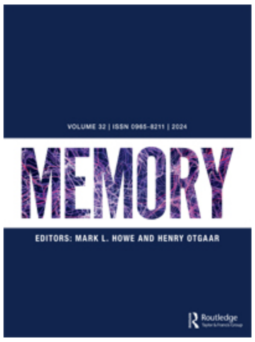

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Spatial context scaffolds long-term episodic richness of weaker real-world autobiographical memories in both older and younger adults

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ABSTRACT

Remembering life experiences involves recalling not only what occurred (episodic details), but also where an event took place (spatial context), both of which decline with age. Although spatial context can cue episodic detail recollection, it is unknown whether initially recalling an event alongside greater reinstatement of spatial context protects memory for episodic details in the long term, and whether this is affected by age. Here, we analysed 1079 personally-experienced, real-world events from 29 older adults and 12 younger adults. Events were recalled first on average 6 weeks after they occurred and then again on average 24 weeks after they occurred. We developed a novel scoring protocol to quantify spatial contextual details and used the established Autobiographical Interview to quantify episodic details. We found improved recall of episodic details after a delay if those details had initially been recalled situated in greater spatial context. Notably, for both older and younger adults, this preservation was observed for memories initially recalled with low, but not high, numbers of episodic details, suggesting that spatial context aided episodic retrieval for memories that required more support. This work supports the notion that spatial context scaffolds detail-rich event recollection and inspires memory interventions that leverage this spatial scaffold.

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Spatial context; autobiographical episodic memory; hippocampus; aging

Central to remembering events in our lives is the rich spatial context in which these events occur (Robin, 2018). We create myriad autobiographical episodic memories embedded in specific spatiotemporal contexts that range from meaningful and cherished experiences to ordinary, moment-to-moment occurrences. When we recollect memories, we conjure the event's spatial context, the defining spatial elements that accompany the event. As an example, suppose one recalls having a picnic at the park last Sunday afternoon. While they recollect the happenings, conversations, and feelings they had during that outing, they will construct a mental representation of the paths they walked along in the park, the picnic tables and trees in the vicinity, and the cool, windy breeze. There is a natural tendency when we recollect memories to generate mental representations of events unfolding within a spatial context (Hassabis & Maguire, 2007; Robin et al., 2016). In light of this, many researchers have proposed that spatial context serves as a scaffold that facilitates autobiographical episodic memory recall (Burgess et al., 2002; Ekstrom & Ranganath, 2018).

Scene construction theory is a prominent framework that explains the relationship between episodic memory and representations of spatial context at a neural level. According to this view, the hippocampus facilitates the mental construction of scenes to which event-specific details can be bound and later visualised during subsequent recollection of the past or during imagination of future events (Hassabis & Maguire, 2007; Robin, 2018; Rubin et al., 2019). In support of this, autobiographical memories in patients with hippocampal damage were limited in spatial and temporal contextual details and perceptual qualities, which compromised their rich re-experiencing of past events (St-Laurent et al., 2009). Similarly, converging evidence from amnesic patients with hippocampal damage and patients with Alzheimer's disease suggest that future event simulations in the absence of hippocampal integrity lacked spatial coherence, which rendered them fragmented and impoverished (Hassabis et al., 2007; Irish et al., 2015). Consistent with the role of the hippocampus in constructing spatially coherent scenes, patients with hippocampal damage did not

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demonstrate the boundary extension effect, whereby one automatically forms and maintains an internal representation of a scene that extends beyond the borders of the presented scene (Maguire & Mullally, 2013; Mullally et al., 2012). Moreover, older adults, who experience age-related declines in the structural and functional integrity of the hippocampus (Gorbach et al., 2017; Kukolja et al., 2009; Rajah et al., 2010), show reduced retrieval of the spatial context of a past event and tend to produce episodic memories with lower contextual detail relative to young adults (Burgess et al., 2001; Spencer & Raz, 1995).

A behavioural manifestation of the close link between spatial context and episodic memory is that spatial context serves as a powerful cue for rich episodic recollection. This research dates to an ancient mnemonic technique called "the method of loci", where one relies on memorised spatial relationships between locations in familiar spatial environments to encode and recollect content (e.g., Dalgleish et al., 2013; Reggente et al., 2020; Roediger, 1980; Yates, 1966). Evidence from recent behavioural investigations has demonstrated that experimenter-provided spatial cues facilitate memory recall. For example, using spatial locations to cue memory for either fictional narratives (Robin et al., 2016) or autobiographical episodic memories (Hebscher et al., 2018; Sheldon & Chu, 2017) led to more vivid recollection and greater recall of event-specific details, relative to using other types of cues (e.g., objects, people, actions, event themes). Additionally, there is a benefit to recalling spatial information early in the retrieval process, such that bringing spatial information to mind first allowed memories to be retrieved faster (Hebscher et al., 2018). Likewise, scene-based details were highest at the outset of autobiographical memory narration, followed by a steady rise in recall of event-specific detail as narration proceeded (Knoff et al., 2022). Moreover, evidence suggests that spatial induction (i.e., orienting participants to recall details about the spatial layout of an unrelated video before generating past or future autobiographical events) enhanced the retrieval of perceptually-based episodic details, relative to control or temporal inductions (Sheldon et al., 2019). Although these findings suggest that explicitly providing spatial cues supports vivid episodic recall, to our knowledge, no studies have examined how spatial context facilitates recall over the lifetime of a memory, as we recall it across multiple, distinct time points. That is, does recalling memories with greater reinstatement of spatial context result in those memories subsequently being better remembered after long delays?

Memory retrieval is thought to be a constructive process, whereby each retrieval or reactivation of an episode incorporates new components of the context at retrieval into the original memory trace, leading to strengthening and reconsolidation of the autobiographical episodic memory (Campbell et al., 2011; Nadel et al., 2007; Schacter et al., 2011). In the current work, we propose that recalling an event's spatial context will shape the subsequent *long-term* representation of the autobiographical episodic memory for that event. In everyday life, we may recall events with various aspects of spatial context naturally interwoven in our memory recollections, such that we relive our events unfolding in a rich spatial context. For instance, one could remember an event by reactivating spatial contextual details from the time of the event, such as objects and landmarks that define the three-dimensional space, descriptions of entities in the scene, the environmental ambiance, spatial relations of the peri-personal and large-scale environment, and sentiments about the space. When one recalls a recent event with greater reinstatement of spatial context, these spatial cues might evoke a stronger sense of the surrounding spatial context where the event took place, which may in turn promote recall of additional episodic and perceptually-rich details of the event. To explicate, we predict that when the episodic details of a memory are recalled embedded in a rich spatial context, the spatial scaffold is strengthened such that episodic richness will be ultimately preserved over time. This proposal draws on theories regarding the constructive nature of memory, such that each recall of a memory will influence the subsequent recollection of that memory (Gurguryan & Sheldon, 2019; St. Jacques et al., 2017), and supports classic ideas on how memory reactivation during retrieval shapes long-term memory representations (McClelland et al., 1995).

Autobiographical episodic memories can be qualitatively different from one another, in relation to how their event-specific details are constructed and subsequently remembered. One way to characterise episodic memory quality is in terms of "memory strength", which is closely related to the degree to which the memory recollection contains rich contextual details that are specific in time and place (Moscovitch et al., 2016; Tulving, 1983, 1985). The episodic memory strength distinction has been well-characterised in work showing that episodic memories may be high in detail specificity and richness (e.g., "stronger"), or contain fewer episodic details such that they are more generic or semanticised in nature (e.g., "weaker") (Levine et al., 2002). Relatedly, autobiographical episodic memory recall is theorised to be composed of highly context-specific information within a narrative structure or conceptual framework (Conway, 2009; Radvansky et al., 2005; St-Laurent et al., 2014), and vivid recollection of our personal past is promoted when there is greater retention of these experiential components of a memory. An open question is whether greater reinstatement of spatial context when a memory is recalled differentially shapes the long-term retention for weaker versus stronger episodic memories. For example, although episodic details of weaker memories may be less durable and more susceptible to forgetting than those of stronger memories (Sadeh et al., 2014), these episodic details from weaker episodic memories might overcome their resistance to forgetting with support from a spatial scaffold, whereas episodic details from stronger episodic memories might generally persist with or without additional scaffolding.

Here, we investigated (1) whether initially recalling autobiographical episodic memories with greater spatial context would promote long-term retention of episodic details of those memories over time and (2) whether this relationship changed with aging, due to age-related declines in hippocampal integrity that may compromise scene construction and episodic memory (Gorbach et al., 2017; Irish et al., 2015; Kukolja et al., 2009). We leveraged an extensive narrative dataset from older and younger adults who collectively recalled over a thousand personally-experienced, real-world events. Recall for these events was tested twice: first at an *initial testing session* (on average 6 weeks after the events occurred) and then again at a *delayed testing session* (on average 24 weeks after the events occurred). To assess spatial contextual details that were spontaneously provided during event recall without prompting from the experimenter in the initial testing session, we developed a novel scoring protocol that enabled a holistic characterisation of multiple aspects of spatial context in real-world memories. To assess episodic richness, we scored recall from both test sessions using an adapted version of the Autobiographical Interview scoring protocol (Levine et al., 2002). Our unique, longitudinal dataset enabled us to ask (1) how the long-term retention of episodic details from real-world memories was affected by whether those details were initially recalled with more spatial context, (2) how this relationship interacted with how well the memory was initially remembered, and (3) whether the aging process affected the relationship between memory for spatial contextual details and long-term episodic richness. We hypothesised that (1) episodic details will be better retained in the long term if they are situated in a spatial context, (2) this effect will be strongest for memories that were recalled with fewer episodic details initially, and (3) due to age-related hippocampal changes, this effect will be diminished in older adults relative to younger adults.

