Title

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Authors

Pu, Kecen
Shi, Aike
Liu, Xiaonan L

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Asymmetric Effects of Retrieval Practice on Temporal and Spatial Dimensions in Episodic Memory

Kecen Pu (kecenpu@link.cuhk.edu.hk)[1], Aike Shi (ak-shi@link.cuhk.edu.hk)[1], Xiaonan Liu (xliu@cuhk.edu.hk)[1,2,3]

[1]Department of Psychology, The Chinese University of Hong Kong

[2]Hong Kong Hub of Obstetric and Paediatric Excellence, The Chinese University of Hong Kong

[3]Centre for Cognition and Brain Studies, The Chinese University of Hong Kong

Abstract

Episodic memories are structured by both temporal and spatial relations, yet how these dimensions shape retrieval remains unclear. We investigated how temporal and spatial dimensions differentially contribute to the benefits of retrieval practice using a behavioral paradigm in which participants encoded items in a structured spatiotemporal environment, followed by selective retrieval practice and a final free recall test ($N = 54$). Across analyses, we replicated contiguity effects in both domains, confirming that recall is influenced by when and where experiences occurred. Retrieval-induced benefits were selective: non-practiced items studied closer in time to retrieved items showed greater facilitation in final recall, following a graded, distance-dependent function. In contrast, spatial proximity predicted recall overall but did not exhibit comparable retrieval-induced spillover. Using continuous, item-level indices of retrieval influence, we demonstrate that retrieval practice selectively amplifies temporal structure rather than uniformly strengthening all organizational dimensions.

Keywords: episodic memory; retrieval practice; memory organization; temporal context

Introduction

Previous research has demonstrated that human memory is organized according to multiple structural principles (Farrell, 2012; Kahana, 2012; Squire et al., 1993). Among the most prominent are temporal and spatial clustering phenomena (Miller et al., 2013; Solway et al., 2012). Specifically, memory tends to be organized according to inherent attributes of the items or events, such as their temporal or ordinal position during encoding, as well as the spatial contexts in which they occur (Curiel & Radvansky, 2014; Howard & Kahana, 2002; Polyn et al., 2009; Yamamoto & Shelton, 2009). Consequently, free recall output often exhibits both temporal clustering, successive recall of items that were close together in time during encoding, as well as spatial clustering, reflected in the grouping of items that shared similar locations during learning. In other words, rather than being stored as discrete, isolated units, individual memory representations are thought to be embedded within a continuous representational space, allowing clustering patterns to emerge naturally during retrieval.

From this perspective, retrieval is not a process of accessing isolated memory traces, but instead involves partial reinstatement of the learning context. When one memory is retrieved, overlapping contextual features may be co-activated, increasing the accessibility of other memories that share similar temporal or spatial contexts. In this sense, retrieval may function like lifting a point on a stretched cloth: nearby regions are pulled upward as well, following a continuous gradient across multiple contextual dimensions.

This conjecture is particularly relevant in light of the retrieval practice effect, whereby actively recalling information can enhance the strength of the retrieved memory (Barenberg & Dutke, 2022; Moreira et al., 2019; Rowland, 2014; Sutterer & Awh, 2016; Zheng et al., 2024). If memory representations are indeed organized continuously, retrieval practice should enhance not only the retrieved item itself but also other memories that share similar contextual features. Such spillover effects would naturally follow the same clustering principles that characterize memory organization.

Support for this idea can be found in well-documented phenomena of retrieval-induced facilitation (RIFA) and retrieval-induced forgetting (RIF) (Aslan & Bäuml, 2011; Chan, 2009; Chan et al., 2006; Jonker et al., 2013; Murayama et al., 2014). These effects demonstrate that retrieval practice on a subset of items can selectively enhance memory for contextually related, non-practiced items, such as items encoded within the same list, while impairing memory for more distant items, such as those encoded across lists.

