# A smartphone intervention that enhances real-world memory and promotes differentiation of hippocampal activity in older adults

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**Abstract**

The act of remembering an everyday experience influences how we interpret the world, how we think about the future, and how we perceive ourselves. It also enhances long-term retention of the recalled content, increasing the likelihood that it will be recalled again. Unfortunately, the ability to recollect event-specific details tends to decline with age, resulting in an impoverished ability to mentally re-experience the past. This shift has been linked to a corresponding decline in the distinctiveness of hippocampal memory representations. Despite these well-established changes, there are few effective cognitive behavioral interventions that target real-world episodic memory. We addressed this gap by developing a smartphone-based application called *HippoCamera* that allows participants to record labelled videos of everyday events and subsequently replay standardized, high-fidelity autobiographical memory cues. In two experiments, we found that older adults were able to easily integrate this non-invasive intervention into their daily lives. Using *HippoCamera* to repeatedly reactivate memories for real-world events improved episodic recollection and it evoked more positive autobiographical sentiment at the time of retrieval. In both experiments, these benefits were observed shortly after the intervention and again after a 3-month delay. Moreover, more detailed recollection was associated with more differentiated memory signals in the hippocampus. We conclude that using this smartphone application to systematically reactivate memories for recent real-world experiences can help to maintain a bridge between the present and past self in older adults.

**Significance Statement**

The ability to vividly recollect our past declines with age, a trend that negatively impacts overall well-being. We show that using smartphone technologies to record and replay brief but rich memory cues from daily life can improve older adults' ability to re-experience the past. This enhancement was associated with corresponding changes in the way memories were stored in the brain. Functional neuroimaging showed that repeatedly replaying memory cues drives memories apart from one another in the hippocampus, a brain region with well-established links to memory function. This increase in differentiation likely facilitated behavior by strengthening memory and minimizing competition among different memories at retrieval. This work reveals a novel, easy-to-use intervention that helps older adults better remember their personal past.

## Introduction

Autobiographical memory enables us to remember our personal past, and by extension contributes to our sense of identity (1, 2), the maintenance of social relationships (3, 4), and the ability to think about a self-relevant future (5-7). Retrieving an autobiographical memory is a complex process that involves recovery of general semantic knowledge (e.g., knowing what typically happens at a youth baseball game), personal semantic knowledge (e.g., knowing that you have a grandson who plays baseball), and recollection of episodic details that were unique to a specific event (e.g., remembering the look on your grandson's face the first time he hit the ball). In neurologically healthy individuals, the ability to retrieve general and personal semantic knowledge typically remains constant across the lifespan, whereas recollection of event-specific details tends to decline with age, compromising our ability to vividly remember the past (8). The trajectory of this decline has been linked to corresponding reductions in the structural and functional integrity of the hippocampus (9, 10), which supports the encoding and retrieval of event-specific details from recent experiences (11, 12). Despite the prevalence of these downward trends and the significant impact that they have on quality of life, very few interventions specifically target autobiographical episodic memory. To fill this gap, we developed a smartphone application called *HippoCamera,* which is inspired by hippocampal function and designed to improve episodic recollection of real-world events in older adults.

*HippoCamera* is a digital memory aid that embodies principles from cognitive psychology and neuroscience known to improve memory, including distributed learning (14), deep encoding (14), the use of self-generated cues (15), the use of multi-modal cues (16), and strengthening contextual associations between events (17). Briefly, this application allows users to record (Fig. 1*A*) and replay (Fig. 1*B*) standardized, high-fidelity autobiographical memory cues from the real-world events that they value most. Each cue comprises an 8-second verbal description of the target event (e.g., "Felix is playing baseball at Tom Brown Park") that is played concurrently with an 8-second speeded video (i.e., a 24-second video played at 3x speed, a design choice that enables efficient review and was inspired by the temporally compressed nature of endogenous hippocampal replay) (18). These detail-rich reminders can then be replayed in sessions of up to five

cues from distinct events. The application automatically curates replay sessions so as to balance distributed learning and prioritization of recent significant events over remote insignificant events. In the current study, a subset of cues was assigned to a replayed condition and viewed multiple times; the remaining cues were never replayed, thus establishing a within-subject baseline condition. Using *HippoCamera* in this way allowed us to characterize the behavioral and neural effects of cued reactivation – i.e., using a cue to reinstate an established memory trace – on autobiographical memory while holding other factors constant.