Methods

Participants

We analysed data from an extensive narrative dataset that was aggregated from three previously conducted studies in which 41 older and younger adults collectively recalled 1079 personally-experienced, real-world events. Sample size was determined by the available data from participants who completed both initial and delayed testing sessions (see *Methods, Procedure, Behavioural Task*). These included 12 older adults from the 10-week intervention reported in Martin et al. (2022), 17 older adults from an 8-week intervention (Meade et al., 2023), and 12 younger adults from a 10-week intervention currently being prepared for publication. We collapsed data from the two older adult interventions into one older adult group to compile an older and younger adult dataset. On aggregate, we analysed data from 29 older adults (M_{age} = 69.07 years, SD_{age} = 4.49 years, 16 females, $M_{events\ analysed}$ = 22.72) and 12 younger adults (M_{age} = 27.08 years, SD_{age} = 5.62 years, 9 females, $M_{events\ analysed}$ = 35.00). By using data collected across multiple studies, we were able to amass a large dataset comprising memories of varying quality, richness, and spatial context. Note that we did not include data from the 2-week intervention reported in Martin et al. (2022), because this study involved multiple, routine events that were collected over the course of a single day. By nature, these events are qualitatively different from the more unique events collected in the longer interventions described above. Finally, data from one participant from the 8-week intervention in Meade et al. (2023) were excluded from the current study because the participant did not complete the delayed testing session.

All older adult participants completed the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005; mean score = 27 out of a possible 30, SD = 2.33). Four participants from the 10-week intervention reported in Martin et al. (2022) scored below the cutoff score of 26 on the MoCA (scores of 20, 24, 25, and 25) and three participants from Meade et al. (2023) scored below the MoCA cutoff (scores of 24, 24, and 25), but all participants from the older and younger adult interventions had no documented history of neurological or cognitive disorder. All participants regardless of MoCA score were included in the analyses. All participants provided written informed consent acknowledging the study requirements and received monetary compensation for their time. These studies were reviewed and approved by the Research Ethics Board at the University of Toronto (protocol 31896 and 39014).

Procedure

Event collection period with HippoCamera application

Data from the current study were collected in the context of an experimental memory intervention, in which participants used a smartphone-based, digital memory aid called HippoCamera for eight to ten weeks. HippoCamera guides users to record and review memory cues for personal, real-world events in a way that is informed by principles from cognitive psychology and neuroscience known to improve memory. As described in Martin et al. (2022), HippoCamera users first capture an 8-second audio recording that comprises a self-generated verbal description of the event. Next, they record a 24-second video of the event. After users capture these events, HippoCamera generates integrated cues that combine the verbal description with a speeded version of the video. Specifically, audio is stripped from the 24-second video and the resulting file is accelerated by a factor of three, resulting in an 8-second speeded video. The speeded video is then coupled with the audio recording containing the 8-second verbal description, which serves as the memory cue. Users later are able to replay their memory cues within sessions that contain up to five sequentially presented cues. In these studies, participants were encouraged to record one event per day and replay one to two times per day. Cues were assigned to either a Replayed condition and viewed multiple times, or a within-subjects Baseline condition and never replayed. These studies used a blocked design such that all cues recorded during a given week were assigned to the Replayed condition, and cues recorded during the next week to the Baseline condition. Participants were randomly assigned to begin their first week of the interventions in either Replayed or Baseline conditions and alternated conditions weekly for the duration of the study. Full details of HippoCamera parameters and functionality can be found in Martin et al. (2022).

The software used to collect the event cues for memory interviews the current project re-analysed was programmed by Tactica Interactive (Winnipeg, Manitoba). This version of the application can be obtained for scientific purposes from Apple's App Store and Google Play. As of the time of writing, this is a research-dedicated application that requires an access code that can be obtained from a corresponding author (MDB).

Behavioural task

To assess memory performance, we administered a modified version of the Autobiographical Interview (AI; Levine et al., 2002). Participants were instructed to recall events for which they had previously recorded an autobiographical cue. These tests were administered twice: first during an *initial test session* and a second time during a *delayed test session*. Specifically, events recalled at the initial test session were tested an average of 6 weeks after the event occurred (Older Adults: $M = 5.7$ weeks, $SD = 2.5$ weeks, range = 0.6–12 weeks; Younger Adults: $M = 6.7$ weeks, $SD = 2.5$ weeks, range = 1.9–13.7 weeks). Events recalled at the delayed test session were tested an average of 24 weeks after the event occurred (Older Adults: $M = 25.5$ weeks, $SD = 6.8$ weeks, range = 12.6–44 weeks; Younger Adults: $M = 21.4$ weeks, $SD = 3$ weeks, range = 15.1–29.6 weeks). For both initial and delayed test sessions, some events were tested closer to, and some events were tested farther from, the time that they were recorded, which accounts for the relatively large variance in delays; means and SDs are presented at the group-level, and ranges are presented at the individual-event level. Note that the experimental design of the two 10-week older and younger adult studies was matched, in which each participant recalled up to 40 memories per test session at initial and delayed recall, whereas in the 8-week older adult intervention (older adults only), there were on average 16 events tested at both initial and delayed recall. For this study, we only included events that were tested at both initial and delayed recall in our analysis. Full details of how events were selected for testing can be found in Martin et al. (2022).

Memory for each event was tested by first having the participant view the event-specific cue (i.e., 8-second verbal description coupled with a 3X speeded version of the video) presented on a computer in a laboratory testing room or over a video-conference call. After participants viewed the cue, they were asked to verbally describe what they remembered in as much detail as possible until their thoughts came to a natural end (e.g., "Please tell me as much as you can remember about the event that was just cued"). In some cases, participants responded to a general probe intended to encourage retrieval of additional details without specific guidance (i.e., "Can you tell me any other details about this particular event?") after they provided a verbal description of what they remembered. Given that memory for up to 40 distinct events was probed at each session in the 10-week older adult and 10-week younger adult interventions, with cued-recall responses ranging from 15 s to 20 min per event, general probes were not consistently administered and were asked for events where participants only minimally elaborated on their memories. For the 8-week older adult intervention, general probes were consistently administered. (Note that, across all interventions in both older and younger adults, elaborations following general probes were very limited). Afterward, participants responded to a series of specific probes designed to elicit further remembering of events, time, time integration, place, sensory information, emotions, and thoughts. We did not score details from specific probes, given that details here were provided in response to experimenter-generated questions and were not spontaneously generated by the participants. As such, all data described in this report reflect the sum of details recalled in initial cued-recall responses and general probes. See Figure 1 for an experimental timeline depicting the HippoCamera event collection period and memory test sessions, as well as the scoring measures used in the study.

Episodic richness coding (AI protocol)

We used an adapted version of the AI scoring protocol to assess the episodic richness (i.e., number of event-specific details recalled as a measure of detailed, vivid re-experiencing) of autobiographical episodic memories at initial and delayed recall (Levine et al., 2002). Recall data from initial and delayed test sessions were transcribed using *Temi*, an automated speech-to-text tool, and manually verified for accuracy (https://www.temi.com/). Statements from transcribed memories were segmented into two main detail groups: (1) internal (i.e., episodic details pertaining to the specified event) and (2) external (i.e., details pertaining to general semantic information, personal knowledge, and/or other non-specified events). Our analyses here focused on internal details, which provide a measure of episodic richness and vivid re-experiencing of the event. This included the following subcategories: Events, Time,