However, existing evidence for such distance-dependent retrieval-induced effects remains limited. In prior work (e.g., Liu et al., 2021), temporal distance was manipulated using categorical contrasts (i.e., within vs. across-list) rather than as a continuous variable. This approach limits the ability to test whether retrieval-induced benefits scale smoothly with temporal proximity. Moreover, such manipulations may inadvertently introduce event boundaries, as items from different lists are not only temporally separated but are also more likely to be perceived as belonging to different events or episodes. A large body of literature has shown that event boundaries serve as powerful cues for memory segmentation and organization (Michelmann et al., 2022; Pettijohn et al., 2016; Radvansky & Zacks, 2017; Sols et al., 2017; Swallow et al., 2009), thereby confounding the specific role of temporal proximity in reactivation and strengthening.

Additionally, in these studies, during retrieval practice, temporal information was often explicitly reinstated, for example by instructing participants to recall items from a particular list. If retrieval-induced spillover effects are driven

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Figure 1: Bird's-eye overview of the experiment environment.

primarily by memory organization established during encoding, similar effects should exist even when temporal context is not explicitly cued during retrieval. Despite strong evidence for both temporal and spatial clustering in free recall (Farrell, 2012; Miller et al., 2013), it remains unclear whether retrieval-induced facilitation follows a comparable distance-dependent gradient in the spatial domain.

To address these gaps, the present study examines whether retrieval-induced memory facilitation follows a distance-dependent gradient along both temporal and spatial dimensions in a continuous, naturalistic context. We developed a naturalistic virtual environment in which participants freely explored a large-scale spatial layout and memorized a set of objects distributed throughout the environment. This paradigm allows precise measurement of both temporal distance (order of encounter during exploration) and spatial distance (Euclidean distance between object locations) relationships among items, enabling us to examine their independent and joint contribution to retrieval-induced effects. Following encoding, participants were directed to return to the locations of a subset of objects and perform retrieval practice by naming the object previously encountered at each location. Retrieval practice was cued by spatial location without explicit temporal information. A final free recall test then assessed memory for all items.

We expect to replicate the well-established temporal and spatial clustering patterns in the final free recall, reflecting the inherent organizational structure of episodic memory. Critically, building on evidence from RIFA, we hypothesize that the mnemonic benefits of retrieval practice for non-practiced items depend on their temporal and spatial proximity to practiced items during encoding.

Specifically, non-practiced items encountered closer in time or space to practiced items are expected to show greater facilitation in the final recall test. Moreover, because retrieval practice was guided solely by spatial cues, any observed relationship between temporal proximity and retrieval-

Figure 2: Example of the in-game scene encountered when participants interact with an item.

induced benefits would suggest that these effects arise from memory organization established during encoding rather than from explicit reinstatement of temporal context during retrieval.

Method

Participants

Participants were recruited from the University community. A total of 64 participants participated in the study. All participants reported no previously diagnosed neurological conditions that could interfere with the experiment, and none reported a history of motion sickness.

Ten participants were excluded from the final analysis for the following reasons: one for the experimenter providing an unintended cue during the task, two for unexpectedly exiting the task, one for misunderstanding the instruction, and six for completing an early version of the experiment paradigm that contained a program error which was corrected afterwards. This resulted in a final sample of 54 participants (65% female; M_{age} = 22.06, SD = 3.63 years). Participants were randomly assigned to the control (n = 28) or experiment (n = 26) group. The study was approved by the Survey and Behavioral Research Ethics Committee (SBRE). All participants provided informed consent prior to participation and received a fixed amount of monetary compensation.

Materials

3D virtual game environment. The virtual environment was developed using Unity Editor (version 2021.3.45f1c2) with a built-in render pipeline (Figure 1). All packages used in the study were obtained from the Unity Assets Store. The virtual environment consisted of a realistic small town with streets and buildings. Some buildings were accessible for participants to explore inside, whereas others were not.

