whether manipulations to the spatial properties of physical boundaries of the buildings would alter participants' event memories of encountering objects.

5. Experiment 2

Experiment 2 was designed to assess if manipulating the spatial properties of the buildings' boundaries within the park environment would influence participants' event memory for encountering objects. First, given the links between episodic memory and egocentric spatial encoding that have been demonstrated previously (e.g. Gomez, Rousset, & Baciu, 2009), it is possible that participants may have encoded object locations in our paradigm schematically, by organising the materials in

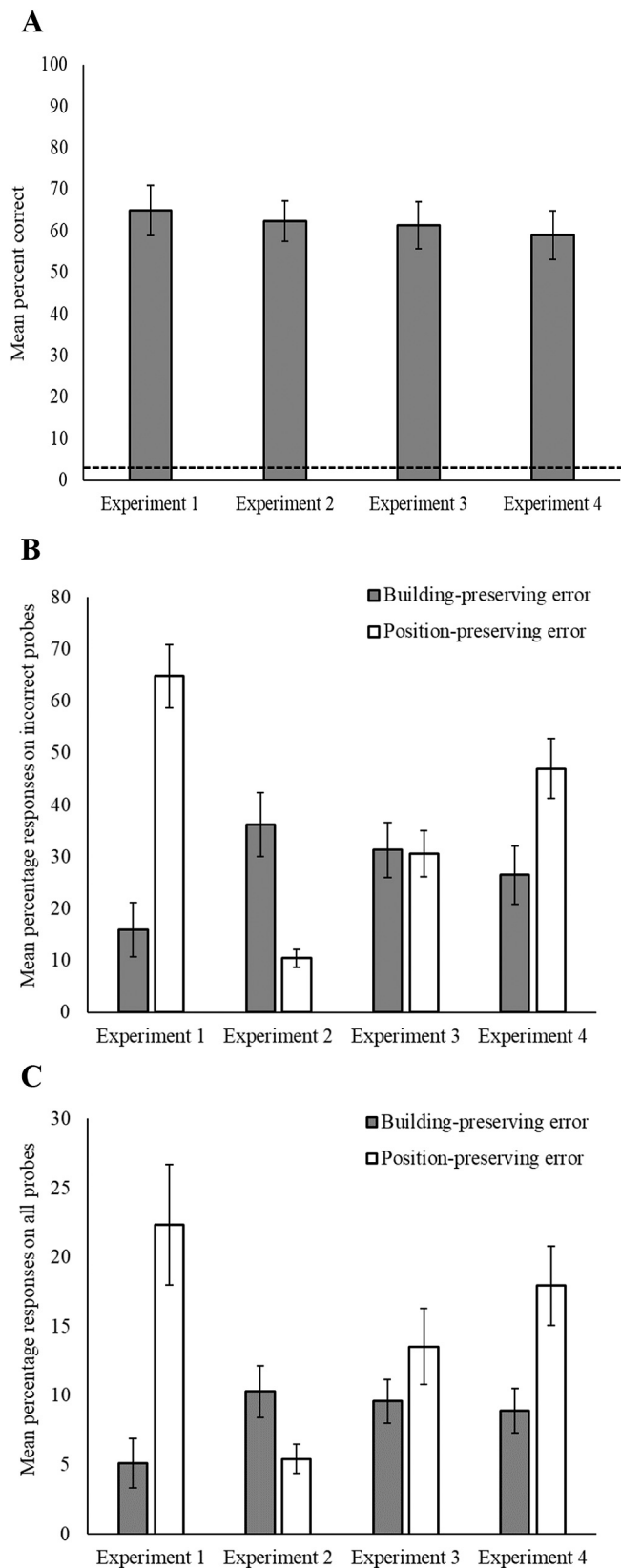


Fig. 5. Participant performance on memory probes. Panel A) Mean percent correct responses across all 36 memory probes, with a dotted line to indicate chance performance (2.78%). Panel B) Position- and building-preserving errors expressed as a mean percentage of only incorrect responses during memory probes. Panel C) Position- and Building-preserving errors expressed as a mean percentage all 36 memory probes. Error bars represent ± 1 SEM.

terms of left-right, and front-middle-back. As the doorways in each building all shared the same locations, the initial view of each object array would be identical for every event model; thus, there would be a high level of interference when recalling object-location bindings. Consequently, it would then be expected that participants confuse the building in which an object was encountered (i.e. commit a position-preserving error) more often than they would confuse the position of an object within a building (i.e. commit a building-preserving error) – the exact result Marchette et al. (2017) reported, and we replicated in Experiment 1.

Second, given what is known from the extensive literature examining how we encode boundary information from the spatial navigational field, it is likely that the geometrically identical buildings also influenced event models in our object-memory paradigm. Both theories of cognitive mapping (e.g. Bicanski & Burgess, 2018; Doeller & Burgess, 2008; Lee, 2017; Poulter, Hartley, & Lever, 2018) and reorientation behaviour (e.g. Cheng, 1986; Gallistel, 1990; Lee & Spelke, 2010; Wang & Spelke, 2002) have suggested that organisms encode a representation of the global boundary shape of an environment. This notion, however, has been contested with a series of shape-transformation experiments in which participants are trained to find a navigational goal with respect to the boundary walls of a rectangle-shaped environment, before being transferred to a kite-shaped arena that contained two right-angled corners. In this novel environment, participants preferentially search in the right-angled corner of the kite that matched the corner that was rewarded during training in the rectangle-shaped arenas (Buckley, Smith, & Haselgrove, 2016a; Lew et al., 2014; see also Pearce, Good, Jones, & McGregor, 2004, Poulter, Kosaki, Easton, & McGregor, 2013), and this transfer of local geometric information has been observed even when the rectangle- and kite-shaped environments were formed from different coloured walls (Buckley, Smith, & Haselgrove, 2016b). In relation to Experiment 1 and experiments conducted by Marchette et al. (2017), these findings suggest that placing objects in buildings that share identical geometries may facilitate confusing memories between buildings (i.e. committing position-preserving errors).

In summary, the bias towards committing position-preserving errors that we observed in Experiment 1 may have occurred because of a high level of interference caused by 1) the egocentric view of the object arrays being identical upon entering a building, and 2) the identical geometry of the boundaries that formed the buildings. To reduce the interference caused by these spatial properties of the environment in current experiment, each building was a unique shape, and we also altered the position of the doorways. We expected these changes would alter the bias towards position-preserving errors relative to Experiment 1.

5.1. Participants

A total of 24 participants (20 female) aged 18–21 ($M = 19.46$, $SD = 0.93$) participated in return for course credit.