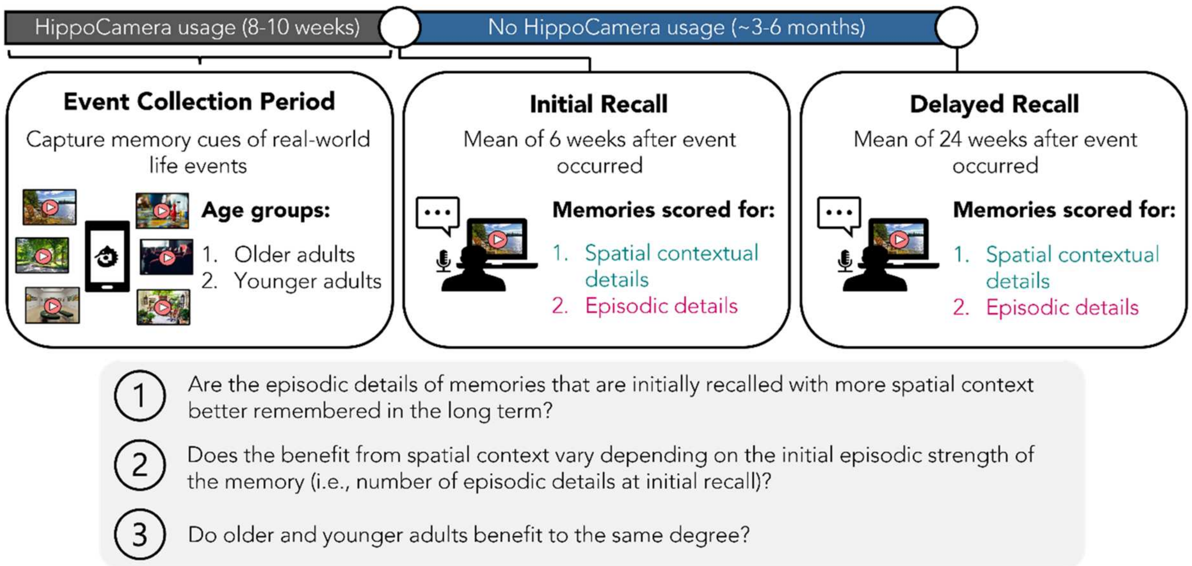

Figure 1. Experimental timeline. Participants used HippoCamera for 8–10 weeks (Event Collection Period) and were then tested on their memory for these events on average 6 weeks after the event occurred (Initial Recall) and then again on average 24 weeks after the event occurred (Delayed Recall). Memories recalled at both time points were scored for spatial contextual details and episodic details so that we could address our three core questions.

Place, Perceptual, and Thought/Emotion. *Events* refer to event-specific episodic information (e.g., happenings, individuals present, weather conditions, physical/emotional actions, reactions in others), *Time* includes date and time of day information (e.g., hour of day, day of week, month, year, season), *Place* consists of the localisation of an event (e.g., building, street, city, part of room), *Perceptual* refers to sensory information across all modalities (e.g., auditory, olfactory, tactile, taste, and visual details, body position, duration), and *Thought/Emotion* represents thoughts and emotional states. The episodic detail count for each event was quantified by summing the number of recalled details across all internal detail subcategories. We omitted recalled episodic details that were apparent in the HippoCamera memory cue from detail counts. This ensured that our measure of episodic richness reflected true re-experiencing of the event rather than what could be recapitulated from watching the multimodal memory cue. See Figure 2 for scoring samples.

All memories that were initially recalled with zero episodic details were excluded and not scored for spatial context, based on the assumption that these memories were already forgotten. In addition, memories that captured mundane events (e.g., personal hygiene, chores, looking out the window) were excluded due to their procedural and non-episodic nature. An exception to this rule was if participants were referring to a mundane event that took place relatively infrequently (e.g., "I am doing laundry during a trip to the cottage with my grandchildren"). This was a judgment call made by the scorer using the event frequency rating that participants provided for each tested event (i.e., 5-point scale to "how frequent is this type of event?", where 1 = unique, 2 = annually, 3 = monthly, 4 = weekly, and 5 = daily), as well as content that participants provided in their autobiographical memory recall. Following these criteria, 126 memories were excluded, resulting in a total of 1079 memories included in the final analysis.

Spatial contextual coding

We developed a novel scoring protocol to assess spatial contextual details (i.e., details pertaining to the location of the event in question) that were spontaneously provided within narrative recall (i.e., after watching an event-specific cue, without the experimenter directly cuing participants to talk about space) of autobiographical episodic memories at initial and delayed recall. This scoring protocol was inspired by previous measures of spatial details (Hassabis et al., 2007; Mullally & Maguire, 2011, 2013) and was developed to allow for a holistic characterisation of spatial context. Spatial contextual details consisted of four subcategories, described in turn below: (1) Space-Defining Entities, (2) Sensory Descriptions of Space-Defining Entities, (3) Spatial Modifiers, and (4) Spatial Thought/Emotion. See Figure 2 for scoring samples. Note that we scored for spatial contextual details at both time points to characterise qualitative changes in richness of spatial detail recall over time, yet we were primarily interested in examining how spontaneously provided spatial contextual details at *initial recall* moderates the long-term retention of episodic richness of autobiographical episodic memories. See *Supplementary Materials, Methods* for the full spatial contextual scoring protocol.

Space-Defining Entities include objects that have utility in coding space and evoke a strong sense of the surrounding 3D space (Mullally & Maguire, 2011, 2013; Troiani et al., 2014). This encompasses objects with

Spatial Contextual Details

Space-Defining Entity | Sensory Description | Spatial Modifier | Spatial Thought/Emotion

Episodic Details

Event | Time | Place | Perceptual | Thought/Emotion

A **Low Spatial Contextual Details & Low Episodic Details at Initial Recall** (Event: Having a picnic and playing ball.)

"*It was a warm day*. A couple of friends and I got together, *walked to the grocery store* and bought salsa, guac, and chips. We sat down to eat on some lawn chairs at the park, and one of my friends brought a volleyball so we decided to play for a bit. I thought it was a fun game. We ended up staying for a pretty long time just relaxing under the trees. I wore running shoes and a light jacket. We also talked about our plans to see a new movie that just came out."

Total # of Spatial Contextual Details: 6

"*It was a warm day*. A couple of friends and I got together, *walked to the grocery store* and bought salsa, guac, and chips. We sat down to eat on some lawn chairs at the park, and one of my friends brought a volleyball so we decided to play for a bit. I thought it was a fun game. We ended up staying for a pretty long time just relaxing under the trees. I wore running shoes and a light jacket. We also talked about our plans to see a new movie that just came out."

Total # of Episodic Details: 15

B **High Spatial Contextual Details & Low Episodic Details at Initial Recall** (Event: Having dinner with the family.)

"This restaurant is East of Austin Street, a couple of blocks away from our house. There is a parkette next to it. We first waited for a spot on the patio but then picked up our menus and *went through a narrow entrance to go inside*. We got hamburgers, fries, and a salad. *The ceiling had these round lights* and I commented on the artwork, these antique-looking paintings they had across the walls. A family with two young kids to our left who had the same meal. We had a good time."

Total # of Spatial Contextual Details: 17

"This restaurant is East of Austin Street, a couple of blocks away from our house. There is a parkette next to it. We first waited for a spot on the patio but then picked up our menus and *went through a narrow entrance to go inside*. We got hamburgers, fries, and a salad. *The ceiling had these round lights* and I commented on the artwork, these antique-looking paintings they had across the walls. A family with two young kids to our left who had the same meal. We had a good time."

Total # of Episodic Details: 12

C **Low Spatial Contextual Details & High Episodic Details at Initial Recall** (Event: Bought fruits for my friend's visit.)

"*My husband and I drove up to the countryside to the bakery*. We found parking at a shaded spot right next to the shop and walked in. We were greeted by one employee who took our order, she had her hair up in a ponytail. The people working there were talking about their weekend plans and they had *instrumental music playing in the background*. It was around midday *so the store was almost empty except for us*, there were two teens sitting at a table at the furthest corner eating croissants and having a good time. We debated whether we wanted to get blueberries but we ended up buying strawberries, peaches, and apple turnovers. The woman who greeted us told us that they just got these peaches delivered from the farmer's market this morning, so she noted they were extra fresh. One employee was decorating a vanilla cake, I thought it was a pretty design. *We walked back to the parking lot* and put the goods in the trunk…"

Total # of Spatial Contextual Details: 9

"*My husband and I drove up to the countryside to the bakery*. We found parking at a shaded spot right next to the shop and walked in. We were greeted by one employee who took our order, she had her hair up in a ponytail. The people working there were talking about their weekend plans and they had *instrumental music playing in the background*. It was around midday so *the store was almost empty except for us*, there were two teens sitting at a table at the furthest corner eating croissants and having a good time. We debated whether we wanted to get blueberries but we ended up buying strawberries, peaches, and apple turnovers. The woman who greeted us told us that they just got these peaches delivered from the farmer's market this morning, so she noted they were extra fresh. One employee was decorating a vanilla cake, I thought it was a pretty design. *We walked back to the parking lot* and put the goods in the trunk…"

Total # of Episodic Details: 24

D **High Spatial Contextual Details & High Episodic Details at Initial Recall** (Event: Went hiking on a mountain trail.)