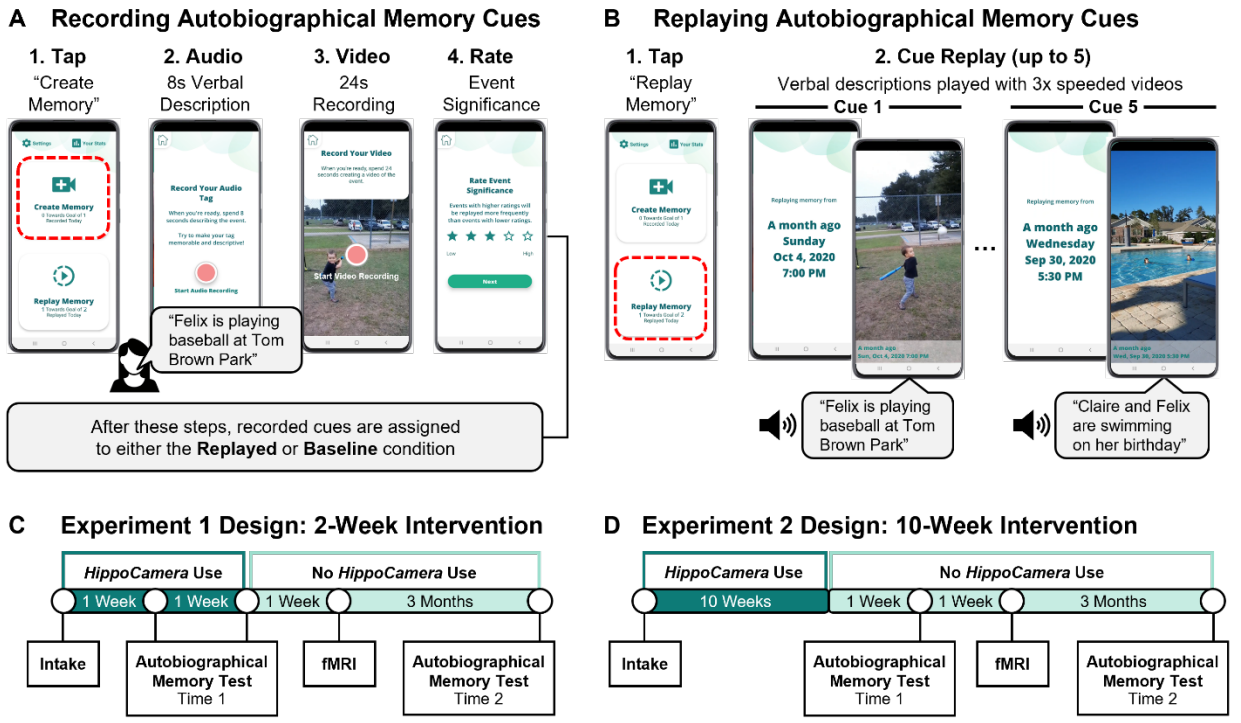


**Fig. 1. *HippoCamera* application and experimental design**. (A) Cues are recorded in a four-step sequence: (1) Select an ongoing real-world event and initiate recording, (2) record an 8-second verbal description of the event, (3) record a 24-second video of the event, and (4) rate the event's significance. Each cue is assigned to either the Replayed or Baseline condition. (B) Replay sessions consisted of up to 5 distinct cues played sequentially. During replay, the 8-second audio is played concurrently with a speeded (3x) version of the video. Each cue is preceded by a text display that denotes approximately how much time has passed since the event as well as its exact date and time. (C) Experimental design for the 2-week record and replay protocol used in Experiment 1. (D) Experimental design for the 10-week record and replay protocol used in Experiment 2.

Previous research has demonstrated that memories can be altered by retrieval (19, 20). Repeatedly cueing retrieval of autobiographical memories with standardized reminders therefore presents an opportunity to modify how past experiences will be recalled (21, 22). Importantly, however, not all memory cues are created equal. Findings from computational modeling (23, 24), behavioral investigations (25, 26), and neuroimaging research (27-29) suggest that a reminder can strengthen an episodic memory when it evokes strong neural reactivation but weaken it when it evokes a moderate degree of neural reactivation. Although the beneficial effects of strong reactivation have been revealed using words, pictures, and movie clips as stimuli in controlled study-test paradigms, it is not known whether this approach can strengthen autobiographical episodic memory for real-world events. The *HippoCamera* application solves three problems that have historically hindered progress toward answering this question. First, it establishes a method for prospectively generating high-fidelity cues that capture the complex and dynamic nature of daily life. Second, it uses these cues to reactivate autobiographical memory traces outside of a laboratory setting. Third, it packages these functions in an easy-to-use application that older individuals can use independently. Against this background, we hypothesized that replaying high-fidelity autobiographical memory cues would evoke strong neural reactivation and that this would be reflected in improved episodic recollection.

To the extent that the hippocampus supports the encoding and retrieval of detail-rich episodic memories, we also anticipated that replaying high-fidelity autobiographical memory cues would alter hippocampal representations of the recent past. Relevant research in young adults has used multivariate pattern analysis methods with functional magnetic resonance imaging (fMRI) data to examine how hippocampal representations change relative to one another either over time or across experimental conditions. This work has variably revealed two outcomes that relate changes in hippocampal activity to improved memory performance: integration and differentiation. Integration is characterized by an increase in neural similarity across memories (30-36), whereas differentiation corresponds to a decrease in neural similarity across memories (37-41). Building on the notion that these divergent outcomes may reflect differences in retrieval demands (42), we hypothesized that, for the older adults in our study, improvements in

detailed episodic recollection would be associated with corresponding increases in hippocampal differentiation.

Across two experiments, we found that older adults were able to use *HippoCamera* to record and replay high-fidelity memory cues from their daily lives in an unsupervised manner. This cognitive behavioral intervention enhanced episodic recollection of real-world events and improved positive feelings associated with everyday events at the time of retrieval. Using fMRI, we revealed that replaying memory cues increased differentiation of activity patterns in the hippocampus, a measure that was positively correlated with the amount of event-specific episodic information that older adults could recollect. These findings suggest that cued reactivation promotes differentiation of autobiographical memory representations in the hippocampus in a manner that facilitates detail-rich episodic retrieval.

## Results

### Cued Reactivation Improved Recollection of Event-Specific Detail

***Experiment 1.*** Participants (N = 22, mean age 69.64 years ± 0.89 SEM, 16 women) used *HippoCamera* to record and replay episodic memory cues for events that took place over two consecutive weeks (Fig. 1*C*). During this time, they were instructed to record 5 events per day and view 6 replay sessions per day. Moreover, they were encouraged to distribute their replay sessions throughout each day, rather than view them in succession. This guidance was reinforced by smartphone notifications that intermittently reminded participants to record and replay. Compliance was generally high with an average of 4.8 ± 0.20 SEM cues recorded per day and 5.4 ± 0.27 SEM replay sessions viewed per day. Cues were randomly assigned to either the Replayed or Baseline condition on a per cue basis (Fig. 1*A*), meaning Replayed and Baseline events were interleaved both within and across days. Cues in the Replayed condition were viewed an average of 8.7 ± 0.42 SEM times prior to memory testing. Cues in the Baseline condition were never replayed and provided a within-subject comparison.

We assessed autobiographical memory performance using a cued-recall test administered at two time points (Fig. 1*C*). Time 1 testing was completed immediately after

the first and second week of *HippoCamera* use, with each assessment targeting memories for a subset of events that were recorded over the previous seven-day period. Time 2 testing was completed after a delay of 3.25 months, during which time participants did not have access to their memory cues. We tested memory for the same subset of recorded events at Time 1 and Time 2 (mean number of Replayed trials = 17.1 ± 0.61 SEM, Baseline trials = 17.2 ± 0.61 SEM). We selected cues for the purpose of testing in a manner that optimized matching between Replayed and Baseline memories at the levels of event significance, event frequency, and memory age (see Methods, Stimulus Selection).