A total of 25 items were placed in fixed locations for participants to find and remember. Some of the items were located inside the buildings, while others were placed in outdoor areas. The stimuli consisted of common real-world objects, including household items (e.g., battery, broom, trash can), tools and devices (e.g., flashlight, radio, coffee maker), recreational objects (e.g., chess board, football, guitar), and food-related items (e.g., fries, pizza, wine). The items were comparable in familiarity and visual complexity.

The target items were highlighted with a white outline to prompt the participants. When participants approached an item, a prompt appeared stating, “After memorizing the object in front of you, please press E.” The object immediately disappeared from the environment upon pressing the key. Three in-game tools were displayed in the top-left corner of the screen. The first was a minimap showing the participant’s location in the environment and nearby surroundings from a bird’s-eye perspective. The minimap was north fixed at the top. The second was a counter displaying “Items Collected: 0/25” which updated automatically as items were collected. The third was a prompt reading “Items in Range: X”, indicating the number of remaining items within the minimap range (Figure 2).

Procedure

The experiment was conducted in a behavioral testing room in the Psychology Department Central Laboratory at the university. The study was run on a Windows 11 desktop computer with stimuli presented on a 24-inch monitor (1920 × 1080 resolution; 60-Hz refresh rate). Participants interacted with the virtual environment using a standard keyboard and mouse. All participants were tested individually in the quiet room.

Upon arrival, participants received standardized instructions from the experimenter to explore a realistic small town in a first-person perspective, using the WASD keys for movement and the mouse to control the camera view.

Initial Study: After the experiment began, a basketball highlighted in white outline appeared directly in front of the participant (Figure 2). This served as a practice trial to familiarize participants with the highlighting and collection procedure. When they approached the basketball, they needed to collect the item by pressing “E”. Upon collecting the basketball, participants began freely exploring the environment to locate and memorize the remaining items. For control group participants, the program automatically exited after the participant had collected all 25 items. For experiment group participants, after they had collected all 25 items, an additional prompt appeared indicating that the retrieval practice phase would begin.

Retrieval Practice: The experimental group participants were directed to six randomly selected locations where they encountered items during the initial study phase, constituting retrieval practice for approximately 25% of the studied items. Upon participants arriving at each target location, a question appeared on the screen asking, “What did you see here?” Participants provided their responses via text input to minimize response constraints and encourage full retrieval of item identity. The retrieval practice phase lasted approximately 10 minutes.

After all six retrieval practice trials were completed, the program automatically exited. To introduce a delay between retrieval practice and the final recall, participants completed the Digit Span Task (Woods et al., 2011), Operation Span Task (Oswald et al., 2014), and Santa Barbara Sense of Direction Questionnaire (Hegarty et al., 2002) as filler tasks. Both the experimental and control groups completed the same set of filler tasks following the study.

Final Test: Following completion of the filler tasks, participants completed a final free recall test. A single text-input box appeared, and participants were instructed to type as many items as they could remember from the virtual environment within three minutes. The encoding phase was self-paced, allowing participants to freely explore and collect items, whereas the final free recall test was timed (3 minutes) for all participants. This design ensured comparable recall conditions across groups while preserving the naturalistic nature of encoding.

Analytic Approach

To examine how memory organization along temporal and spatial dimensions relates to recall performance, we defined several measures capturing both clustering patterns and retrieval-related influences at the item level.

First, recall transitions were analyzed to assess clustering effects. A recall transition was defined as the sequential transition from one recalled item to the next during the free recall test. These transitions were used to quantify temporal and spatial contiguity effects.

Second, to capture how retrieval practice influences memory for non-practiced items, we constructed continuous indices reflecting the proximity of each item to retrieved items during encoding. Specifically, we defined a Temporal Retrieval Influence Index (TRII) and a Spatial Retrieval Influence Index (SRII), which quantify the degree to which each item is temporally or spatially close to retrieved items, respectively. Both indices were computed using distance-weighted functions, such that items closer to retrieved items receive higher influence values.