"It was a Sunday, we started the hike at the *South side of* the *mountain. The trail was rocky and there were massive trees, a lot of moss*, and a couple of purple flowers. It was very pleasant, and my friend wanted to take a photo next to the wooden signpost. The trail we were walking on was *wide*, and at one point I remember there was a couple walking their dog behind us so I moved to the right to let them pass. *Once we got halfway up the trail*, my friend suggested we stop at a bench to have lemonade and eat sandwiches. *We were trying to locate where we were in relation to the parking lot. Once we finally reached the top of the* mountain, I saw people paddling and biking in the distance. We walked down the mountain which took one hour and we decided to take a detour onto a narrow path, *which took us to a creek. It was very windy* on the way back but I was happy to be out in nature…"

Total # of Spatial Contextual Details: 22

"It was a Sunday, *we started the hike at the South side of the mountain. The trail was rocky* and *there were massive trees*, a *lot of moss*, and a couple of purple flowers. It was very pleasant, and my friend wanted to take a photo next to the wooden signpost. *The trail we were walking on was wide*, and at one point I remember there was a couple walking their dog behind us so I moved to the right to let them pass. *Once we got halfway up the trail*, my friend suggested we stop at a bench to have lemonade and eat sandwiches. *We were trying to locate where we were in relation to the parking lot*. Once we finally *reached the top of the mountain*, I saw people paddling and biking in the distance. We walked down the mountain which took one hour and we decided to take a detour onto a narrow path, *which took us to a creek. It was very windy* on the way back, but I was happy to be out in nature…"

Total # of Episodic Details: 25

Figure 2. Illustrative examples of four autobiographical episodic memories scored according to spatial contextual details (on the left) and episodic details (on the right). For illustration, we show memories that are initially recalled with (A) low spatial contextual details and low episodic details, (B) high spatial contextual details and low episodic details, (C) low spatial contextual details and high episodic details, and (D) high spatial contextual details and high episodic details. Bolded/coloured text refers to the segment of the statement that is scored, corresponding to the spatial contextual or episodic detail subcategories identified in the legend at the top of the figure. Italicised text denotes overlap between spatial contextual and episodic richness coding where there was a direct one-to-one relationship between scored details. The total number of spatial contextual and episodic details are tallied and summed. Note that these examples have been compressed for illustrative purposes.

greater permanence/low portability (i.e., rarely move spatial locations), rather than objects with less permanence/high portability which are less anchored to the surrounding space. Additional to these space-defining objects, this subcategory also includes space-defining entities such as real-world spaces or landmarks that make up the large-scale environmental space (e.g., essential to serving as a spatial navigational reference). Examples of these entities include: *building, kitchen, lake, tree, forest, room, door, window, bench, stairs, patio, bed*.

Sensory Descriptions of Space-Defining Entities describe properties of Space-Defining Entities across all modalities (i.e., visual, auditory, olfactory, gustatory, tactile), which was adapted from Hassabis et al. (2007). Included in this subcategory were statements that contained time-dependent properties of entities that the participant experienced at the event (e.g., "there was a *long lineup* at the boardwalk that morning"), non-time-dependent properties of entities that the participant knew to be true from personal experience or culturally-shared knowledge (e.g., "their patio is *rectangular* and *small*"), as well as general weather and atmospheric descriptions that characterise features of a space (e.g., "it was *warm and sunny on the hill*").

Spatial Modifiers comprise spatial prepositions, directional adjectives, and cardinal directions that describe relative positions of entities or directions relative to a vantage point in space. Examples of these include the following: *above, across, against, ahead of, along, among, around, aside, away from, backward, beginning, behind, below, beneath, beside, between, beyond, cross, close, down, east, end, far, farther, forward, in front of, inside, left, middle, near, next to, north, on the bottom, on the corner, on the side, on the top, onto, opposite, outside, over, relative to, right, past, south, straight, toward, under, up, upside down, west, within*. In addition to these, this subcategory also encompasses explicit measurements (e.g., "five feet high"). To ensure that Spatial Modifiers included elements that best captured reinstatement of spatial context, a conservative decision was applied such that certain prepositions (e.g., at, from, in, on, to) were not scored.

Spatial Thought/Emotion are statements that contain introspective thoughts or feelings pertaining to spatial details, such as the small-scale peri-personal space, large-scale environmental space, and/or individual-to-environment spatial relations (e.g., "I've always admired the architectural feature of having a waterfall in the middle of the lobby", "I was thrilled that I was so close to my old childhood home again", "it's relaxing to be away from the hubbub of the crowd").

Repetitions of spatial contextual details were not scored. In other words, if a participant named the same location where the event took place multiple times throughout their recall, that entity was only scored once (e.g., "I went to the *supermarket*" [scored as a Space-Defining Entity at first utterance]; "I bumped into my neighbour at the *supermarket*" [not scored if mentioned again further along in their recall]). One exception is if participants encountered the same location at distinct times during a single event. For example, if a participant described a visit to the bookstore and mentioned walking down a *hallway* to get to the historical fiction collection and walking down the same *hallway* on their way out, the hallway was scored as a Space-Defining Entity twice.

Spatial contextual details that were apparent in the HippoCamera memory cue were omitted from detail counts the first time that they were mentioned during event recall. For example, if the verbal description that the participant recorded for an event was "Attended a jazz festival on Yorkville Avenue" and they recalled "it was in *Yorkville*", *Yorkville* would not be scored as a spatial contextual detail when it is mentioned for the first time. Similarly, if the video that participants recorded for an event included an image of the "park" they went to, and they recalled "I was at the *park*", *park* would not be scored the first time that it is mentioned. However, if participants provided the same spatial information again at any point after their first utterance in their recall, it would be scored once. In addition, if the video shows a bright sunny day, the recall "it was *beautiful and sunny outside*" was not scored, whereas additional spatial contextual details that are not visually depicted in the video (e.g., "there was a *chilly breeze* in the air") were scored. In this way, we ensured that our spatial contextual detail measure reflected spatial contextual reinstatement rather than recall of spatial features that any observer watching the multimodal memory cue could have described. (Note that across all scored events, omitted counts were consistently and uniformly distributed across episodes and were considerably low for both older adults (*Median* Initial Recall = 2; *Mean* Initial Recall = 2.62, *SD* Initial Recall = 2.44; *Median* Delayed Recall = 1; *Mean* Delayed Recall = 1; *SD* Delayed Recall = 1.10) and younger adults (*Median* Initial Recall = 3; *Mean* Initial Recall = 3; *SD* Initial Recall = 2.23; *Median* Delayed Recall = 0; *Mean* Delayed Recall = 0.67; *SD* Delayed Recall = 0.96)).

Scoring for spatial contextual details was completed by M.C. Episodic details were scored by C.B.M., K.S., M.E.M., and M.C. In scoring for spatial contextual details, M.C. was blind to previously scored episodic details (i.e., event recall for a given test session for each participant was presented as a fresh transcript on a word document). Moreover, episodic details were scored at a separate time point, prior to spatial contextual detail scoring, and data files were kept separately until they were combined during subsequent data analysis. Furthermore, initial recall transcripts across all participants were scored before the delayed recall transcripts were scored. As such, one event's delayed recall was not scored immediately after the event's initial recall was scored.

To assess interrater reliability, we followed the approach from the standardised Autobiographical Interview scoring protocol (Levine et al., 2002), in which 10% of the memories were selected at random and scored for spatial contextual details by a second trained scorer (J.D.), with memories from each participant in both age groups represented. Inter-rater reliability of the composite spatial contextual detail score for a total of 108 memories was assessed with the intraclass correlation (ICC; two-way random, absolute agreement) between two independent trained scorers. The coefficient for the spatial contextual detail score composite was 0.94, indicating an excellent degree of agreement in our measure of spatial context.

Overlap between spatial contextual and episodic richness coding

We acknowledge that in certain cases, some details could be separately counted as both a spatial contextual and an episodic detail. Given the characterisation of episodic details per the AI protocol, the definition of episodic memory makes it guaranteed that a subset of episodic details may be spatial. For example, "it was *raining* on the path" is scored as a Sensory Description of Space-Defining Entity detail with the spatial contextual measure but is also scored as an Event detail with the episodic richness measure. Comparing the two scoring procedures, only spatial contextual details that are non-time-dependent and/or based on general knowledge (e.g., "the *building* is *north* of the *parking lot*" or "the *marketplace* is *always crowded*") are semantic and do not overlap with episodic details. Since spatial context was defined as details pertaining to the location of the event, it is expected that some spatial contextual details will also be "episodic" in nature, but other spatial contextual details that are "semantic" in nature were also included, as they also pertain to where the event took place. Importantly, we were primarily interested in determining which elements of episodic memory (e.g., spatial contextual details) are most beneficial to the preservation of episodic details in the long term.

In order to assess the extent to which episodic details recalled overlapped with spatial contextual details, we coded the proportion of overlap between these two measures. This was quantified as the number of episodic details recalled that were also scored as spatial contextual details, divided by the total number of episodic details recalled for each memory. Proportions of overlap were reported for both initial and delayed time points. It is important to note that details were deemed overlapping only if there was a direct one-to-one relationship between spatial and episodic scoring. For instance, "we walked to the *restaurant*" is counted as an overlapping detail because "restaurant" is scored as a Space-Defining Entity with the spatial contextual measure, and the whole statement is scored as an Event detail with the episodic richness measure. In other words, cases where the spatial contextual detail (e.g., the Space-Defining Entity of "restaurant") was central to the episodic detail (e.g., the event of walking to the restaurant) were counted as overlapping. In contrast, cases in which an episodic detail could be understood or provided in another way without the aspect that was scored as a spatial contextual detail were not counted as overlapping. Examples of non-overlapping details include (spatial contextual details italicised for reference): "I was very happy in *the aisles of the store*", "he went *to the counter* to ask the owners for a smoothie", "a family with two kids arrived late and sat *beside us*". Of note, this method allowed us to characterise whether the *episodic details at delayed recall* were primarily spatial contextual details, or whether there was a considerable proportion of episodic details at delayed recall that were distinct and therefore scaffolded by spatial contextual details at initial recall.