On each trial of our autobiographical memory tests, participants viewed one of their self-generated cues and then verbally described their memory for the corresponding event. Specifically, they were encouraged to provide as many details as possible about the target event and were provided with an example response at the beginning of each assessment (SI Methods, Autobiographical Memory Tests, Administration). Responses were scored to quantify retrieval of Internal and External details (8, 43). Internal details are event-specific and reflect episodic re-experiencing (e.g., recollecting the look on your grandson's face when the first time he hit a baseball). External details reflect retrieval of general semantic information (e.g., knowing what tends to happen at a baseball game), personal semantics (e.g., knowing that your grandson is 4 years old), or details from a non-target event (e.g., recollecting what happened in a different baseball game that your grandson played) (SI Methods, Autobiographical Memory Tests, Scoring).

Internal detail counts are shown in Fig. 2*A*. A Poisson generalized linear mixed model revealed a significant main effect of Condition (Replayed vs. Baseline: b = 0.144, SE = 0.0196, z = 7.336, $P < .001$), such that memories for Replayed events were recalled with significantly more Internal details than were those for events in the Baseline condition (see SI, Behavioral Methods, for model details; Tables S1-S2). Proportionally, this reflected a 37.4% increase in Internal details for Replayed relative to Baseline trials at Time 1. In addition to a main effect of Condition, we found a main effect of Test Session (Time 1 vs. Time 2: b = -0.271, SE = 0.0320, z = -8.476, $P < .001$), indicating that participants recalled significantly more Internal details at Time 1 than they did at Time 2.

Although the overall number of Internal details declined over time, the relative benefit of cued reactivation was preserved: Replayed events were recalled with 36.5% more event-specific details than Baseline events at Time 2. Together, this pattern of results suggests that cued reactivation initially enhances episodic autobiographical memory and that these enhancements persisted three months after discontinuation of *HippoCamera* use. These effects were selective to event-specific details, as we did not find evidence for an influence of replay or test session on the number of External details recalled (main effect of Condition: b = -0.0275, SE = 0.0182, z = -1.513, *P* = .130; main effect of Test Session: b = -0.0660, SE = 0.0410, z = -1.608, *P* = .108) (see SI, Behavioral Results, Overall External Details in Fig. S1A and Tables S1-S2; SI, Behavioral Results, External Details by Subtype in Fig. S2 and Tables S3-S4).

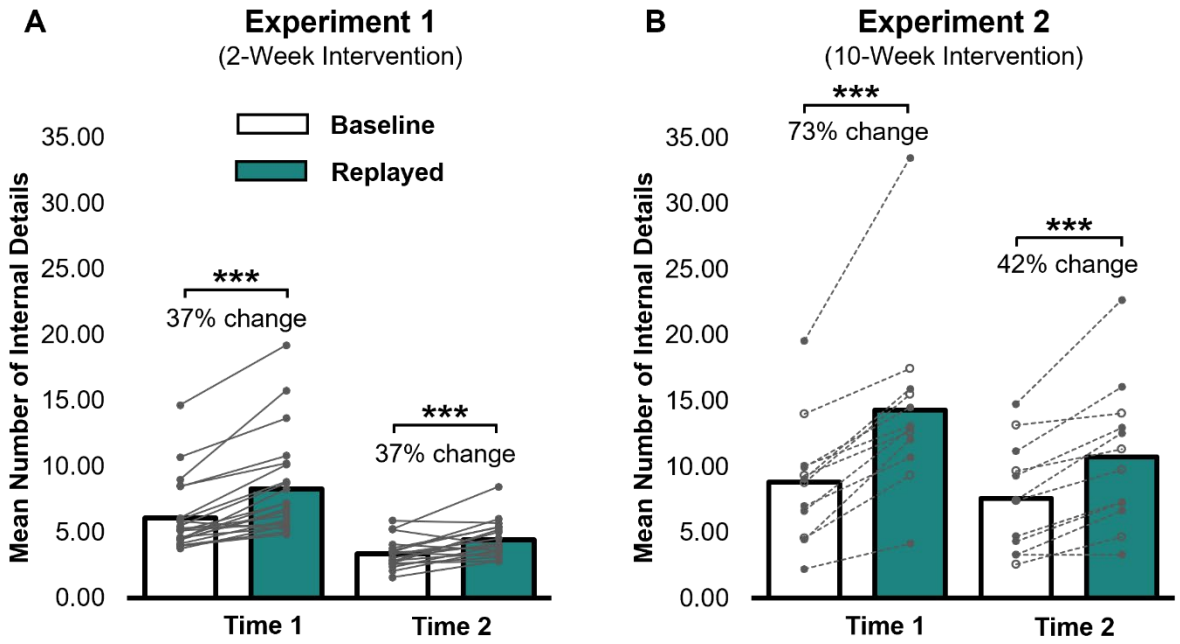


**Fig. 2. Cued reactivation improved episodic recollection.** Mean number of Internal details for (A) Experiment 1 and (B) Experiment 2. Time 1 corresponds to behavioral performance measured during (Experiment 1) and shortly after (Experiment 2) *HippoCamera* use. Time 2 corresponds to behavioral performance after a 3-month delay, during which time participants did not have access to their memory cues. Percent change values are included for illustrative rather than inferential purposes. Open markers are used to denote Experiment 2 participants who failed the Montreal Cognitive Assessment. *** = *P* < .001. See Fig. S1-S2 for External detail counts and Tables S3-S4 for corresponding statistical analyses.