5.2. Materials

In the current experiment, the shape of each building was distinct, such that the environment comprised a blue isosceles triangle (wall lengths 8 m \times 24.33 m), yellow square (wall lengths 13.33 m), red isosceles trapezium (wall lengths 8 m \times 14.42 m \times 24 m), purple irregular pentagon (wall lengths 16 m \times 8 m \times 11.31 m), a grey regular hexagon (wall lengths 8.67 m), and the same green rectangular building used in Experiment 1. In keeping with Experiment 1, the shape of the object-arrays in each building matched the geometry of the buildings in the current experiment, and so two objects were placed, equidistant, at the ends of the building facing the centre and the outside of the park environment, with the remaining two objects in each building being placed along the centre of the wall(s) connecting each end of the building (see Fig. 2). Consequently, position-preserving errors across buildings were still possible, based on an ordinal location of the objects

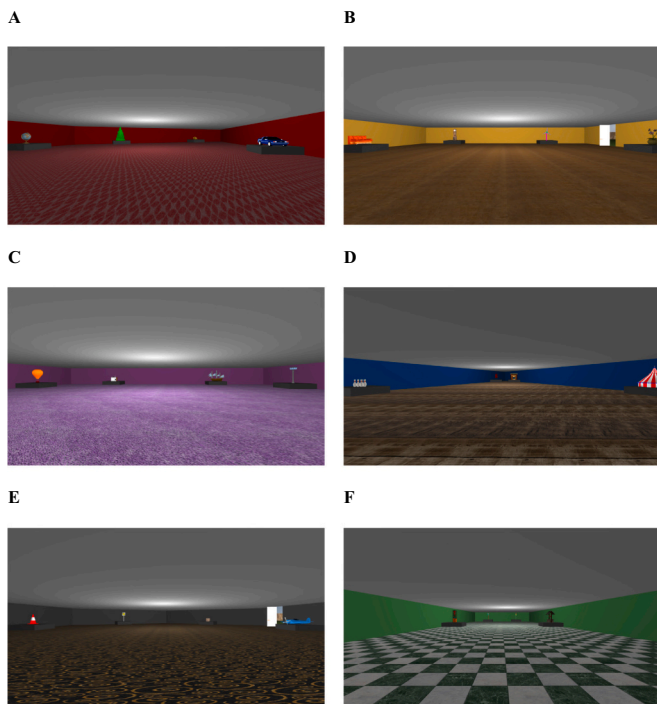


Fig. 6. Screenshots of the environment used in Experiment 2, demonstrating the similarity between the ordinal position of each object within the trapezium- (Panel A), square- (Panel B), pentagon- (Panel C), triangle- (Panel D), hexagon- (Panel E), and rectangle-shaped (Panel F) buildings. The view of each building is taken from a position between the two objects that were located on wall nearest the middle of the park environment, facing towards the wall of the building closest to the perimeter fence of the park. Note that to capture the remaining objects in each screenshot, it was necessary to increase the field of view compared to what participants experienced (see Fig. 3).

within each building (see Fig. 6). In addition, we manipulated the doorway locations such that the doorway to the blue and green buildings were midway along the wall(s) facing the centre of the park environment, the doorways to the red and purple buildings were one-third along the side wall(s) of the building, and the doorways to the grey and yellow buildings were two-thirds along the side wall(s) of the building (see Fig. 2).

5.3. Procedure

All procedural details were the same as Experiment 1.

6. Results

6.1. Behaviour during exploration

Each participant visited every building during exploration, again there was a tendency for participants to visit buildings in a clockwise or anticlockwise order from the first building they chose to visit (21 out of 24 participants displayed this pattern of exploration). As shown in the middle-left bars of Panels A and B in Fig. 4, there was no difference in the amount of time spent exploring objects inside each of the six buildings, and participants also visited each building equally. A one-way repeated measures ANOVA, with a factor of building (North, North-East, South East, South, South-West, North-West), revealed no significant differences in the time participants spent inside each building, $F(5, 115) = 0.90$, $p = .49$, $\eta_p^2 = 0.04[0.00-0.07]$, or the number of times each building was visited, $F(5, 115) = 0.73$, $p = .61$, $\eta_p^2 = 0.03[0.00-0.06]$.

6.2. Overall behavioural performance

As shown in the middle-left bar of Panel A of Fig. 5, the mean percentage of trials in which participants successfully navigated to the correct location of the environment ($M = 62.38$, $SD = 23.92$) far exceeded what would be expected by chance, $t(23) = 12.21$, $p < .001$, $d = 2.49$.

6.3. Building-preserving and position-preserving errors

All participants committed at least one error during the memory probes. As shown in the middle-left two bars of Panel B of Fig. 5, in contrast to the results of Experiment 1, the percentage of incorrect trials in which participants committed a position-preserving error ($M = 10.48$, $SD = 8.38$) was less than the percentage of incorrect trials in which participants made a building-preserving error ($M = 36.21$, $SD = 29.97$). A paired-samples t -test revealed this difference was significant, $t(23) = 3.65$, $p = .001$, $d = 1.13[0.45-1.87]$.

In keeping with the result above, and also in contrast to Experiment 1, the middle-left two bars of Panel C of Fig. 5 show that the percentage of all memory probes in which participants committed a position-preserving error ($M = 5.44$, $SD = 5.01$) was less than the percentage of all memory probes in which participants made a building-preserving error ($M = 10.30$, $SD = 9.14$). A paired-samples t -test revealed this difference was significant, $t(23) = 2.78$, $p = .011$, $d = 0.66[0.15-1.16]$.

7. Discussion

Having freely explored an environment that contained 36 objects distributed equally among 6 buildings, participants demonstrated correct recall on over 60% of the subsequent memory probes. For trials with incorrect recall, however, participants demonstrated a novel bias. Whilst in Experiment 1 (see also Marchette et al., 2017) recall was biased towards remembering the location of an object within a building but not the building itself (position-preserving errors), in Experiment 2 we observed a bias for remembering the building an object was located in, but not the location within the building (building-preserving errors). The current data, therefore, demonstrate that the spatial properties of physical boundaries do not only serve to segment events in episodic memory, but also exert some control over recollection of event models. From the present data, however, it is not clear what aspect of the physical boundaries influenced this change in error bias, since both doorway position and building geometry differed from Experiment 1 – an issue we address in Experiment 3 and 4.

To understand why the physical boundaries of the environment exerted different biases in event memory between Experiments 1 and 2, it is useful to consider the interference effects that were noted in the introduction (e.g. Gurguryan et al., 2021). In Experiment 1, when spatial properties of the buildings were identical, there would be a high degree of overlap between the spatial contexts that defined each event, leading to a high level of interference when recalling what object was associated with an event. In Experiment 2, the spatial properties of the boundaries ensured each building was distinct, causing less interference between event models, and ultimately meaning participants could recall which objects were associated with what events more easily. A possible avenue for future research, here, albeit based on animal experiments in which learned behaviours have been observed to transfer between rectangle- and kite-shaped landmark arrays (e.g. Esber, McGregor, Good, Hayward, & Pearce, 2005), is to examine the relative contributions of the shape of the building boundaries and the shape of the array of objects within a building, in determining the contextual similarity controlled by the building boundaries.