Data analysis

Age effects in recall of spatial context, episodic detail, and the overlap between the two

We assessed the effect of age and recall time point in our three measures: (1) recall of spatial contextual details, (2) recall of episodic details, and (3) the overlap between the two detail types. For recall of spatial contextual details and episodic details, we conducted separate generalised linear mixed models using Poisson distributions with the *lme4* package (Bates et al., 2015) on R 4.2.2 (R Core Team, 2022). Poisson models were used to best account for the count-based nature of the number of details recalled (Bolker et al., 2009). For the proportion of overlap between episodic and spatial contextual details, we conducted a linear mixed model with the *lme4* package (Bates et al., 2015). For all models, we estimated fixed effects for age and recall time point and included participants as a random intercept to control for by-subject variability. Age was effect-coded, with younger adults coded as "1" and older adults coded as "−1", and recall time point was effect-coded, with initial recall coded as "1" and delayed recall coded as "−1".

Role of spatial context in preserving long-term episodic recall of memories in older and younger adults

We also investigated (1) the effect of spontaneously provided spatial contextual details and episodic details at initial recall on the number of episodic details at delayed recall (i.e., retention of episodic richness) and (2) whether this relationship changed with age. Here, we conducted a generalised linear mixed effects regression using a Poisson distribution with the *lme4* package (Bates et al., 2015) predicting the number of episodic details at delayed recall, with fixed effects estimated for spatial contextual details at initial recall, episodic details at initial recall, age (i.e., Older adults vs. Younger adults), and their interactions. Crucially, we included the number of episodic details at initial recall to ensure that we were comparing memories recalled with varying levels of spatial context to other memories that had a comparable number of episodic details initially. This approach allowed for a fair point of comparison so that memories scored as having high levels of spatial context were not merely memories with high levels of episodic details. That is, we could assess the influence of spatial contextual details on the retention of episodic richness and examine how the effect of spatial context on long-term episodic richness interacted with how well the memory was initially remembered.

In accordance with best practices, we fit the model with the maximal random effect structure (Barr et al., 2013). In the model, participants were included as a random intercept to control for by-subject variability and a random slope was estimated for spatial contextual details at initial recall, episodic details at initial recall, and their interaction. The model included the following covariates: the replay condition (Replayed vs. Baseline) and the delay between initial and delayed recall. We did this to control for the influence that these variables had on the retention of episodic richness (see *Supplementary Materials, Table S1*). See Martin et al. (2022) for a report on how repeatedly replaying autobiographical memory cues improved detail-rich episodic recollection in a subset of memories that were analysed in the present study.

Spatial contextual details at initial recall and episodic details at initial recall were centred within-participants, whereas the delay between initial and delayed recall (i.e., number of days that elapsed) was grand-mean centred because there was only one observation per participant for this measure. It is important to note that the critical comparisons were made within a single memory and within a single participant. Thus, our analyses take into consideration the inherent variabilities in how different participants may describe their memories (e.g., one individual may tend to recall with flowery language and many details, whereas another individual may tend to be more sparse in sharing details). As noted above, age was effect-coded, with younger adults coded as "1" and older adults coded as "−1". Replay condition was effect-coded, with replayed events coded as "1" and baseline events coded as "−1". Interactions were probed using simple slopes tests with the *emmeans* (Lenth, 2021) and *ggeffects* packages (Lüdecke, 2018). For visualisation and descriptive purposes, we predicted estimated marginal means from the generalised linear mixed model for centred episodic and spatial contextual detail counts according to −/+ one standard deviation within each participant. As such, for each participant, memories with total episodic details at initial recall below one standard deviation were considered to be initially recalled with "low episodic details" and memories with total episodic details at initial recall above one standard deviation were considered to be initially recalled with "high episodic details". We also applied this approach for spatial contextual details at initial recall. By using this approach, we were able to describe memories that were "weaker" and initially recalled with fewer episodic details, as well as memories that were "stronger" and initially recalled with greater episodic details, for events with both low and high spatial contextual details. It is important to note that although visualised in a binned fashion, our model included episodic and spatial contextual details at initial recall as continuous variables.

The *lmerTest* package was used to obtain *p* values corresponding to each fixed effect using likelihood ratio tests with the Satterthwaite approximation for degrees of freedom (Kuznetsova et al., 2017). To determine model fits, we obtained the intraclass correlation (ICC) and conditional and marginal coefficients of determination (R^2C and R^2M values) using the *performance* package (Lüdecke et al., 2021). The ICC for intercept-only models of episodic details at delayed recall was 0.818. For the generalised linear mixed effects regression, the R^2C value was 0.896 and the R^2M value was 0.427. Inferences regarding significance were based on the standard $p < .05$ criteria.

By predicting the effect of our variables of interest on the number of episodic details at delayed recall, we remove concerns of mathematical coupling that can affect measures like forgetting scores (i.e., number of episodic details at delayed recall subtracted from number of episodic details at initial recall). More specifically, when one variable directly or indirectly contains part of another variable, regression analyses measuring changes from baseline can lead to erroneous results (Archie, 1981; Blance et al., 2005). In our case, the number of episodic details at initial recall, an important fixed effect in the current design, would have been a common component of the forgetting score measure.

Results

Recall of spatial context shows no age differences whereas recall of episodic detail was greater in younger adults

Table 1 provides older and younger adult descriptive statistics for spatial contextual details, episodic details, and the proportion of overlap between the two measures at initial and delayed recall. Mean values were derived from the number of details recalled averaged first for events within participants and then averaged across participant means. In terms of spatial contextual details, older and younger adults provided a comparable number of spatial contextual details ($\beta = 0.013$, $SE = 0.09$, $z = 0.14$, $p = .889$). However, in terms of episodic details, younger adults recalled significantly more episodic details than older adults ($\beta = 0.36$, $SE = 0.09$, $z = 4.04$, $p < .001$). Not surprisingly, when comparing across time points, there were more spatial ($\beta = 0.23$, $SE = 0.01$, $z = 27.44$, $p < .001$) and episodic ($\beta = 0.19$, $SE = 0.005$, $z = 37.91$, $p < .001$) details recalled at initial, relative to delayed, recall. Moreover, the proportion of spatial details that overlapped with episodic details was equivalent across age ($\beta = -0.03$, $SE = 0.68$, $t(32.93) = -0.04$, $p = .969$) and across time points ($\beta = -0.17$, $SE = 0.29$, $t(2053) = -0.56$, $p = .574$). On average, the proportions of spatial/episodic overlap were quite

Table 1. Descriptive statistics for measures of spatial context, episodic richness, and the overlap between the two measures at initial and delayed recall for older ($n = 29$, $M_{\text{events analysed}} = 22.72$) and younger adults ($n = 12$, $M_{\text{events analysed}} = 35.00$).

	Mean (SD)			
	Initial recall		Delayed recall	
Measure	Older adults	Younger adults	Older adults	Younger adults
Total spatial contextual details	9.27 (7.35)	8.63 (7.72)	5.14 (4.60)	5.56 (5.89)
Subcategories of spatial contextual details				
Space-defining entities	4.71 (3.86)	4.99 (4.51)	3.03 (2.65)	3.31 (3.46)
Sensory descriptions of space-defining entities	2.17 (2.25)	1.44 (1.83)	0.88 (1.24)	0.83 (1.38)
Spatial modifiers	2.22 (2.26)	1.99 (2.11)	1.16 (1.47)	1.38 (1.97)
Spatial thought/emotion	0.15 (0.38)	0.21 (0.46)	0.07 (0.20)	0.05 (0.20)
Total episodic details***	19.02 (11.09)	33.21 (23.82)	10.80 (8.15)	24.56 (19.13)
Proportion (%) of spatial/episodic overlap	11.50 (12.34)	11.13 (10.26)	11.43 (14.26)	11.55 (11.48)

*** $p < .001$ for age-group comparisons.

low, with 11.50% overlap for older adults and 11.13% overlap for younger adults at initial recall, and 11.43% overlap for older adults and 11.55% overlap for younger adults at delayed recall. This suggests that the majority of episodic details recalled were separate from spatial contextual details.

Weaker memories that had been initially recalled with greater spatial context were better preserved in both older and younger adults

A Pearson correlation revealed that spatial contextual details and episodic details at initial recall had an overall correlation ($r = 0.59$, $p < .001$). This is driven by the nature of memory recall, given that the provision of more episodic details when recalling an event offers more opportunity to also recall corresponding spatial contextual details, especially since these details were measured from the same event description. However, it is important to note that there was not a 1-to-1 relationship between spatial contextual details and episodic details at initial recall. Critically, measures of variance inflation factor (VIF) and tolerance were examined to ensure that multicollinearity was not an issue in our data and that there was no redundancy between spatial contextual details at initial recall and episodic details at initial recall in the context of our model. The presence of multicollinearity is detected by VIF values above 5 and tolerance values below 0.2. All VIF and tolerance values in our model fell within the range of accepted recommendations (Spatial Contextual Details at Initial Recall: VIF = 1.21, Tolerance = 0.83; Episodic Details at Initial Recall: VIF = 1.19, Tolerance = 0.84), indicating that multicollinearity was not a concern for our model and therefore allowing us to assess the influence of spatial contextual details at initial recall on the number of episodic details at delayed recall.