***Experiment 2.*** Experiment 2 was designed with two goals in mind. First, we wanted to replicate findings revealed in Experiment 1 using a condition that reflected long-term autonomous *HippoCamera* use. To this end, participants (*n* = 12, mean age 66.7 ± 0.81 SEM, 6 women) recorded and replayed autobiographical memory cues for a duration of 10-weeks (Fig. 1*D*). They were encouraged to record one event per day and view one replay session per day. Compared to Experiment 1, this protocol better approximated how older adults might use a digital memory aid outside of an experimental context. Compliance was high with an average of 0.95 ± 0.07 SEM cues recorded per day and 1.05 ± 0.03 SEM replay sessions viewed per day. Cues in the Replayed condition were viewed an average of 7.8 ± 0.53 SEM times over the 70-day use period. By design, the mean number of replays per cue was comparable across experiments (Experiment 1 mean = 8.7) but distributed over a longer period of time in Experiment 2.

Our second goal was to minimize the potentially confounding effect that replay expectancy may have had on behavioral performance in Experiment 1. Participants in Experiment 1 could not definitively know whether a given cue was assigned to the Baseline condition because assignment was randomized. Consequently, most reported that they either hoped or expected that some Baseline cues would be replayed. Counter to our experimental design, these expectations may have evoked un-cued memory reactivation. We resolved this potential problem in Experiment 2 by assigning cues to either the Replayed or Baseline condition in a blocked manner, rather than on a per cue basis. Condition assignment alternated across weeks and was counterbalanced across participants. All participants were explicitly informed of these weekly condition switches to ensure that they never anticipated replay of cues in the Baseline condition.

In Experiment 2, the Time 1 memory test was completed one week after the 10-week *HippoCamera* use period. Participants did not have access to their memory cues during the week between *HippoCamera* discontinuation and the Time 1 memory test. The Time 2 memory test was completed approximately 3.25 months after the Time 1 test. Participants did not have access to any of their cues during this three-month interval. We tested memory for the same subset of events at Time 1 and Time 2 (the mean number trials was identical across the Replayed and Baseline conditions: M = 19.7 ± 0.33 SEM).

Cues were selected to optimize matching between Replayed and Baseline memories at the levels of event significance, event frequency, and memory age (see Methods, Stimulus Selection for additional detail).

Results from Experiment 2 (Fig. 2*B*) replicate and extend those from Experiment 1. The benefit of cued reactivation on episodic recollection of real-world events was apparent both shortly after *HippoCamera* use and more than three months after completion of our record and replay protocol. A Poisson generalized linear mixed model revealed that more Internal details were recalled in the Replayed condition than in the Baseline condition (main effect of Condition: b = 0.222, SE = 0.0264, z = 8.407, $P < .001$), as well as at the Time 1 memory test relative to the Time 2 memory test (main effect of Test Session: b = -0120, SE = 0.0312, z = -3.840, $P < .001$) (SI, Behavioral Results; Tables S1-S2). There was also a significant interaction between Condition and Test Session (b = -0.0369, SE = 0.0142, z = -2.607, $P = .009$), driven by the fact that the difference in Internal details between Replayed and Baseline events was larger at Time 1 than it was at Time 2 (b = -0.313, SE = 0.0641, z = -4.881, $P < .001$). Proportionally, these differences can be quantified as a 72.6% increase in the number of event-specific details recalled for the Replayed as compared to the Baseline condition at Time 1, and a 47.4% increase for the same comparison at Time 2. Notably, significantly more event-specific details were recalled in Experiment 2 relative to Experiment 1 (main effect of Experiment: b = 0.362, SE = 0.07394, z = 4.903, $P < .001$), suggesting that cognitive behavioral interventions aimed at improving autobiographical memory may benefit from targeting a limited number of higher-quality events per day and distributing review over a longer period of time.

We did not find any evidence for differences in recall of External details across Conditions (SI, Behavioral Results, Overall External Details in Fig. S1B and Tables S1-S2; SI, Behavioral Results, External Details by Subtype in Fig. S2 and Tables S3-S4), suggesting that replaying autobiographical memory cues does not influence subsequent retrieval of semantic information. This result is consistent with findings from Experiment 1, and the broader notion that semantic knowledge tends to be relatively stable over time (8). Contrasting with results from Experiment 1, we found that the number of External

details recalled did differ significantly across Time 1 and Time 2 (main effect of Test Session: b = -0.138, SE = 0.0323, z = -4.288, $P < .001$), reflecting the fact that participants recalled significantly more External details at Time 1 than Time 2. Although we did not predict this outcome, we speculatively suggest that there may be some dependency between Internal and External details, such that a high number Internal details is accompanied by a relatively high number of External details that situate the target event in a broader context.

**Cued Reactivation Evoked More Positive Autobiographical Sentiment at Retrieval**

Having revealed that using *HippoCamera* to replay autobiographical memory cues selectively increased recall of event-specific episodic details, we next asked whether there were qualitative differences in the kind of language used to describe Replayed and Baseline memories (Fig. 3). To examine whether cued reactivation was associated with more positive memory-based event descriptions, we used a text-based sentiment analysis (Valence Aware Dictionary and sEntiment Reasoner; VADER) (44). This approach uses natural language processing to identify subjective states and quantify their polarity (i.e., positivity and negativity). As an example, the statement "*We had an amazing time, and Felix was overjoyed when he hit the ball"* will receive a more positive score than "*We had a nice time, and Felix was pleased when he hit the ball"*. Similarly, "*We had a terrible time, and Felix was devastated when he struck out"* will be scored more negatively than "*We had a bad time, and Felix was disappointed when he struck out"*.

We used paired-samples t-tests to probe for differences between normalized composite sentiment scores that capture overall positivity and negativity for Replayed and Baseline memories. For Experiment 1, this approach revealed that sentiment scores were significantly more positive for Replayed memories than Baseline memories at Time 1 ($t(21) = 2.54$, $P < .01$, $d = 0.54$), and Time 2 ($t(19) = 2.11$, $P < .05$, $d = 0.47$). A similar result was obtained for Time 1 in Experiment 2 ($t(11) = 2.42$, $P < .05$, $d = 0.70$). This effect did not persist, however, at Time 2 ($t(11) = 0.28$, $P = 0.4$, $d = 0.08$). Comparing across experiments, we found that Experiment 2 was generally associated with higher sentiment scores than Experiment 1 ($t(32) = 3.68$, $P < .001$, $d = 1.32$). This difference may reflect

an increase in the importance of the events recorded in Experiment 2, for which we encouraged participants to record just one event per day.