In summary, in contrast to the position-preserving bias observed in Experiment 1, in the memory probes of the current experiment we observed a bias towards building-preserving errors – a finding that is likely the consequence of improved discriminability of events due to the

unique (Experiment 2), as opposed to identical (Experiment 1) spatial properties of the building boundaries. What is not clear from the data of Experiments 1 and 2, however, is whether the change from a position-preserving bias to a building-preserving bias was due to manipulations to the geometry of the buildings, the position of the doorways, or a combination of both. Experiment 3 was performed to assess participants' memories for object-location bindings under circumstances in which the buildings shared the same geometry but were differentiated by the location of the doorways.

8. Experiment 3

By manipulating the spatial properties of the physical boundaries between Experiment 1 and 2, we observed a shift from position-preserving to building-preserving errors at recall, which was likely to be a result of the increased discriminability of events in Experiment 2 relative to Experiment 1. The purpose of the current experiment was to begin to determine the relative contributions of our manipulations (position of the doorways and the geometries of the buildings) in reducing the levels of interference between Experiments 1 and 2. In Experiment 3, we returned to an environment in which each building shared the same rectangular geometry, but in which doorway locations were not the same across all buildings. If the change in memory bias between Experiments 1 and 2 was solely caused by the change in building geometries, then the present Experiment should replicate the position-preserving bias we observed in Experiment 1. Similarly, if the change in memory bias between Experiments 1 and 2 was due to the different doorway positions, then the current experiment should replicate the building-preserving bias we observed in Experiment 2. In contrast, our manipulations to the building geometry and the locations of the doorways between Experiments 1 and 2 may have both reduced interference in recalling object-location associations. That being the case, the environment in Experiment 3 should serve to reduce interference relative to the environment used in Experiment 1, but not to the same extent as the environment in Experiment 2. In this case, we might expect no significant difference between position-persevering or building-preserving responses in the current experiment.

8.1. Participants

A total of 24 participants (21 female) aged 18–23 ($M = 19.42$, $SD = 1.25$) participated in return for course credit.

8.2. Materials

Material details were the same as reported for Experiment 1, except for changes in the positions of the doorways into some buildings in the environment. Whilst the blue and green buildings maintained a doorway in the middle of the short wall facing the centre of the park environment, the doorway to the red and purple buildings was now located one-third along a longer wall of the building, and the yellow and grey buildings had doorways positioned two-thirds along a longer wall (see Fig. 2). As pairs of buildings shared the same doorway position, the spatial layout of objects arrays that participants would see upon entering the yellow and grey, red and purple, and blue and green building pairings would be identical. By having pairs of buildings share the same doorway location, we were able to perform an additional analysis (See Section 8.4) to examine if position-preserving errors were driven by encoding of object locations relative to the doorway. Here, we assessed if position-preserving responses were distributed across all buildings in the environment, or occurred more often between buildings that shared identical doorway locations.

8.3. Procedure

All procedural details were the same as Experiments 1 and 2.

8.4. Data analysis

The spatial layout of the environment for Experiment 3 ensured that the egocentric view of object locations upon entering the blue and green, red and purple, and grey and yellow buildings were identical. We therefore performed an additional analysis in the present experiment, in which we compared whether position-preserving errors were likely to be directed towards the building that shared the same doorway location as the correct building. For each participant, we calculated the proportion of position-preserving errors that were committed to the building that was paired with the correct building, and then compared these values to chance (20%: five possible position-preserving errors, one of which was could be committed inside the building that shared the same doorway location as the correct building).

9. Results

9.1. Behaviour during exploration

Each participant visited every building during exploration, and, as in Experiments 1 and 2, participants explored the environment in a clockwise or anticlockwise order from the first building they entered (23 out of 24 participants displayed this pattern of exploration). As shown in the middle-right bars of Panels A and B in Fig. 4, participants spent roughly equal amounts of time exploring objects inside each of the six buildings, and there were no differences in visits to each building. A one-way repeated measures ANOVA, with a factor of building (North, North-East, South East, South, South-West, North-West), revealed no significant differences in the time participants spent inside of each building, $F(5, 115) = 1.79$, $p = .12$, $\eta_p^2 = 0.07[0.00-0.12]$, or the number of visits to each building $F(5, 115) = 1.60$, $p = .17$, $\eta_p^2 = 0.07[0.00-0.11]$.

9.2. Overall behavioural performance

As shown in the right-middle bar of Panel A of Fig. 5, overall participant performance was almost identical to that reported in Experiments 1 and 2. The mean percentage of trials in which participants successfully navigated to the correct location of the environment ($M = 61.34$, $SD = 28.05$) was greater than chance, $t(23) = 10.22$, $p < .001$, $d = 2.09$.

9.3. Building-preserving and position-preserving errors

Three participants made no errors during the memory probes and were omitted from our analysis of position- and building-preserving errors that were expressed as a function of incorrect responses. As shown in the middle right two bars of Panel B of Fig. 5, the percentage of incorrect trials in which participants committed a position-preserving error ($M = 30.62$, $SD = 20.17$) appeared no different to the percentage of incorrect trials in which participants made a building-preserving error ($M = 31.32$, $SD = 24.43$). A paired-samples t -test revealed this difference was not significant, $t(20) = 0.08$, $p = .93$, $d = 0.03[-0.71-0.77]$.

In keeping with this result, the middle-right two bars of Panel C of Fig. 5 show that the percentage of all memory probes in which participants committed a position-preserving error ($M = 13.54$, $SD = 13.44$) appeared no different to the percentage of all memory probes in which participants made a building-preserving error ($M = 9.61$, $SD = 7.73$). A paired-samples t -test revealed this difference was not significant, $t(23) = 1.45$, $p = .16$, $d = 0.36[-0.14-0.85]$.

Six participants did not commit a position-preserving error during the memory probes. To examine if position-preserving errors were more likely to be directed to the building that shared the same doorway location as the correct building in the remaining 18 participants, we expressed position-preserving errors committed to the building paired with the correct building as percentage of all position-preserving errors

committed. The resulting data ($M = 32.33$, $SD = 29.40$), did not differ from what would be expected by chance, $t(17) = 1.78$, $p = .09$, $d = 0.36$.

10. Discussion

Participants again freely explored an environment that contained 36 objects, distributed equally among six rectangular buildings. In the current experiment, however, only two buildings in the environment had doorways located in the same position with respect to the geometry of the building boundaries, as compared to all six buildings in Experiment 1. In the memory probes that followed the exploration phase of the experiment, in keeping with Experiments 1 and 2, participants demonstrated correct recall on over 60% of trials. However, unlike our previous experiments, there was no significant difference between position- or building-preserving errors. We also observed that position-preserving errors were not committed to the building that shared the same doorway location as the correct building any more than would be expected by chance.