Using a Poisson generalised linear mixed-effects model, we predicted the number of episodic details at delayed recall (i.e., long-term retention of episodic richness) from spatial contextual details at initial recall, episodic details at initial recall, and age (older vs. younger adults), and all their relevant interactions. *Supplementary Materials, Table S1* contains all fit statistics and fixed-effects parameter estimates from the generalised linear-mixed model. We found that the episodic details produced at delayed recall were predicted by a significant main effect of both spatial contextual details at initial recall ($\beta = 0.14$, $SE = 0.04$, $z = 3.62$, $p < .001$) and episodic details at initial recall ($\beta = 0.47$, $SE = 0.04$, $z = 12.85$, $p < .001$). Notably, the number of episodic details at delayed recall were predicted by a significant two-way interaction between spatial contextual details at initial recall and episodic details at initial recall ($\beta = -0.12$, $SE = 0.02$, $z = -4.75$, $p < .001$). Indeed, the two-way interaction was driven by the fact that initially recalling memories with greater spatial context promoted long-term recall of episodic details, but only for memories that were initially recalled with low episodic details ($\beta = 0.25$, $SE = 0.05$, $z = 5.30$, $p < .001$). In contrast, long-term recall of episodic details for memories initially recalled with high episodic details was not influenced by spatial context ($\beta = 0.02$, $SE = 0.04$, $z = 0.40$, $p = .686$), suggesting that the effect of spatial context on long-term episodic recall differed according to the number of episodic details that were initially recalled for the memory.

Although the three-way interaction between spatial contextual details at initial recall, episodic details at initial recall, and age was not significant ($\beta = -0.03$, $SE = 0.02$, $z = -1.30$, $p = .194$), given our stated aim to investigate the effects of aging, we conducted a simple slopes exploratory analysis to characterise the pattern of results described above in our two separate age groups. The results indicate that the two-way interaction described above was apparent in both older and younger adults. That is, regardless of age, initially recalling memories with greater spatial context enabled those memories to be remembered with greater episodic details at delayed recall, but only for memories initially recalled with low episodic details (Older Adults: $\beta = 0.17$, $SE = 0.06$, $z = 3.10$, $p = .002$; Younger Adults: $\beta = 0.34$, $SE = 0.08$, $z = 4.32$, $p < .001$; Figure 3A) and not for memories initially recalled with high episodic details (Older Adults: $\beta = -0.002$, $SE = 0.05$, $z = -0.03$, $p = .974$; Younger Adults: $\beta = 0.04$, $SE = 0.07$, $z = 0.52$, $p = .605$; Figure 3B). Additionally, for memories initially recalled with low episodic details, the relationship between spatial context provided at initial

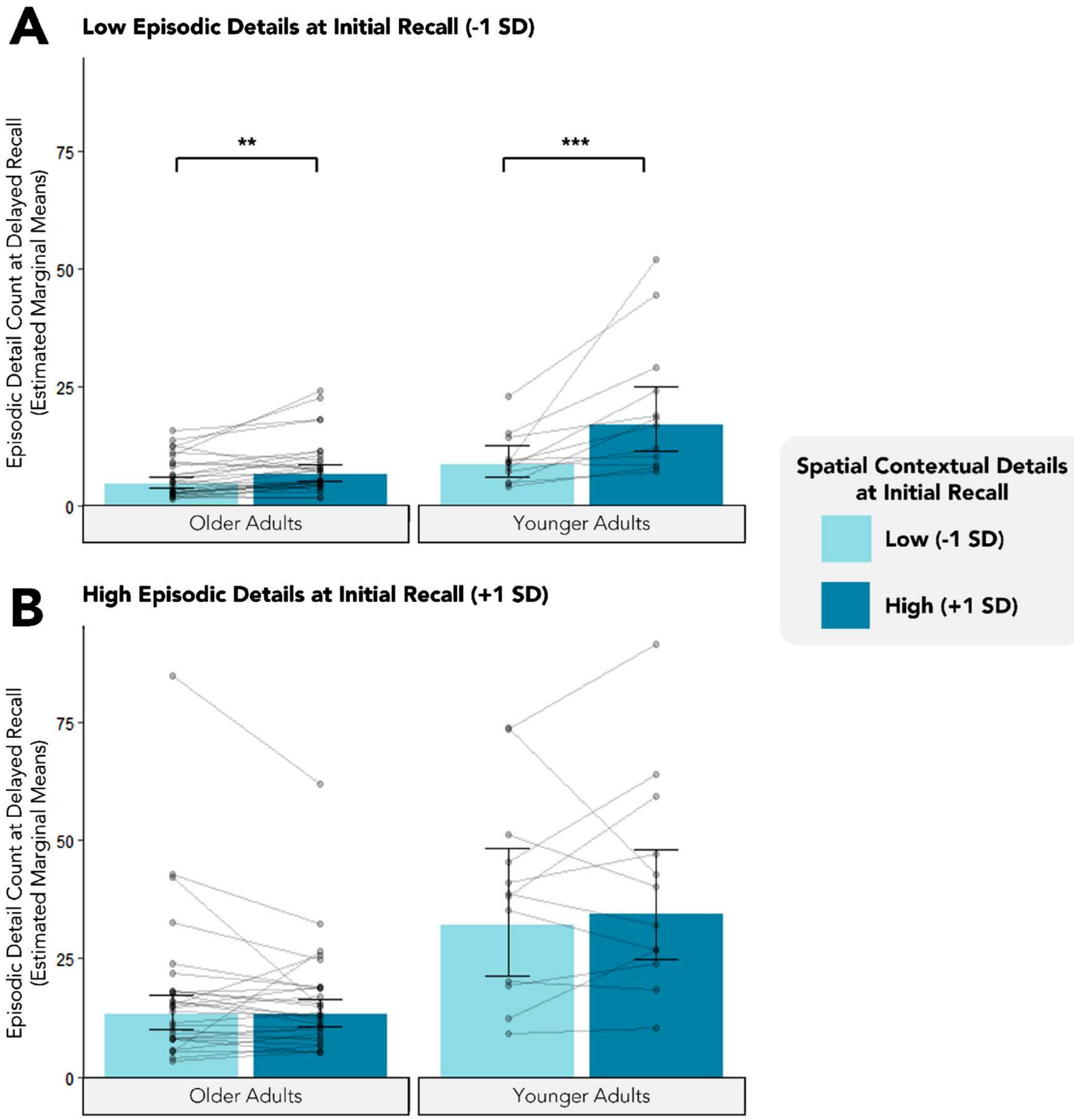

Figure 3. Spatial context selectively preserved long-term retention of episodic richness for memories that were initially recalled with low numbers of episodic details, in both older and younger adults. Estimated marginal means of episodic details at delayed recall for (A) memories that were initially recalled with low episodic details and (B) memories that were initially recalled with high episodic details. Error bars depict confidence intervals. Episodic details at initial recall (low vs. high) and spatial contextual details at initial recall (low vs. high) are binned for visualisation purposes by estimating predicted marginal means of the corresponding centred detail counts according to −/+ one standard deviation within each participant; the statistical model treated these as continuous variables. ** $p < .01$, *** $p < .001$.

recall and the number of episodic details provided at delayed recall was comparable across age groups (Older Adults vs. Younger Adults: $\beta = -0.17$, $SE = 0.10$, $z = -1.75$, $p = .080$) (Figure 3). Thus, in summary, there was not a statistically significant difference between older and younger adults in the extent to which providing spatial context at initial recall strengthened long-term episodic richness of memories.

Interestingly, the pattern of results for our analyses remained unchanged when the seven older adult participants who scored below the cut-off score of 26 on the MoCA were excluded. To explore the presence of systematic differences within our older adult sample, we examined episodic memory at initial recall across MoCA performance. We found that there was no difference in the number of episodic details provided at initial recall between MoCA passers ($M = 16.88$; $SD = 15.12$) and MoCA failers ($M = 17.41$; $SD = 17.37$); ($\beta = -0.04$, $SE = 0.12$, $z = -0.30$, $p = .764$), although we might not have had sufficient power to reveal differences in episodic richness across MoCA performance.

Taken together, the above results capture the degree of reinstatement of spatial context at initial recall and its contribution to long-term episodic richness for memories that were initially recalled with varying levels of episodic detail. We assessed the effect of spatial context on the number of episodic details at delayed recall, while controlling for the number of episodic details initially recalled. Our results demonstrate that long-term retention of weaker autobiographical episodic memories (as defined by fewer episodic details provided at initial recall) can be preserved if those details are recalled accompanied by spatial contextual details. That is, for weaker memories that needed the most support, initially remembering those events with spatial contextual details protected their episodic richness in the long term. Moreover, this effect benefited both older and younger adults to a comparable extent.