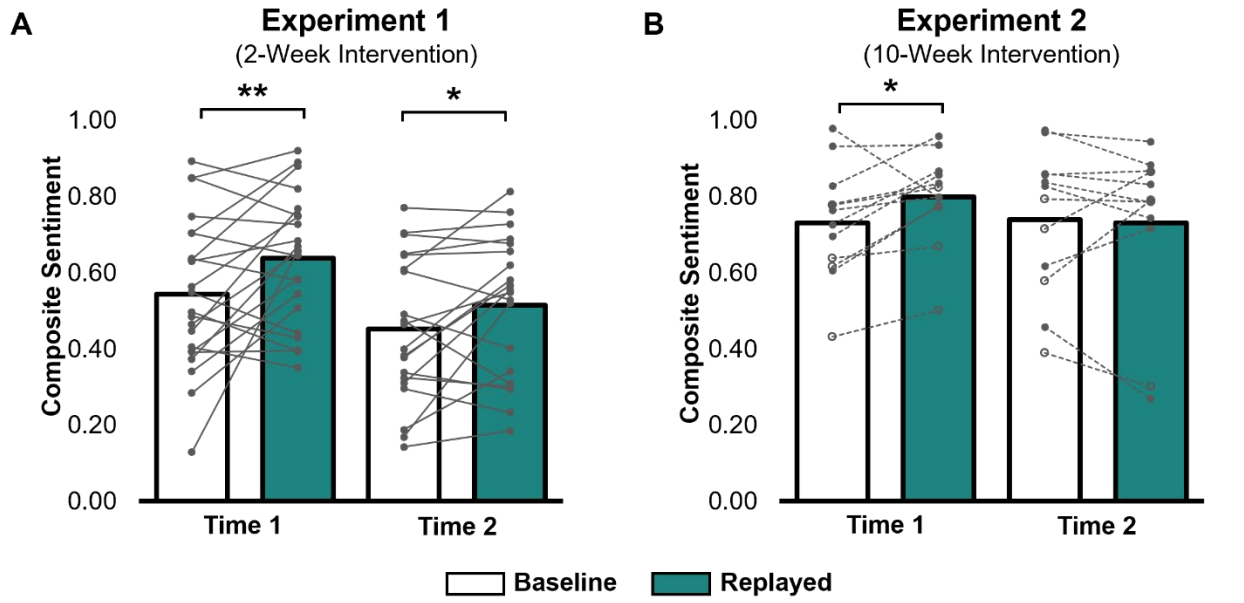


**Fig. 3. Replay evoked more positive sentiment in autobiographical retrieval.** Sentiment analysis performed on cued-recall responses. (A) Composite sentiment scores from Experiment 1. Composite values range from -1 (negative sentiment) to 1 (positive sentiment). (B) Composite sentiment scores from Experiment 2. Open markers are used to denote Experiment 2 participants who failed the Montreal Cognitive Assessment. * = $P < .05$, ** = $P < .01$.

## Cued Reactivation Promoted Differentiation of Activity Patterns in the Hippocampus

Having revealed that replaying autobiographical memory cues enhanced episodic recollection in older adults, we next sought to determine whether this effect was associated with increased differentiation of activity patterns in the hippocampus. To this end, we combined fMRI data (N = 25) obtained from participants in Experiment 1 (N = 13 of 22 total participants) and Experiment 2 (N = 12 of 12). For both experiments, cues were replayed a comparable number of times (Experiment 1 = 8.64; Experiment 2 = 7.77) and fMRI scanning was completed seven days after the Time 1 autobiographical memory test (Fig. 1*C-D*). In Experiment 1, our recruitment efforts focused on finding older adults who were willing to use the *HippoCamera* application and visit our laboratory on a regular basis; willingness to be scanned was not a requirement for participation and several of

our participants had medical implants (e.g., pacemaker), claustrophobia, arthritis, or other exclusions that made scanning not possible. For Experiment 2, we completed extensive pre-screening for all participants, including mock scanning sessions, to ensure that they would be able to complete the fMRI component of our experiment.

Each fMRI scanning session was designed to measure brain activity related to memory for the participant-specific events that were probed in the Time 1 autobiographical memory test. We did this using three task components: Watch Cue, Mentally Relive, and Episodic Probe. The Mentally Relive task component was unique to Experiment 2. During the Watch Cue stage participants watched / listened to one of their cues without having to make a behavioral response (Fig. 4*A*). After a brief fixation, they were then asked to Mentally Relive the event that was just cued in an unconstrained manner (45). They were instructed to do this by recollecting details from the cued event rather than simply visualizing the cue that was just played. No behavioral response was required during this stage. After another brief fixation, they completed the Episodic Probe task that involved recollection of event-specific details. Specifically, they were asked to make a yes/no judgment in response to a centrally presented word that referred either to a true aspect of the cued event (i.e., a target), or to a person, place, thing, or action that could have plausibly been associated with the target event but was not (i.e., a lure). For example, we would use “KITE” as a target probe if a participant indicated during her Time 1 memory test that her grandson was distracted by a kite flying in the park where he was playing baseball, and use “ICE CREAM” as a plausible lure that she did not indicate as a detail from the baseball game. Target words did not refer to information that was captured within the cue itself, meaning that accurate responses on target or lure trials required recollection of event-specific details that went beyond the cue. This procedure (i.e., Watch Cue, Mentally Relive, and Episodic Probe) was repeated once for each tested memory, with repetitions appearing in separate runs. For the episodic probe task, one instance used a target probe word and the other used a lure. Participants correctly responded ‘yes’ to 86% ± 0.08 SEM of the target trials, and ‘no’ to 79% ± 0.11 SEM of the lure trials, indicating that our probes were successful in promoting recollection of event-specific details.