The data from the present experiment are informative in understanding how our manipulations to the spatial properties of the boundaries between Experiments 1 and 2 (changing the locations of the doorways in the buildings and changing the geometry of buildings) led to a shift from position-preserving errors (Experiment 1) to building-preserving errors (Experiment 2). As position-preserving errors were not directed towards the building that was paired with the correct building, it is unlikely that object locations were being encoded with respect to the positions of the doors in our paradigm. Instead, altering the positions of the doorways changed the egocentric view of the object arrays upon entering a building, and this reduced interference in schematic encoding of object locations within event models compared to circumstances in which doorway locations were shared across multiple buildings (i.e. Experiment 1). Moreover, given that the data from the present experiment did not replicate either of the biases we observed in Experiments 1 and 2, it appears that both the geometry of buildings and the egocentric perspective upon entering buildings contributed to reducing interference between event models. What remains to be determined, though, is whether manipulating only building geometries has any effect on event memory – an issue we address in Experiment 4.

Prior to reporting Experiment 4, it is pertinent to discuss the results of the current experiment in relation to Experiment 2 reported by Marchette et al., in which participants entered buildings via different doorways in the exploration and test phases of the experiment. Here, during exploration, participants entered the buildings via doorways located in the middle of the wall that faced the centre of the wider park environment, but at test these doors were locked shut and participants instead gained access to the buildings via doors located on the sides of each building. Despite a seemingly similar manipulation to that which we employed in the current experiment, Marchette et al. (2017) reported a bias towards position-preserving errors over building-preserving errors, whereas we have observed no significant difference. To understand these different patterns of data, it is necessary to consider how the manipulations to doorway locations targeted different stages of memory. In the experiments reported by Marchette et al., changing the location of the doorways between exploration and test phases might impose some difficulty at recall; however, the extent to which this viewpoint manipulation would interfere with recall is unclear given that we have observed that object locations do not seem to be encoded with respect to the doorway. In contrast, in the present experiment, pairs of buildings were differentiated by their doorway locations during exploration, suggesting that the location of doorways during encoding of object-location bindings influences interference when subsequently recalling event models. As we have noted previously, this is likely to be a result of different doorway locations better separating the egocentric perspective of individual events, as compared to shared doorway locations, during encoding.

11. Experiment 4

In Experiments 1–3, we have observed an overall position-preserving bias when building geometries and doorway locations were shared among all buildings (Experiment 1), an overall building-preserving bias when building geometries and doorway locations were unique among all buildings (Experiment 2), and no significant difference between position- and building-preserving errors when building geometries were shared among all buildings but doorway locations were only shared between pairs of buildings (Experiment 3). These different patterns of data suggest that building geometries influence event memory, but it is not yet clear whether changes to building geometry alone led to observable differences in recall of object-location bindings, or whether changes to building geometry are only observed to have an effect when manipulated in combination with doorway locations. To address this issue, in the present experiment, participants explored an environment in which each building was a unique shape but, in keeping with Experiment 1, the doorways in each building were located in the centre of the walls that faced the middle of the park environment.

11.1. Participants

A total of 24 participants (11 female) aged 18–28 ($M = 20.96$, $SD = 3.01$) participated in return for course credit.

11.2. Materials

Material details were the same as reported for Experiment 2, except for changes in the positions of the doorways into some buildings in the environment. In the present experiment, all buildings had doorways located in the centre of the wall(s) that faced the middle of the park (see Fig. 2)

11.3. Procedure

All procedural details were the same as Experiments 1–3.

12. Results

12.1. Behaviour during exploration

Each participant visited every building during exploration, and 19 of the 24 participants explored the environment in a clockwise or anti-clockwise pattern from the first building they visited. As shown in the rightmost bars of Panels A and B in Fig. 4, participants spent roughly equal amounts of time exploring objects inside each of the six buildings, and there were no differences in the number of visits made to each building. A one-way repeated measures ANOVA, with a factor of building (North, North-East, South East, South, South-West, North-West), revealed no significant differences in the time participants spent inside each building, $F(5,115) = 0.78$, $p = .56$, $\eta_p^2 = 0.03$ [0.00–0.06] or the number of visits to each building, $F(5,115) = 1.05$, $p = .39$, $\eta_p^2 = 0.04$ [0.00–0.08].

12.2. Overall behavioural performance

As shown in the rightmost bar of Panel A of Fig. 5, overall participant performance appeared similar to that observed in Experiments 1–3. The mean percentage of trials in which participants successfully navigated to the correct location of the environment ($M = 59.03$, $SD = 28.87$) was greater than chance, $t(23) = 9.55$, $p < .001$, $d = 1.95$.

12.3. Building-preserving and position-preserving errors

Two participants made no errors during the memory probes and were, therefore, omitted from our analysis of position- and building-

preserving errors that were expressed as a function of only incorrect responses. As shown in the rightmost two bars of Panel B of Fig. 5, the percentage of incorrect trials in which participants committed a position-preserving error ($M = 46.98$, $SD = 27.12$) appeared greater than the percentage of incorrect trials in which participants made a building-preserving error ($M = 26.49$, $SD = 26.42$); however, a paired-samples t -test revealed this difference was not significant, $t(21) = 1.91$, $p = .07$, $d = 0.77[-0.06-1.58]$.

The rightmost two bars of Panel C of Fig. 5 show that the percentage of all memory probes in which participants committed a position-preserving error ($M = 17.94$, $SD = 13.90$) appeared greater than the percentage of all memory probes in which participants made a building-preserving error ($M = 8.91$, $SD = 7.86$). A paired-samples t -test revealed this difference was significant, $t(23) = 3.16$, $p = .004$, $d = 0.80 [0.25-1.34]$.

13. Discussion

Having freely explored objects that were housed within six uniquely-shaped buildings that all shared the same doorway location, participants' recall of object-location bindings in the present experiment was biased towards position-preserving errors over building-preserving errors, at least when these responses were expressed as a percentage of all memory probes. At face value, this pattern of performance mirrors the bias we observed in Experiment 1 in which buildings shared the same geometries as well as doorway locations, but to determine if changing the building geometries between Experiment 1 and 4 had any effect on the number of position- and building-preserving errors, it is necessary to compare performance across experiments.