Results

Clustering in Temporal and Spatial Dimensions

Temporal Contiguity Effect First, we examined whether our data replicated the classical temporal contiguity effect. To assess temporal clustering, we calculated lag-based conditional response probability (lag-CRP) as a function of the absolute lag of the study order (Howard & Kahana, 1999). Lag values were restricted to ±10 to produce an informative yet concise figure. Figure 3A shows lag-CRP as a function of temporal lag during study, plotted separately for the control and experimental groups. Both groups exhibited strong temporal clustering, consistent with the temporal contiguity effect, with recall transitions most likely to occur between items studied close together in time. Specifically, transitions peaked at lag +1, indicating a strong tendency to recall items that were studied immediately after the previously recalled item. This forward asymmetry was observed in both groups.

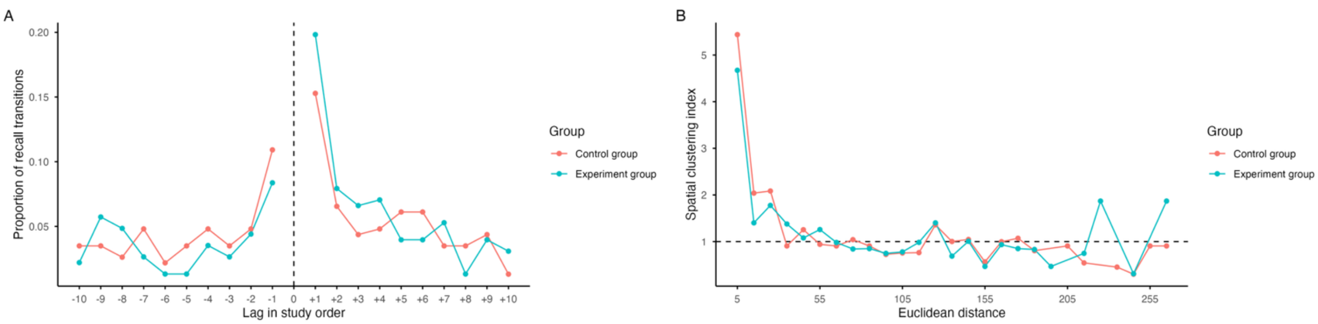

Figure 3: Temporal and spatial clustering effects in recall. (A) Recall transitions were more likely for items studied closer together in time, with comparable effects across the two groups. (B) Euclidean distances were binned in 10-unit intervals. After correction for chance, the spatial clustering index peaked at shorter Euclidean distances and decreased with increasing distance.

As absolute lag increased, the probability of recall transitions declined monotonically in both forward and backward directions, suggesting reduced temporal clustering as study distance increased. Together, these results indicate that temporal structure during encoding strongly constrained recall organization.

Spatial Contiguity Effect To examine the spatial contiguity effect, we first calculated the Euclidean distances between every pair of items. The lag-CRP method was not applied here because spatial distances were continuous, unlike study order, which is inherently discrete. Because spatial distances were continuous, we binned the distances using a bin with a width of 10 units to discretize the variable and produce a CRP-like function. We then calculated the recall transitions within each bin divided by all recall transitions as the observed probability of recall transitions.

Because the distances between every two items followed a non-uniform distribution, we calculated a base-rate probability of recall transitions to assess whether observed spatial clustering exceeded chance. The base-rate probability was calculated as the proportion of all item-item distances falling within each bin relative to all item-item distances. A spatial clustering index was then defined as the ratio of the observed probability of recall transitions to the base-rate probability. Values greater than 1 indicate above-chance spatial clustering. In contrast, for temporal contiguity, the lag-CRP normalizes transition probabilities by the set of available lags (Howard & Kahana, 2002), providing an implicit baseline. Therefore, additional normalization is not required for temporal analyses.

As shown in Figure 3B, both groups exhibited the strongest spatial clustering at the smallest distance bins, indicating a strong tendency to transition between spatially nearby items during recall. As spatial distance increased, the clustering index rapidly declined and approached the baseline level (i.e., index = 1), suggesting reduced spatial organization for more distant item pairs. Across most distance bins, the control and experimental groups showed highly similar spatial clustering patterns, with both curves fluctuating around baseline at medium and large distances. The results indicate that recall transitions were also constrained by spatial proximity during encoding.