Our results indicated that using *HippoCamera* to replay autobiographical memory cues fundamentally altered the representational structure of episodic information in the hippocampus by promoting differentiation of memory-related activity patterns. We quantified differentiation of hippocampal activity patterns within each experimental condition separately using a representational similarity analysis (46) (Fig. 4*B*). Briefly, single-trial activity was estimated using a general linear model and extracted as spatially distributed patterns across the hippocampus. Activity patterns were averaged across two trials for each event cue, resulting in separate memory-specific estimates for the Watch Cue task component, the Mentally Relive task component, and the Episodic Probe task component. For each of these tasks we first quantified similarities between all pairs of Replayed memories and between all pairs of Baseline memories using Pearson's r. These values were then subtracted from one and averaged to produce global measures of differentiation for Replayed and Baseline activity separately (Fig. 4*C*) (41).

A linear mixed model revealed a significant main effect of Condition (Replayed vs. Baseline: b = 2.865×10-2, SE = 6.846×10-3, $t(24) = 4.184$, $P < .001$) and a significant interaction between Condition and Task ($F(2, 2186) = 13.932$, $P < .001$) (see SI, fMRI Methods for model details, Tables S5-S6). This was primarily driven by increased differentiation in hippocampal activity patterns for Replayed compared to Baseline events during the Episodic Probe task component (b = 0.0940, SE = 0.0157, $t(45) = 5.981$, $P < .001$) and the Mentally Relive task component (b = 0.0641, SE = 0.0204, $t(101) = 3.146$, $P = .0022$). We found no evidence for a difference between Replayed and Baseline differentiation during the Watch Cue task component (b = 0.0138, SE = 0.0157, $t(45) = 0.875$, $P = .386$). Lastly, we did not find evidence for a significant main effect of Task (Watch Cue vs. Mentally Relive vs. Episodic Probe: $F(2, 11) = 1.532$, $P = .257$).

To provide a more comprehensive picture of the effect that cued reactivation had on activity patterns in the hippocampus, we probed for potential differences in differentiation across the hippocampal long axis (47, 48) (SI, fMRI Results; Fig. S3, Tables S5-S6). Briefly, this analysis revealed evidence for increased differentiation for Replayed as compared to Baseline trials in the anterior but not posterior hippocampus. Additionally, we performed an exploratory analysis focused on activity patterns in

ventromedial prefrontal cortex (vmPFC), which revealed increased differentiation for Replayed as compared to Baseline memories during the Episodic Probe task component (SI, fMRI results; Fig. S4, Tables S5-S6).

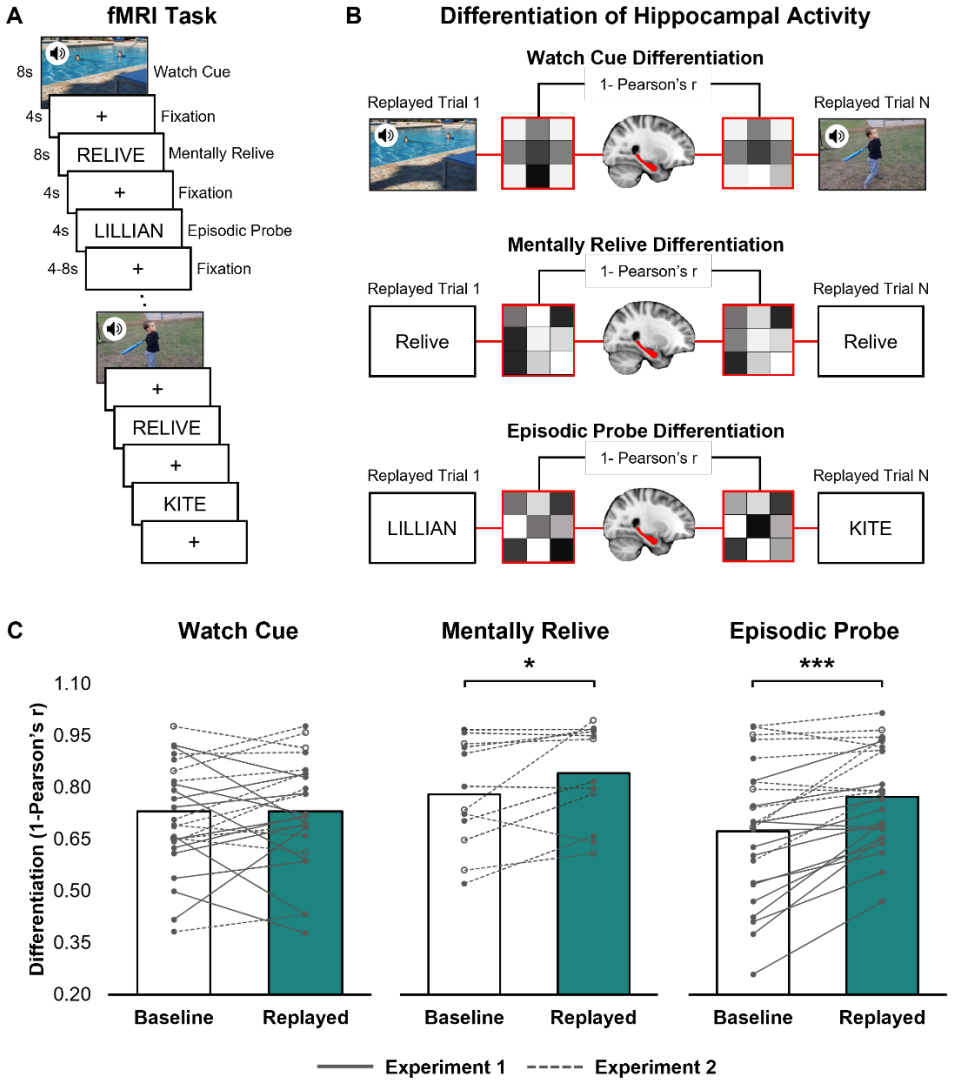


**Fig. 4. Replay enhanced differentiation of activity in the hippocampus.** (A) fMRI experimental design. Each trial was presented twice, with the first and second instance in different runs. Event-specific episodic probes varied across repetitions. Mean multivoxel activity patterns were obtained by averaging across repetitions. The Mentally Relive task component was unique to Experiment 2. (B) For each task (Watch Cue, Mentally Relive, Episodic Probe) we quantified differentiation (1 – Pearson's r) between mean activity patterns obtained for all pairs of Replayed memories (illustrated here) and between all pairs of Baseline memories (not illustrated here). (C) Differentiation scores for each component of the fMRI task. Solid lines depict data from Experiment 1 and dashed lines depict data from Experiment 2. Open markers are used to denote Experiment 2 participants who failed the Montreal Cognitive Assessment. * = $P < .05$, *** = $P < .001$.