14. Overall analysis

Thus far, we have reported our data as four separate experiments, which is faithful to how the data were collected. However, the conclusions we have drawn regarding how the spatial properties of environmental boundaries influence event memory, and those we will go on to draw in the general discussion, require comparisons of memory performance across environments. Consequently, we provide here a statistical comparison of the data gathered from all four experiments. Behaviour during exploration, in terms of both time spent in buildings and number of visits to buildings did not differ across experiments. There was also no significant difference in the percentage of correct responses recorded across all experiments (see supplementary materials), although more non-systematic errors were noted in Experiment 2 compared to Experiment 1 (see analysis of non-systematic errors in section 15)

14.1. Building-preserving and position-preserving errors

To compare performance on memory probes across experimental environments, we subjected data to a two-way mixed ANOVA, with a within-subjects factor of response type (building-preserving or position-preserving error), and a between-subjects factor of experiment (1–4). Although within-subjects comparisons of response type have already been detailed within the results of each experiment, the outcome of ANOVA analyses are determined by pooled variance; thus, we report pairwise comparisons both across and within experiments here.

For data in which position-preserving and building-preserving errors were expressed as a percentage of only memory probes on which participants committed errors (Fig. 5b), this analysis revealed main effects of response type $F(1, 85) = 5.51$, $p = .02$, $\eta_p^2 = 0.06[0.01-0.16]$ and experiment $F(3, 85) = 9.34$, $p < .001$, $\eta_p^2 = 0.24[0.11-0.35]$, and a significant interaction $F(3, 85) = 12.34$, $p < .001$, $\eta_p^2 = 0.30 [0.15-0.40]$. Across Experiments, pairwise comparisons revealed that more position-preserving errors were committed in Experiment 1 than Experiment 2 ($p < .001$), Experiment 3 ($p < .001$), and Experiment 4 (p

$= .009$), significantly fewer position-preserving errors were committed in Experiment 2 compared to Experiment 3 ($p = .003$) and Experiment 4 ($p < .001$), and significantly more position-preserving errors were committed in Experiment 4 compared to Experiment 3 ($p = .018$). Building preserving errors were more frequent in Experiment 2 compared to Experiment 1 ($p = .011$), but these responses did not differ between Experiment 1 and 3 ($p = .061$), Experiment 1 and 4 ($p = .19$), Experiment 2 and 3 ($p = .54$), Experiment 2 and 4 ($p = .22$), or Experiment 3 and 4 ($p = .55$). Pairwise comparisons of building- and position-preserving errors within experiments were largely in keeping with the data reported for each experiment, with there being a bias towards position-preserving errors in Experiment 1 ($p < .001$), a bias towards building-preserving errors in Experiment 2 ($p = .004$), and no significant difference in Experiment 3 ($p = .94$). With pooled variance in the ANOVA, however, there was a significant bias towards position-preserving errors in Experiment 4 ($p = .028$), which was not observed in our paired samples t -test (see Section 9.3).

For data in which position-preserving and building-preserving errors were expressed as a percentage of all memory probes (Fig. 5c), there was a significant main effect of response type $F(1, 92) = 14.73$, $p < .001$, $\eta_p^2 = 0.14[0.05-0.25]$, and a significant response type by experiment interaction $F(3, 92) = 7.87$, $p < .001$, $\eta_p^2 = 0.20[0.08-0.30]$, but no significant main effect of Experiment $F(3, 92) = 2.26$, $p = .086$, $\eta_p^2 = 0.07[0.00-0.14]$. Across experiments, pairwise comparisons revealed that significantly more position-preserving errors were committed in Experiment 1 compared to Experiment 2 ($p < .001$) and Experiment 3 ($p = .04$), but there was no significant difference between Experiments 1 and 4 ($p = .30$). Significantly fewer position-preserving errors were committed in Experiment 2 compared to Experiments 1 ($p < .001$) and 4 ($p = .004$), but there were no significant differences between Experiments 2 and 3 ($p = .058$), or Experiments 3 and 4 ($p = .30$). Building preserving errors were more frequent in Experiment 2 compared to Experiment 1 ($p = .034$), but these responses did not differ between Experiments 1 and 3 ($p = .065$), Experiments 1 and 4 ($p = .12$), Experiments 2 and 3 ($p = .78$), Experiments 2 and 4 ($p = .57$), or Experiments 3 and 4 ($p = .78$). Pairwise comparisons of building- and position-preserving errors within experiments were largely in keeping with the data reported for each experiment, with there being a bias towards position-preserving errors in Experiment 1 ($p < .001$) and Experiment 4 ($p = .008$), and no significant difference in Experiment 3 ($p = .24$). With pooled variance in the ANOVA, however, there was no significant bias towards building-preserving errors in Experiment 2 ($p = .14$) – which was observed in our paired samples t -test (see Section 6.3).

15. Non-spatial interference

To explore possible sources of non-spatial interference in our task, we assessed if the order of encountering objects during exploration influenced subsequent recall of object-location bindings. For each participant, we calculated the percentage of correctly recalled object-location bindings within each building, the percentage of responses for which partial recall was observed for objects in a given building (i.e. a position- or building-preserving error was committed), and the percentage of responses in which a non-systematic error was committed. Inspection of Panel A of Fig. 7 suggests that objects in the first-visited building were recalled correctly more than objects in the other buildings. In contrast, Panel B suggests that objects in the first-visited building were least likely to be only partially recalled, with partial recall being most prevalent for the objects housed in the fourth-, fifth- and sixth-visited buildings. The data presented in Panel C of Fig. 7 suggest that recall in which participants remembered neither the building an object was housed in, nor the position of an object within a building, was observed less for the first-visited building compared to other buildings. These data were entered into two-way mixed-measures ANOVA, with a within-subjects factor reflecting the order in which participants first visited the buildings during exploration (first through