Retrieval-Induced Effect in Temporal and Spatial Dimension

Our central question concerns whether retrieval practice interacts with the organization of memory along temporal and spatial dimensions. To address this question, we tested whether retrieval success exerted graded spillover effects on recall performance as a function of temporal and spatial proximity. In other words, we asked whether items studied closer in time or space to successfully retrieved items were more likely to be recalled, and whether such proximity effects differed between the experimental and control groups.

To examine our hypothesis, we first computed an index that captures how the strength of retrieval-induced effects on recall varies as a function of distance. For the temporal dimension, we constructed a Temporal Retrieval Influence Index (TRII) to serve as this indicator. First, we filtered out the items that were retrieved during the retrieval practice phase and extract their study timestamps in the study phase. Next, we calculated the temporal distance between each non-retrieved item and each correctly retrieved item (d_{ij}). For each participant, we also calculated the mean temporal distance across all non-retrieved items (τ).

For each non-retrieved item (i), each retrieved item (j) contributed a weight (w_{ij}) (Equation 1), and the sum of these weights (Equation 2) defined the TRII of that item. We applied an exponential decay function to weight temporal distance because the influence of previously encountered items on recall is expected to decrease continuously as temporal distance increases. This formulation assigns greater weight to temporally nearby items while allowing more distant items to contribute progressively less, thereby capturing the graded nature of temporal influence in memory.

$$w_{ij} = e^{-\left(\frac{d_{ij}}{\tau}\right)} \quad \text{(Equation 1)}$$

$$TRII_i = \sum_{j=1}^{N} w_{ij} \quad \text{(Equation 2)}$$

$$SRII_i = \sum_{j=1}^{N} w_{ij} \quad \text{(Equation 3)}$$

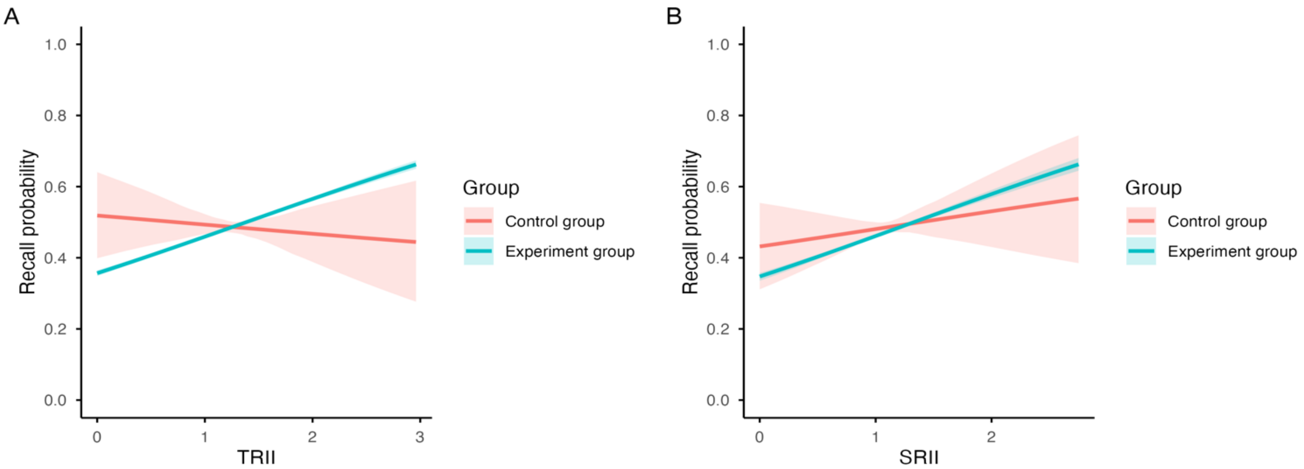

Figure 4: Recall probability as a function of temporal and spatial retrieval influence. (A) Recall probability increased with higher TRII, with a stronger effect observed in the experiment group than in the control group. (B) Recall probability as a function of SRII, showing a weaker and less differentiated pattern across groups. Shaded regions indicate 95% confidence intervals.