Discussion

Here, we demonstrate that initially recalling autobiographical memories in a rich spatial context can scaffold the long-term retention of the *episodic* details of those memories. We leveraged an extensive, longitudinal autobiographical memory dataset from older and younger adults containing narrative recall of 1079 personally-experienced, real-world events that were recalled at two time points (first an average of 6 weeks after the events occurred, and then again an average of 24 weeks after the events occurred). We found that long-term memory for the episodic details of these memories was more likely to be preserved if they were initially recalled situated in greater spatial context. Notably, this preservation of episodic detail was selective to memories initially recalled with low episodic details and was not observed in memories recalled with high episodic details. Moreover, this effect was consistent across older and younger adults. Taken together, these results suggest that remembering the episodic elements of events with greater spatial context scaffolded long-term retention of episodic richness for memories that needed the most support, and that the benefit of the spatial scaffold was unaffected with aging.

Our primary finding that space acted as a scaffold for the episodic richness of memories is consistent with scene construction theory, which posits that the construction of spatially coherent scenes facilitates autobiographical memory recall (Hassabis & Maguire, 2007; Maguire & Mullally, 2013; Robin, 2018). Prior work suggests that cuing spatial information makes memories more accessible, which leads to more detailed and vivid recall (Robin & Moscovitch, 2014; Sheldon et al., 2019; Sheldon & Chu, 2017). One distinction between our work and the earlier work is that we assessed spatial contextual details that participants spontaneously generated after they were presented with an event-specific cue and prompted to recall the cued event. In other words, we captured the degree of reinstatement of spatial context naturally provided within narrative recall for each memory, without the experimenter directly cuing participants to recall spatial details. Whereas previous work focused on experimenter-controlled settings, our unique dataset also provided access to dynamic real-world events, suggesting that our results could be generalisable to autobiographical memory in everyday contexts. Moreover, the longitudinal nature of our dataset allowed us to characterise how spatial context at *initial recall* influences the preservation of episodic details after *long delays*. Thus, our findings provide evidence that embedding episodic details of memories in a rich spatial context at initial recall helped recover and preserve event-specific details that were bound to the space where the event took place.

Critically, we found evidence that spatial context aided recall of episodic information, but only for memories that had been initially recalled with a low number of episodic details. This finding highlights that spatial context is especially important for scaffolding retrieval of episodic details from weaker memories that required more support. This is consistent with the idea that episodic details from weaker memories are less accessible and more vulnerable to forgetting over time, and as a result, their long-term recall may require more powerful contextual cues. Intriguingly, this selective benefit of scaffolding for weaker memories has been observed in other contexts. For instance, prior semantic knowledge has been hypothesised to improve recall for information that was previously weakly or incompletely encoded (Hemmer & Steyvers, 2009; Tompary & Thompson-Schill, 2021), and sleep-dependent benefits on memory retention have also been found to be greater in weaker, relative to stronger memories (Petzka et al., 2021). The weaker episodic memories in our dataset may have been initially remembered with fewer episodic details due to different factors, such as more overlap among memory representations (e.g., multiple episodes of the same event in one's life), less personal relevance, or shallow encoding. Our results here provide evidence that reinstatement of spatial context during initial retrieval can help protect long-term memory for these weaker episodic memories that would otherwise be most vulnerable to losing their episodic richness over time.

In contrast, we found that memories that were initially recalled with high numbers of episodic details were still recalled with high episodic detail after a delay, regardless of the amount of spatial context provided at initial recall. One explanation for this finding is that memories are inherently associative, such that one detail can cue another detail. Spatial context may be an especially good cue for retrieval of additional details, but episodic details can certainly cue additional episodic details associated with the memory. For this reason, these memories with high episodic details may not have needed the spatial scaffold to facilitate retrieval. Interestingly, a recent study demonstrated that scene-based details were provided most at the outset of autobiographical memory narration (Knoff et al., 2022) and preceded a peak in event-specific details, yet scene-based details tapered as event-specific details increased, highlighting a related scenario in which the spatial scaffold is prioritised when it is most needed. Another explanation could be that these high-episodic memories themselves might be more self-defining, emotionally intense, or strongly integrated within participants' life trajectories (Blagov & Singer, 2004; El Haj &

Antoine, 2017; Sutin & Robins, 2007). As a result, other factors might have preserved the salience of these memories and enabled them to continue to be well-remembered over the 4-month delay between testing sessions. Finally, it could also be that the delay period of approximately 4 months after the initial testing session was not enough for the spatial scaffold to show a protective effect in the highest-quality memories. Future studies could determine whether the preservation of episodic details after a delay can also be explained by differences in affective and social content and the extent to which a given memory ties into one's identity or life trajectory. Nevertheless, we anticipate that a longer delay will render even the highest-quality memories more vulnerable to forgetting, allowing spatial context to have a chance to scaffold long-term episodic richness.

In addition, our findings are in line with the notion that autobiographical episodic memory retrieval is a constructive process that involves generating and visualising the spatial context (Herweg et al., 2020; Maguire et al., 2016; Miller et al., 2013; Rubin et al., 2019), as well as reactivating the mental representations that were present at the original encoding event (Conway, 2001; Kent & Lamberts, 2008; Oedekoven et al., 2017; Rugg et al., 2015). Importantly, we show that a stronger recollection of space at initial recall enabled event-specific details to be better constructed again at delayed recall. These findings are in accordance with work showing that the way we retrieve autobiographical episodic memory can have persistent effects on how it is subsequently represented (Gurguryan & Sheldon, 2019) and remembered in the long term (Sekeres et al., 2016; St. Jacques et al., 2017). For example, past work has shown that preferentially emphasizing spatial-perceptual contents of events during initial retrieval dynamically restructured the mental representations that participants have of past experiences on a neural and behavioural level, suggesting that reactivation of spatial contextual information facilitates access to event-specific details and provides a framework for other event details to reside (Gurguryan & Sheldon, 2019). The present work bridges ideas regarding the constructive nature of autobiographical memory with scene construction theory, showing that greater reinstatement of spatial context imbues memories with episodic and perceptually-rich details, which can have prolonged, beneficial effects on memory retrieval over the lifetime of a memory.

Given the nature of our coding protocols, an important question is the extent to which episodic details at delayed recall overlapped with spatial contextual details. To address this, we quantified the proportion of episodic details recalled that had a one-to-one relationship with spatial contextual details. Using this approach, we showed that there was a considerably low proportion of overlap between these two measures, such that only 11.43% and 11.55% of episodic details at delayed recall were also separately coded as spatial contextual details in older and younger adults, respectively. Moreover, when we split memories according to whether the number of episodic details produced at initial recall were −/+ one standard deviation within-participant, we still found that the proportion of overlapping spatial/episodic details were relatively low. Specifically, for memories initially recalled with low episodic details, the proportions of overlap at delayed recall were 10.70% for older adults and 9.56% for younger adults. For memories initially recalled with high episodic details, the proportions of overlap at delayed recall were 11.99% for older adults and 13.84% for younger adults. Thus, although some details can be characterised as both a spatial contextual detail and episodic detail, our results reveal that a substantial proportion of episodic details at delayed recall were distinct from the details that were also coded as spatial contextual details. This suggests that initially retrieving spatial contextual details helped long-term retrieval of event-specific elements of real-world memories that extend beyond their accompanying spatial contextual detail.

Another central finding from the current work was that although numerically older adults showed a reduced benefit of the spatial scaffold on long-term recall of episodic details for weaker memories relative to younger adults, this age difference did not reach significance. To the extent that age-related declines in hippocampal integrity impair the ability of older adults to construct rich spatial representations (Gorbach et al., 2017; Kukolja et al., 2009; Levine et al., 2002; Robin, 2018; St-Laurent et al., 2016), we predicted that spatial contextual details initially recalled by younger adults would be more effective at scaffolding episodic details than those provided by older adults. Contrary to our prediction that changes to hippocampally-dependent processes such as scene construction would lead to reductions in the extent to which spatial context scaffolds episodic memory in older adults, we found no significant age differences. These findings, however, corroborate past work showing that reinstatement of spatial context (e.g., familiar real-world spatial contextual cues) provided an equivalent benefit for detailed event memory in older and younger adults, despite general age-related declines in episodic memory (Craik & Schloerscheidt, 2011; Robin & Moscovitch, 2017). Nevertheless, it is important to note that the unequal sample sizes in our age groups might have affected the sensitivity of age differences. Future work involving a larger younger adult sample might alleviate within-group variance and result in a more reliable age comparison.