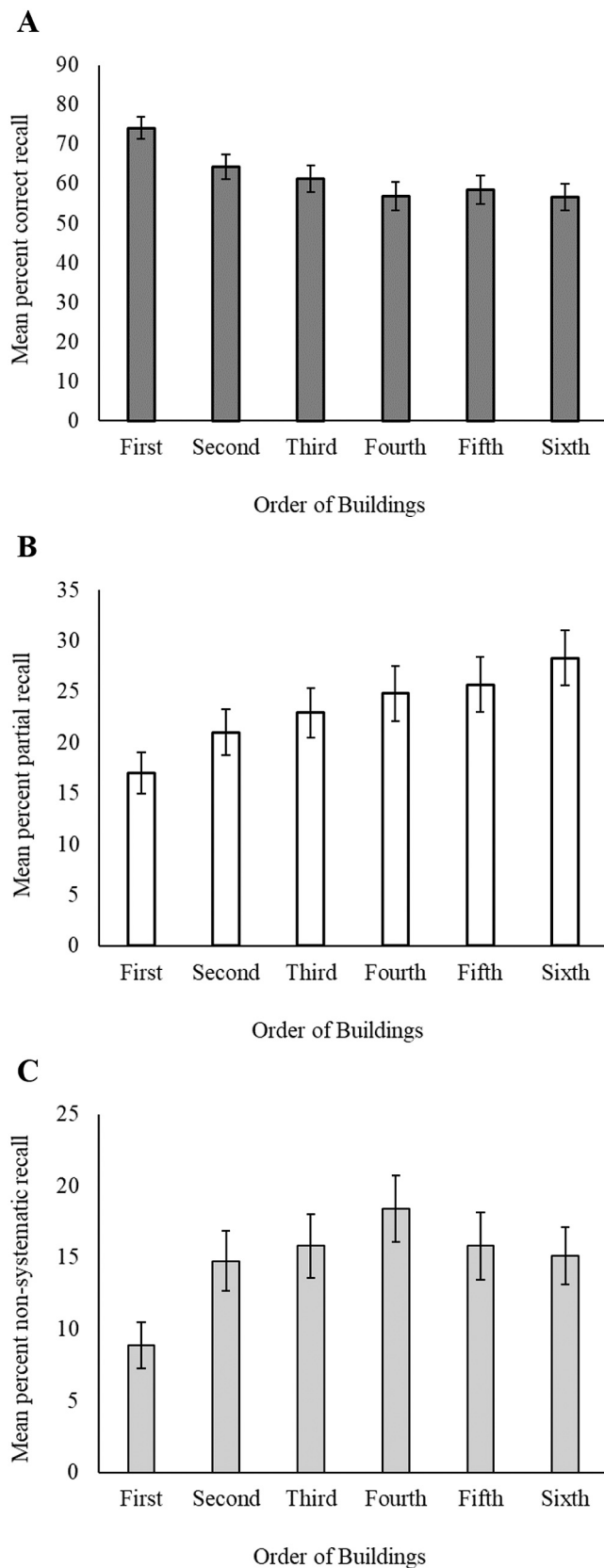


Fig. 7. Participant performance on memory probes as function of the order in which buildings were visited during training. Panel A) Mean correct recall for the objects in each building. Panel B) Mean partial recall (i.e. position- and building-preserving errors) for the objects in each building. Panel C) Mean non-systematic recall for the objects in each building. Error bars represent ± 1 SEM.

to sixth), and a between-subjects factor of Experiment (1–4).

For correct recall, this analysis revealed a main effect of building order $F(5, 460) = 10.74, p < .001, \eta_p^2 = 0.11[0.05–0.14]$, but no main effect of Experiment $F(3, 92) = 0.19, p = .90, \eta_p^2 = 0.006[0.00–0.02]$, nor an interaction $F(15, 460) = 1.68, p = .053, \eta_p^2 = 0.05[0.00–0.06]$. Pairwise comparisons revealed that objects located in the first building a participant visited were recalled correctly more often than objects housed in all other buildings (all $ps < 0.001$). Correct recall of objects in the second building participants visited did not differ to correct recall of objects in the third-visited building ($p = .28$), but was significantly higher than recall of objects in the fourth- ($p = .01$), fifth- ($p = .045$) and sixth-visited ($p = .01$) buildings. All remaining comparisons were non-significant ($ps > 0.052, < 0.95$).

For partial recall, our analysis revealed a main effect of building order $F(5, 460) = 4.58, p < .001, \eta_p^2 = 0.05[0.01–0.07]$, but no main effect of Experiment $F(3, 92) = 2.26, p = .09, \eta_p^2 = 0.07[0.00–0.14]$, nor an interaction $F(15, 460) = 1.28, p = .21, \eta_p^2 = 0.04[0.00–0.04]$. In keeping with the fact that objects in the first-visited building were recalled correctly more often than objects in any other building (see analysis above), pairwise comparisons revealed that partial recall was significantly lower for objects in the first-visited building compared to the buildings visited third ($p = .023$), fourth ($p = .002$), fifth ($p = .002$), and sixth ($p < .001$), but there was no difference in partial recall between the first- and second-visited building ($p = .08$). Objects located in the sixth-visited building were also partially recalled more often than objects in the second- ($p = .008$), and third-visited buildings ($p = .028$). All remaining comparisons were not significant ($ps > 0.073, < 0.742$).

For non-systematic recall, the ANOVA revealed a main effect of Experiment $F(3, 92) = 3.71, p = .014, \eta_p^2 = 0.11[0.01–0.19]$, building order $F(5, 460) = 4.29, p = .001, \eta_p^2 = 0.04[0.01–0.07]$, but no interaction $F(15, 460) = 1.20, p = .27, \eta_p^2 = 0.04[0.00–0.04]$. For the main effect of Experiment, post-hoc pairwise comparisons revealed that more non-systematic errors were committed in Experiment 2 compared to Experiment 1 ($p = .001$), but all other comparisons were not significant ($ps > 0.07, < 0.75$). For the main effect of building order, post-hoc pairwise comparisons revealed that fewer non-systematic errors were committed for the objects housed in the first-visited building compared to all other buildings ($ps < 0.004$), but all other comparisons were not significant ($ps > 0.098, < 0.87$).

As the data entered into the analyses above were not strictly continuous (calculating percentages across the 6 objects in each building meant there were only 7 possible values, ranging from 0 to 100 in one-sixth increments) we also performed non-parametric within-subjects ANOVAs (i.e. collapsed across experiments) to assess the effect of building order on correct, partial, and non-systematic recall. For correct recall, this Friedman test was significant, $X^2(5) = 32.7, p < .001$, and Durbin-Conover pairwise comparisons revealed that correct recall in the first-visited building was significantly higher than recall in all other buildings ($p < .005$). Correct recall was also higher for the second- versus the fourth- ($p = .047$) and sixth-visited building ($p = .018$), but all other comparisons were not significant ($ps > 0.18, < 0.95$). For partial recall, the Friedman test was also significant, $X^2(5) = 16.70, p = .005$. Durbin-Conover pairwise comparisons revealed that partial recall in the first-visited building was significantly less than partial recall in the fourth-, fifth-, and sixth-visited buildings ($p < .01$), and also that partial recall was less in the second-visited building compared to the sixth ($p = .012$). All other comparisons were not significant ($p > .05, < 0.85$). For non-systematic recall, the Friedman test was also significant $X^2(5) = 17.9, p = .003$, and Durbin-Conover pairwise comparisons revealed that incorrect recall was observed less in the first-visited building compared to all other buildings ($ps < 0.017$), but comparisons between all other buildings were not significant ($ps > 0.01, < 0.92$).