Predictor	**β (mean)**	**β 95% CI**	***OR* (mean)**	**OR 95% CI**	**P(p < .05)**	**P(β > 0)**
TRII model						
Group	-0.02	[-0.08,0.04]	0.98	[0.92,1.05]	0.00	0.27
TRII	-0.07	[-0.34,0.20]	0.94	[0.71,1.22]	0.08	0.32
TRII x Group	0.34	[0.09,0.60]	1.42	[1.09,1.83]	0.52	1.00
SRII model						
Group	-0.04	[-0.10,0.03]	0.96	[0.90,1.03]	0.00	0.14
SRII	0.12	[-0.14,0.39]	1.14	[0.87,1.48]	0.06	0.82
SRII x Group	0.16	[-0.08,0.41]	1.19	[0.92,1.51]	0.03	0.91
TRII & SRII						
Group	0.24	[0.13,0.35]	1.28	[1.14,1.41]	0.00	1.00
TRII	-0.22	[-0.60,0.18]	0.82	[0.55,1.20]	0.26	0.13
TRII x Group	0.24	[-0.14,0.60]	1.29	[0.87,1.83]	0.09	0.90
SRII	0.30	[-0.03,0.63]	1.37	[0.97,1.88]	0.21	0.96
SRII x Group	0.02	[-0.28,0.34]	1.04	[0.76,1.40]	0.00	0.57

Table 1: Fixed-effect estimates from logistic mixed-effects models predicting recall probability as a function of TRII and SRII. For each predictor, the table reports the posterior mean of the regression coefficient (β), the corresponding odds ratio (OR), and 95% credible intervals. P(p < .05) refers to the posterior probability that the effect is significant, and P(β > 0) refers to the posterior probability that the effect is positive.

To examine whether temporal structure effects depend on retrieval practice rather than reflecting a generic property of temporal proximity, we constructed TRII values for the control group. Specifically, we first computed the average number of correctly retrieved items per participant in the experimental group. For each control participant, we then randomly selected the same number of items to serve as pseudo-retrieval anchors. These pseudo-retrieval items were treated identically to retrieved items in the experimental group for the purpose of TRII computation, allowing us to derive a temporal proximity measure under the assumption that retrieval occurred randomly. This procedure was repeated 300 times, and TRII values were averaged across iterations to ensure robustness against sampling variability. Using this two-group TRII measure, we fitted a generalized linear mixed-effects model predicting recall of non-retrieved items from TRII, group, and their interaction, with random intercepts for participants and items.

Figure 4A shows that in the experimental group, recall probability increased monotonically with TRII, indicating that items studied closer in time to retrieved items were more likely to be recalled in the final free recall test. In contrast, the control group exhibited no reliable positive relationship between TRII and recall probability.

This pattern was confirmed by the generalized linear mixed-effects model (Table 1). The interaction between TRII and group was positive and robust ($\beta = .34$, OR = 1.42), with 99.7% of Monte Carlo iterations yielding a positive coefficient, indicating that the effect of temporal proximity on recall was selectively enhanced in the experimental group. In contrast, the main effect of TRII was not reliable in the control group ($\beta = -.07$, OR = 0.94), and there was no reliable main effect of group.

For spatial dimension, the same procedure was applied to compute a Spatial Retrieval Influence Index (SRII) for both the experimental and control groups (Equation 3). Figure 4B shows that, in both groups, recall probability increased modestly with SRII. Consistent with this pattern, the generalized linear mixed-effects model revealed a weak main effect of SRII ($\beta = 0.12$, OR = 1.14), but no reliable interaction between SRII and group ($\beta = 0.16$, OR = 1.19), indicating that retrieval-induced effects did not vary as a function of spatial proximity.