We observed that older adults recalled memories with fewer episodic details at initial and delayed recall compared to younger adults, yet older adults spontaneously provided an equivalent amount of spatial contextual details as younger adults (see Table 1). This inconsistency with literature showing that age-related hippocampal changes impact scene construction could imply that our metric is not sensitive to aging. Prior work in older adults and patients with hippocampal damage have demonstrated that memory for a schematic representation of the environment may be preserved, whereas the detailed, rich re-experiencing of scenes and events is impaired, the latter of which is highly dependent on the hippocampus (Hassabis et al., 2007; Hirshhorn et al, 2011; St. Laurent et al., 2009). In our case, although older adults were able to provide spatial contextual details, which were captured effectively by our protocol, they might be unable to visualise the spatial context they described as coherently as younger adults. One paper tried to capture the coherence of spatial visualisation in terms of a spatial coherence index (i.e., a measure of the contiguousness and spatial integrity of the imagined scene) (Hassabis et al., 2007). The authors revealed that newly constructed experiences from patients with hippocampal amnesia were fragmented and deficient in spatial coherence, which was likely driven by the inability of the hippocampus to provide an integrated spatial context for details to be bound. Unfortunately, we were working with existing datasets that had been more focused on episodic recall and did not ask participants these questions regarding spatial coherence. Nonetheless, our novel measure of spatial context allowed for a detailed investigation of a broad range of spatial contextual details in real-world memories. Our scoring protocol was inspired by previous measures of spatial details (Hassabis et al., 2007; Mullally & Maguire, 2011, 2013), but adopts a more holistic approach. For example, our definition of spatial context extends beyond the *Place* subcategory encapsulated by the AI scoring protocol in that we introduce criteria for other spatial elements (see *Method: Spatial Contextual Coding*). We also built upon a notable scoring measure developed by Hassabis et al. (2007) but extended it in important ways to allow the examination of spatial contextual details. Specifically, we refined the original Entities, Sensory Descriptions, Spatial References, and Thought/Emotion/Action subcategories from Hassabis et al. (2007) to ensure that we definitively captured spatial information, each discussed in turn below. Our Space-Defining Entities subcategory includes only objects and entities that are essential to the construction and maintenance of scenes, discounting other entities that are less anchored in space (Mullally & Maguire, 2011, 2013). Next, we distinguished Sensory Descriptions that are spatially-based from those that are more perceptually-based, such that our spatial sensory description subcategory solely described space-defining entities rather than small-scale entities. Additionally, our Spatial Modifiers subcategory was modelled on the Spatial References subcategory in Hassabis et al. (2007), which we sought to make more concrete by specifying three characteristic features (i.e., spatial prepositions, directional adjectives, cardinal directions). Lastly, our Spatial Thought/Emotion subcategory specifically captured thoughts pertaining to spatial details rather than thoughts that are non-spatial and more event-specific in nature. As such, we aimed to implement a spatial contextual scoring protocol that collectively allowed us to assess multiple aspects of spatial context that are narrated in autobiographical memory recall.

We acknowledge that spatial contextual details can either be time-dependent/episodic (e.g., "I walked down this really *narrow, gravel road*") or non-time-dependent/semantic (e.g., "The *swimming pool* is *south of* the *hotel*"). Reinstatement of time-dependent spatial contextual details might better scaffold episodic details bound to the space where the specified event took place. On the other hand, non-time-dependent spatial contextual details could be used by participants to set the background for the experimenter during narrative recall. Accordingly, non-time-dependent spatial contextual details may be more schematic and generalisable across different and unrelated events. Although we lack sufficient detail counts to investigate this here, future work could characterise whether time- versus non-time-dependent spatial context on retention of episodic richness interacts with aging. For instance, given that there are age-related gains in semantic knowledge and shifts toward more semanticised recollection (Levine et al., 2002; Spreng & Turner, 2019), embedding memories in non-time-dependent spatial context might serve as a scaffold for episodic richness in older adults when time-dependent spatial context is lacking. On the other hand, it might be the case that preservation of episodic richness is stronger with reactivation of time-dependent spatial contextual details, or when time-dependent spatial contextual details are provided in conjunction with non-time-dependent spatial contextual details. Moreover, the connotation of time-dependent versus non-time-dependent spatial contextual details parallels the idea that memory for spatial representations is organised according to egocentric (i.e., one's relation to landmarks in space from the perspective of the individual) and allocentric (i.e., object-to-object relationships independent of one's position) navigational frames of reference. Additionally, the ability to process and continuously update complex scenes and flexibly switch between spatial representations are important for successful navigation (Colombo et al., 2017; Ladyka-Wojcik & Barense, 2021), suggesting that better spatial abilities may support retrieval of a rich spatial context for event details to unfold. To integrate work in the domain of spatial navigation, scene construction, and episodic memory, future research could disentangle how one's ability to switch between egocentric and allocentric frames of reference relates to one's memory for spatial context and how this facilitates the overarching effect of the spatial scaffold on long-term retention of episodic richness.

Although our narrative dataset captured the idiosyncrasies of real-world, everyday life events, we recognise that one limitation of our results is that we could not explore the influence of individual differences. For example, the effect of the spatial scaffold might differ according to one's preferred cognitive style, with some individuals showing a more spatial cognitive style, where they might utilise perceptually salient landmarks, visuospatial images, and spatial relations to scaffold episodic memory retrieval (Kozhevnikov et al., 2005). Similarly, individual differences in spatial navigational styles, such as one's propensity to use map-based or scene-based strategies during navigation could impact the fine-grained representation of spatial context (Brunec et al., 2019). In contrast, individuals with lower mental imagery or visualisation abilities might rely on schematic representations to anchor episodic details (Bocchi et al., 2019; Fan et al., 2023; Vannucci et al., 2020). Moreover, cognitive reserve, which can be indexed by one's level of education, occupation, and engagement in cognitively stimulating activities, may have positive compensatory effects on cognitive function (Opdebeeck et al., 2016). Furthermore, cognitive reserve has also been found to moderate the effect of smaller hippocampal volume on episodic memory performance (Reed et al., 2010; Vuoksimaa et al., 2013), suggesting that it may promote hippocampally-dependent processes like scene construction. Finally, we note that 61% of our participants were women, and that women usually outperform men in episodic memory performance (Herlitz & Rehnman, 2008). Therefore, to confirm the generality of the spatial scaffold effect across genders and sexes, future work will need to test these factors as moderators in a larger sample.

Altogether, our findings have implications for enriching memory recollection in a variety of age-related and clinical conditions. From a clinical standpoint, our findings expand prior work showing that immersion in environmental settings that reconstruct the cultural, sensory, and contextual aspects of the past provides retrieval support for autobiographical memory recall in patients with dementia (Kirk et al., 2019; Miles et al., 2013). There is also evidence showing that therapeutic techniques that target scene construction can circumvent over-general, ruminative thinking patterns and instead evoke richer and more detailed memories (Holmes et al., 2016; Rubin et al., 2019). Furthermore, our findings extend prior work that demonstrated how better performance on spatial imagery tasks and greater ability to flexibly process spatial representations bolster episodic retrieval in Alzheimer's disease (El Haj et al., 2019; Serino & Riva, 2014). Indeed, it may be that better spatial imagery abilities (e.g., rotating object representations; scanning spatial characteristics; determining relationships between objects in space) underlie the ability to construct a coherent spatial context for memories to reside.

In summary, we found that initially recalling weaker real-world autobiographical episodic memories embedded in greater spatial context preserved their long-term episodic richness. Our findings suggest that a robust spatial scaffold can support vivid re-experiencing and promote retention of rich episodic details comprising our life events. Intriguingly, we also demonstrated that older and younger adults generated similar levels of spatial contextual details when recalling memories, and that the extent to which spatial context strengthened long-term retention of episodic details was equivalent across age. More generally, our findings may be relevant for the development of portable, non-invasive, and accessible digital memory aids such as HippoCamera (Martin et al., 2022). For example, an important line of future investigation will be to determine whether memory cues of personally-experienced events that better facilitate retrieval of spatial context can be leveraged for smartphone-based memory interventions that mitigate age-related memory decline. The current research may inspire the design of interventions that encourage scene construction, spontaneous reinstatement of spatial context, and flexible use of spatial representations such that individuals better reinstate themselves in the space where their events took place to ultimately preserve detail-rich recollections of the past.

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Authors' contributions

M.C. and M.D.B. were involved in project conceptualisation, methodology, and development of the spatial contextual scoring protocol. B.H., K.S., M.E.M., and C.B.M. contributed to project conceptualisation, development of the spatial contextual scoring protocol, and data collection, transcription, and scoring of episodic details for the memory interviews that the current study analysed. M.C. performed interview scoring of spatial contextual and episodic details and statistical analyses for the current study. M.C., B.H., and M.D.B. discussed statistical analyses and interpretation of results. J.D. contributed to inter-rater reliability scoring and analysis. M.C. wrote the initial draft of the manuscript, with input from M.D.B, and both M.C. and M.D.B. revised and wrote the final manuscript. All authors provided feedback on the manuscript and approved the final version of the manuscript for submission.

Disclosure of interest

B.H., C.B.M, and M.D.B. own shares in Dynamic Memory Solutions Inc., a company focused on developing digital tools to improve memory. The University of Toronto holds the ownership rights to the HippoCamera technology used to collect the event cues for memory interviews the current project re-analysed but has given Dynamic Memory Solutions the rights to commercialise. No person, nor organisation received any financial remuneration for the use of the HippoCamera application in these studies. At the time of publication, this is a research-dedicated application that we will make available to other memory scientists at no charge.

Data availability statement

The data that support the findings of this study are openly available on OSF [https://osf.io/u38q2/] at https://doi.org/10.17605/OSF.IO/U38Q2.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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