16. General discussion

In the four experiments reported here, participants explored an

environment that contained 36 objects split equally among six buildings. Following this exploration phase, participants received memory probes in which they were required to recall object-location bindings. Experiment 1 was conducted with rectangle-shaped buildings, each of which had a doorway located in the wall facing the centre of the park environment. Under these circumstances, participants displayed an overall bias towards remembering the location of an object within a building, but not the building itself. In Experiment 2, each building within the environment was a unique shape, and the egocentric view of object arrays upon entering each building was also unique owing to the different doorway locations. Here, we found evidence of the opposite overall bias, and participants were more likely to remember the building an object was located in, but not the position of an object within a building. In Experiment 3, the environment comprised six rectangular buildings, of which only pairs of buildings shared the same doorway locations, and we observed no significant difference in recall based on the position of an object within a building or the identity of the building. Finally, in Experiment 4 the building shapes were unique, but all doorways were located in the centre of the wall(s) that faced the middle of the park environment. Under these circumstances, we again observed an overall bias towards position-preserving errors.

As we detailed in the introduction, it has been consistently demonstrated that physical boundaries serve to segment the continuous stream of sensory information we receive into discrete episodic events (e.g. Radvansky et al., 2011; Radvansky & Copeland, 2006). The data we report here extend our knowledge of how the spatial properties of boundaries (i.e. boundary geometries, and the locations of doorways within boundaries) influence event memory, by demonstrating that manipulations to these spatial properties exert some control over event models. In keeping with the event segmentation literature (e.g. Gurguryan et al., 2021), the effects we have observed across the four experiments are likely to reflect differing levels of interference based on the similarity of the spatial properties of the physical boundaries. When these spatial properties were identical (Experiment 1), we observed that participants frequently mis-remembered the event in which objects were encountered; however, when the spatial properties of boundaries were distinct in Experiment 2, participants were more accurate in remembering the event in which they encountered an object. Importantly, the data from Experiment 3 and 4, in which buildings were differentiated only by doorway locations or their geometries, respectively, failed to replicate the building-preserving bias we observed in Experiment 2 – suggesting that manipulating both doorway locations and building geometries both contributed to the switch from position-preserving to building preserving errors between Experiments 1 and 2. That said, manipulations to only doorway locations (Experiment 3) served to attenuate the position-preserving bias observed in Experiment 1 more than manipulations to the building geometries (Experiment 4). Whilst in Experiment 3 we observed no significant difference between building- and position-preserving errors, in Experiment 4 there was still an overall bias towards committing position-preserving errors, but these were committed less frequently than what was observed in Experiment 1 in our analysis in which preservation errors were expressed as a function of incorrect responses. Taken together, the pattern of data we have observed across four experiments reveals that the spatial properties of physical boundaries in an environment can promote or reduce interference between event models when recalling object-location bindings. Importantly, these biases in memory across the four experiments were a consequence of our manipulations to the spatial properties of the boundaries, and not caused by differences in overall recall accuracy, which was remarkably similar across all experiments.

Following Marchette et al. (2017), our analysis focussed on whether participants correctly recalled object-location bindings, or instead partially retrieved only the position of an object within a building, or only the building in which an object was housed. Of course, as we discussed at various points throughout this manuscript, it is possible that participants encoded the locations of objects by scaffolding onto spatial

schema that are different to those we have imposed in our analysis. For instance, rather than there being 6 locations to encode in each building of Experiment 1, participants may have organised objects in terms of being located at the front, middle, or back of the building, and either on the left- or the right-hand side. Were this to be the case, however, it would not change the interpretation of our data. Given the identical spatial properties of the physical boundaries in Experiment 1, participants in this experiment may have been subject to the least interference in encoding the position of an object within a building, but most subject to confusing these positions between buildings owing to the symmetric structure of the boundaries. Experiment 4 contained a single manipulation (changing the layout of the objects to match the different building geometries) that would be expected to cause at least some interference in scaffolding onto spatial schema relative to Experiment 1 – and we observed evidence for this in terms of position-preserving errors being less frequent in Experiment 4 compared to Experiment 1. Moreover, Experiment 3 contained a single manipulation (changing the view of the object layouts upon entering the building) that would also be expected to interfere with schematic organisation of materials into front-middle-back and left-right – which we again observed in terms of there being no significant difference between position- and building-preserving responses in Experiment 3. Finally, when both manipulations to doorways and geometries were used in conjunction (Experiment 2), there was the most disruption of schematic encoding of position within a building, leading to more building-preserving errors in Experiment 2 relative to Experiment 1. In some respects, then, the manner in which participants encoded object locations is somewhat orthogonal to the conclusion we wish draw from our experiments, which is that the spatial properties of boundaries (i.e. the locations of doorways in the boundaries and the shapes formed by the boundaries) can determine interference in recalling event models. This conclusion is broadly consistent with the literature on partial source retrieval (e.g. Simons, Dodson, Bell, & Schacter, 2004), in that it is harder to distinguish between events that occur within boundaries that share similar spatial properties, and becomes easier to distinguish between event models as the spatial properties of boundaries become more distinct.

Importantly, in relation to the above conclusion, the data we report here demonstrate interference in event memory based on the spatial properties of physical boundaries, rather interference effects from non-spatial cues present in the environment. In every experiment we report here, the colour of the walls forming the buildings and the texture of the patterns on the floors within each building were unique. In every experiment, therefore, participants had the opportunity to associate objects with a readily discriminable event during exploration. Despite this, we observed different biases in event memories within each experiment, which was related to the distinctiveness of the spatial properties afforded by the boundaries of the buildings. That said, comparisons of performance across experiments (see supplementary materials) revealed there were more non-systematic errors committed in Experiment 2 compared to Experiments 1. This suggests our manipulation to both the boundary shape and doorway locations in Experiment 2 did not only influence object-event associations, but also other characteristics of participants' memory traces. A possibility here is that as the spatial properties of the boundaries became more distinct, the amount of information that needed to be encoded increased (i.e. participants could not easily encode position within a building by scaffolding on to spatial schema in Experiment 2 compared to Experiment 1), and this led to participants committing more non-systematic errors at test.

In relation to spatial encoding of information, the data reported here (see also Marchette et al., 2017) suggest that we encode the location of objects in our environment in multiple spatial reference frames, mirroring conclusions drawn in the spatial reorientation literature (Buckley et al., 2016a; Buckley, Smith, & Haselgrove, 2019). Specifically, we can retrieve the locations of objects at only a local-level (remembering only the position within a building), or only a global-level (remembering only the identity of the building). However, in previous experiments using

the same object-memory paradigm as we employed here (Marchette et al., 2017), and the location updating paradigm (Horner et al., 2016), it has been observed that participants fail to remember to global context in which an object has been encountered. In discussing these patterns of results, Marchette et al. liken this phenomena to remembering the position of a passage of text on a page of a book, but not the exact page the excerpt is from. A more navigationally relevant example might be shopping in a supermarket to which you are unaccustomed, and using the memory of product locations in a familiar store to guide behaviour in the unfamiliar store. It is important to note, though, that everyday future-oriented navigation based only upon local-level representations would lead to rather erratic behaviour. For instance, notwithstanding the contribution of semantic memory, one might remember that medicines are located and dispensed from behind a counter in a building (local-level representation), but not whether that counter was located at the pharmacy or the airport (global-level representation). Our data suggest that the spatial properties of boundaries may help resolve this problem. When doorway locations and environmental geometries are distinct (Experiment 2), participants were able to correctly recall, and navigate to, the building in which they had previously encountered a given object, even if they could not always retrieve the local-level information about the precise location within the building. What remains to be determined is whether local- and global- representations are retrieved independently, or whether there is some dependency in recall of these representations, such that the probability of recalling a local-level representation is increased having recalled a global-level representation (or vice versa). Our data are unable to speak to this question, and it is likely that designs to address this issue will need to be amenable to dependency analyses (Horner & Burgess, 2013, 2014; see also Joensen, Gaskell, & Horner, 2020; Ngo & Newcombe, 2021).