Because temporal and spatial proximity were inherently correlated in the current design, we conducted a joint analysis including both TRII and SRII (Table 1). TRII and SRII were significantly correlated ($r = .59$, 95% CI [.54, .64], $p < .001$), indicating shared variance between the two indices. In this model, the interaction between SRII and group remained negligible ($\beta = 0.02$, OR = 1.04), whereas the interaction between TRII and group remained positive in direction but was attenuated relative to the single-predictor model ($\beta = 0.24$, OR = 1.29).

General Discussion

The present study examines how episodic memories are organized across temporal and spatial dimensions, and how these dimensions differentially contribute to the benefits of retrieval practice. Across analyses, we replicated well-established contiguity effects in both temporal and spatial domains (Howard & Kahana, 2002; Kahana, 1996; Miller et al., 2013; Sederberg et al., 2008), confirming that memory is structured by both when and where experiences occurred. Critically, however, retrieval practice did not uniformly amplify these organizational dimensions. Instead, retrieval-induced benefits showed a clear dependence on temporal proximity, such that non-practiced items studied closer in time to retrieved items exhibited greater facilitation in final recall, with effects decreasing as temporal distance increased. In contrast, although spatial proximity was associated with recall overall, retrieval-induced spillover effects did not differ reliably from baseline levels in the spatial domain.

The interaction between TRII and group provides converging evidence that retrieval-induced spillover operates primarily along the temporal dimension, consistent with the prior work on RIFA (e.g., Anderson et al., 1994; Liu & Ranganath, 2021). Extending these literatures, the current results demonstrate that retrieval-induced effect follows a continuous, distance-dependent gradient, rather than a categorical or list-based effect (Howard & Kahana, 2002; Lohnas et al., 2015). Importantly, this graded temporal spillover emerged even though temporal context was not explicitly reinstated during retrieval practice, suggesting that retrieval-induced facilitation reflects memory organization established during encoding, rather than being driven solely by explicit temporal cues at retrieval.

The absence of a comparable retrieval-induced spillover in the spatial dimension suggests that retrieval influence is selective rather than uniform across representational dimensions. While caution is warranted when interpreting null interactions, this pattern is broadly consistent with evidence that spatial context may play a different organizational role than temporal context (Bellmund et al., 2018; Eichenbaum, 2014; Ekstrom & Ranganath, 2018). Unlike temporal context, which is thought to drift continuously, spatial representations may provide a relatively stable scaffold (Ekstrom & Ranganath, 2018; Miller et al., 2013). Changes in spatial context may involve more abrupt shifts (e.g., remapping of place cell representations) than gradual drift (Barry et al., 2012; Copara et al., 2014; Fyhn et al., 2007; Keinath et al., 2021; Wills et al., 2005). This distinction may also help explain why the spatial contiguity effect in the current study was more localized, whereas temporal contiguity effects exhibit a more graded profile.

One limitation of the present design concerns the interval period between groups. Participants in the experiment group completed an additional retrieval task during this interval, whereas the control group did not, resulting in differences in duration and cognitive demands. This raises the possibility that greater cognitive load or fatigue in the experiment group may have influenced recall. Although the overall pattern of results is more consistent with a retrieval-based account, future work should aim to more tightly equate interval structure across groups.

Taken together, these findings suggest that episodic memory is organized along interacting axes of time and space, but retrieval practice reveals an asymmetry in how these are expressed. Retrieval-induced effects appear to propagate primarily along the temporal axis, consistent with the idea that temporal context may drift continuously over experience, whereas spatial context may be organized in a more stable or discretized manner. Methodologically, the present study introduces a continuous, item-level measure of retrieval influence that conceptualizes retrieval as a graded field rather than a discrete event. By quantifying temporal and spatial proximity using distance-weighted indices (TRII and SRII), this approach captures how retrieval reshapes the memory landscape in a multidimensional and continuous manner (Healey et al., 2024; Sadeh et al., 2014). An important direction of future research is to extend this framework to other domains in which memory is embedded in structured spaces, such as narratives, semantic networks, or navigation in naturalistic environments.

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