**Hippocampal Differentiation Was Positively Correlated with Episodic Recollection**

We next found that degree of hippocampal differentiation was positively correlated with recollection of event-specific detail on the unscanned Time 1 and Time 2 autobiographical memory tests (Fig. 5). Memory-specific differentiation scores were estimated by calculating mean pairwise pattern dissimilarities between a given memory and all other memories within the same condition. We then computed the correlation (Pearson's r) between hippocampal differentiation and recall of Internal details across trials for each participant separately. Because there is no principled reason to believe that the relationship between hippocampal differentiation and recall behavior differ qualitatively across our experimental conditions, we did not distinguish between Replayed and Baseline trials for the purpose of this analysis. Directional one-sample *t*-tests against chance (i.e., correlation equal to zero) were performed using within-subject Fisher z-transformed correlation values. Using this approach, we found that degree of hippocampal differentiation measured during the Episodic Probe component of the fMRI task was positively correlated with number of Internal details recalled at Time 1 ($t(24) = 3.97$, $P < .001$, $d = 0.795$) and Time 2 ($t(22) = 2.51$, $P < .01$, $d = 0.523$). A similar result was obtained for the Mentally Relive component used in Experiment 2 at Time 1 ($t(11) = 3.45$, $P < .01$, $d = 0.997$) and Time 2 ($t(11) = 3.04$ $P < .05$, $d = 0.877$). We also found above chance correlations between differentiation at the Watch Cue component and the number of Internal details recalled at Time 2 ($t(22) = 2.76$, $P < .05$, $d = 0.576$). Conversely, we did not find evidence for any meaningful positive or negative associations between degree of hippocampal differentiation and recall of External details (all $P$'s > .35; see SI, fMRI Results, Fig. S6). Taken together, results from our pattern dissimilarity analyses revealed that replaying rich autobiographical memory cues promoted hippocampal differentiation, which in turn was positively correlated with recollection of event-specific episodic details on unscanned autobiographical memory tests administered one week earlier and three months later. Following-up on results from our exploratory analysis focused on medial prefrontal cortex, we found a significant positive correlation between differentiation of activity in this region during the Episodic Probe task and recall of Internal details from the Time 1, but not Time 2, autobiographical memory tests (SI, fMRI Results, Fig. S5).

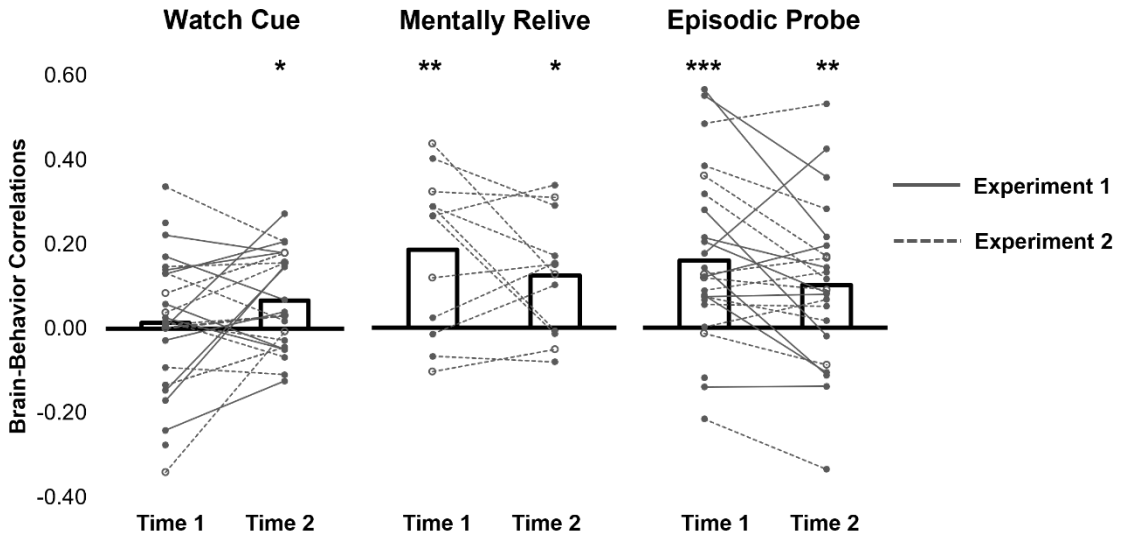


**Fig. 5. Degree of hippocampal differentiation is positively correlated with recollection of event-specific Internal details.** Correlations (Pearson's r) between hippocampal differentiation and recall of Internal details during the Time 1 and Time 2 autobiographical memory tests. Each marker denotes the Fisher-z transformed r value obtained for individual participants. Note that the Mentally Relive component was unique to Experiment 2. Solid lines connect subject-level correlation values at Time 1 and Time 2 for participants in Experiment 1. Dashed lines connect subject-level correlation values at Time 1 and Time 2 for participants in Experiment 2. Open markers are used to denote Experiment 2 participants who failed the Montreal Cognitive Assessment. Significance values indicate correlations greater than chance, i.e., correlation of zero, at the group level. * = $P < .05$, ** = $P < .01$, *** = $P < .001$.