The observation that people frequently confuse memories between events that share the same spatial properties (Experiments 1, see also Marchette et al., 2017) may have practical applications in the design of large buildings. For instance, the present findings may be especially important in the context of designing ‘dementia friendly’ care homes. Declines in navigational abilities are among the first symptoms of Alzheimer’s Disease and Mild Cognitive Impairment (e.g. Gellersen, Coughlan, Hornberger, & Simons, 2021; see also dePolvi, Rankin, Mucke, Miller, & Gorno-Tempini, 2007; Pengas et al., 2010), and Alzheimer’s Disease is also associated with poorer binding of items in memory (e.g. Lowndes et al., 2008; see Dubois et al., 2014 for a comprehensive review) – observations that are consistent with the brain areas affected in early stages of these conditions (Coughlan, Laczó, Hort, Miniñane, & Hornberger, 2018). A number of guidelines for producing dementia friendly care homes emphasise the importance of wall colours in defining different regions of the care home environment (see O’Malley, Innes, & Wiener, 2017); however, our data suggest that such cues may not help care home residents if the spatial properties of physical boundaries are too similar. Instead, our data indicate that architects of care homes should focus on creating floor plans in which spatial layouts are not repeated, and symmetry avoided. In keeping with this proposal, previous research that has found L-shaped corridors (not symmetrical) produce less disorientation than H-shaped corridors (symmetrical) in care home settings (Elmståhl, Annerstedt, & Ahlund, 1997) and, together with the data presented here, such findings may well reflect that walls and doorways seem particularly important in place cell responding (O’Keefe & Burgess, 1996; Spiers, Hayman, Jovalekic, Marozzi, & Jeffery, 2015; see Jeffery, 2019 for a review).

Given that the spatial properties of boundaries influence both event segmentation (e.g. Radvansky & Zacks, 2017), and the discriminability of events within bounded environments (our current data), future research may consider the influence of boundary information in relation to spatial scaffolding theories of episodic memory (see Robin, 2018 for a review). According to this class of theories, spatial representations act as a template onto which we can bind our memories for non-spatial components of events. This notion has received support from numerous

studies of autobiographical memory (e.g. Robin, Wynn, & Moscovitch, 2016), in which it has been observed that memories of events are more detailed for familiar relative to unfamiliar contexts (e.g. Arnold, McDermott, & Szpunar, 2011; Robin & Moscovitch, 2014, 2017; Szpunar & McDermott, 2008), and that the retrieval of spatial cues elicits more detailed recall of episodic events compared to event and object cues (Hebscher, Levine, & Gilboa, 2018; Sheldon & Chu, 2017). Whilst the experiments we have reported here focussed on object-location associations formed during free-exploration, studies in our laboratory are currently examining whether the distinctiveness of spatial boundaries in object-memory paradigms influences temporal judgements related to event models. We also note here that, in our paradigm, participants were cued with an object and required to recall a location. Under the proposals of spatial scaffolding, this may be expected to generate poorer recall compared with cueing with a location and being asked to recall an object. The pattern of biases that emerge when participants are cued with a spatial location, rather than with an object as in our current experiments, remains to be tested.

In addition to assessing spatial determinants of interference in recalling object-location associations, we also conducted exploratory analyses to examine non-spatial sources of interference in recalling events in our task. Here, our analysis revealed that objects that were encountered in the first building a participant visited during exploration were recalled correctly more often than objects that were housed in any other building. Moreover, objects housed in the second-visited building were recalled correctly more often than objects in latter-visited buildings. These data indicate a primacy effect, in which encoding of object-location associations encountered early during the exploration phase were least subject to interference. There was no complimentary recency effect in the data for correct recall; however, partial recall (i.e. committing a position- building-preserving error) was more common for objects housed in the sixth-visited building than the first- and second-visited buildings. To understand why the recency effect we observed emerged in partial recall of object-location bindings, it is important to note that the purpose of our experiments was to examine spatial determinants of interference between events, and our paradigm was not optimal for detecting non-spatial sources of interference. Crucially, as participants were able to freely explore the environment during exploration, once all six buildings had been visited for the first time, we had no control over how many buildings were then re-visited by each participant, or the order in which buildings were re-visited. The analyses discussed above, therefore, focussed on the order in which participants visited buildings for the first (but not the last) time. Consequently, our analysis of recall for the sixth-visited building does not reflect traditional assessments of recency effects, in which analyses focus on the stimuli that were encoded last. To fully address non-spatial determinants of interference in the object-memory paradigm in future research, participants could be led on a ‘guided tour’ of the buildings during exploration, which would permit the necessary level of control to examine primacy and recency effects, and also offer the opportunity to design manipulations that examine whether different patterns of exploration behaviour influence subsequent recall.

In summary, a coherent body of literature has demonstrated that physical boundaries in the world serve as a useful cue in segmenting events in episodic memory. The data presented across the four experiments reported here extend our knowledge of how the spatial properties of physical boundaries exert an influence on event models beyond event segmentation, by demonstrating that the spatial properties of physical boundaries within an environment (i.e. doorway locations and building geometries) are key determinants of interference between event models. There are higher levels of interference between events that occur within bounded environments that share spatial properties, but events become more distinguishable as the spatial properties of boundaries become more distinct from each other. Our data also suggest that the recall of events is subject to interference from non-spatial sources; specifically, the order in which events are experienced.

CRedit authorship contribution statement

Matthew G. Buckley: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Liam A.M. Myles:** Software, Investigation, Data curation, Writing – review & editing. **Alexander Easton:** Writing – review & editing, Supervision. **Anthony McGregor:** Conceptualization, Methodology, Data curation, Writing – review & editing, Supervision, Funding acquisition.

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Appendix A. Supplementary data

Data for each experiment reported here can be obtained from <https://osf.io/eqpj5/> (DOI 10.17605/OSF.IO/EQPJ5). Supplementary data to this article can be found online at [<https://doi.org/10.1016/j.cognition.2022.105091>].

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