## Discussion

Here, we describe a novel smartphone-based intervention that uses self-generated, high-fidelity cues to improve memory for everyday events in older adults. Across two experiments, we found that replaying rich autobiographical memory cues improved detail-rich recollection shortly after a 14-day (Experiment 1) and a 70-day (Experiment 2) period during which participants used the application to record and replay personally meaningful moments from their daily lives. This behavioral enhancement was also evident when memory was assessed a second time, three months after participants stopped using the application. Moreover, replaying memory cues evoked more positive autobiographical sentiment at the time of retrieval. We used a pattern-based analysis approach with fMRI data to reveal changes in hippocampal activity related to our cued-reactivation protocol. This approach revealed increased differentiation of activity in the hippocampus related to memories for events that were previously replayed as compared

to those that were recorded but never replayed. The extent of differentiation of memory-specific activity in the hippocampus was positively correlated with behavioral measures of episodic re-experiencing. Together, these findings support the conclusion that recording and replaying autobiographical memory cues can enhance episodic recollection by promoting differentiation of underlying representations in the hippocampus.

Our primary behavioral finding was that replaying autobiographical memory cues enhanced later recollection of event-specific details in older adults. Specifically, we revealed a 37% increase in detailed episodic recollection after using *HippoCamera* to record and replay real-world memory cues for only 14 days (Experiment 1), and a 73% increase after doing so for 70 consecutive days (Experiment 2). This effect was selective in that our replay protocol did not consistently affect retrieval of semantic information (Fig. S1-S2). The significance of these results is apparent against a background of prior research that has revealed age-related declines in the episodic component of autobiographical memory (8, 49, 50). Our results indicate that replaying brief but detail-rich cues from daily life can combat the tendency for older adults to recall events at the level of their gist (e.g., “Felix played baseball”) by helping to preserve event-specific information in memory (e.g., “Felix played baseball and it was such a thrill to see the joy on his face the first time he hit the ball”). Moreover, this enhancement persisted over a three-month period, such that episodic recollection declined less precipitously for events that had previously been replayed than it did for events that were recorded but never replayed. Accordingly, by contributing to the preservation and accessibility of detail-rich memories, our cognitive behavioral intervention helps to bridge the present with the episodic past in older individuals.

How does replaying real-world autobiographical memory cues improve episodic recollection? Previous research has demonstrated that remembering an event influences the probability and quality of future recollection (19, 20); successful retrieval is thought to beget future retrieval success, whereas incomplete or failed retrieval attempts reduce the likelihood of future retrieval success (23-29). Our behavioral results are consistent with the idea that replaying high-fidelity, self-generated cues from everyday events evokes

strong reactivation of event memories and therefore strengthens associations among episodic details. Moreover, they extend prior research by revealing a link between memory reactivation and enhanced recollection of complex and dynamic real-world events, rather than paired associates or naturalistic video stimuli. We obtained this result despite using a cued-reactivation protocol that was not accompanied by explicit retrieval demands, which have been shown to improve subsequent memory relative to mere re-exposure of previously encountered information (51, 52). Although this study was not designed to reveal potential differences between the effect of re-exposure and retrieval demands on subsequent memory, we note that our behavioral results reflect improved episodic recollection of event details that were not apparent in the memory cues themselves (Fig. 2). This observation suggests that re-exposure to sufficiently rich cues can improve memory for un-cued information even in the absence of any retrieval demands.

Results from our pattern similarity analyses indicated that replaying detail-rich cues accentuated differentiation of memory-related activity in the hippocampus. In other words, repeated reactivation minimized similarities between episodic memory representations by reducing representational overlap. Importantly, the degree to which a given memory representation was differentiated predicted the quality of episodic recollection, such that greater dissimilarity was associated with retrieval of more event-specific details. By linking the differentiation of activity in the hippocampus to enhanced episodic recollection, our results dovetail with evidence from computational modeling suggesting that greater differentiation among memory representations can reduce competition at retrieval and therefore facilitate detail-rich recollection (24, 53). This pattern of results cannot be fully explained by hippocampal pattern-separation, which is thought to minimize overlap among memory representations at the time of encoding (54-56), because differentiation emerged in response to post-encoding replay sessions that were distributed over time. Accordingly, we believe that using HippoCamera to replay memory cues differentiates underlying representations in a manner than protects detail-based information from being lost.

Although the current set of experiments was designed to characterize the effect of cued memory reactivation on memory, it is worth noting that *HippoCamera* also enriches encoding in a number of important ways. As such, because the Replayed and Baseline conditions had identical encoding protocols, events in *both* conditions were processed at encoding in a fundamentally different way from the incidental manner by which we typically learn about the world and encode new events. By incentivizing the creation of memory cues, *HippoCamera* use encourages a shift from incidental encoding to intentional encoding, which significantly improves future retrieval success in older adults (57). Anecdotally, many of our participants reported increased awareness of the world around them (e.g., one individual described their experience as a participant as follows, "… *It was very motivational. I started to have more confidence in myself and started to be more aware of things around me. I think it made my memory go up a shot*."). Creating self-generated memory cues also promotes deep processing of event details and meaning, which *HippoCamera* achieves by requiring a brief verbal description of the event, a video that captures diagnostic perceptual information, and a rating of the personal significance of the event (Fig. 1*A*). Importantly, this deep processing ensures correspondence between the retrieval cue and the information encoded in memory (15). Lastly, numerous participants reported having varied their behavioral repertoire out of a desire to record and replay interesting content. For example, one participant noted "… *Sometimes I would be sitting at home and realize that I needed to film something so I would go out to the library or the church just to have something to do*.". Considering these points together, it is likely that the results reported here underestimate the beneficial effects of using *HippoCamera* due to enriched encoding of events in both Replayed and Baseline conditions. Ultimately, further research is required to isolate and quantify the contribution of enhanced encoding. At another level, we also note that it is not immediately clear how to best establish a baseline condition when conducting research outside of a controlled laboratory environment. We opted for a relatively conservative approach to ensure that we did not overestimate our effects.

In sum, we have developed a smartphone-based memory aid that uses cued reactivation of real-world events to improve episodic recollection in older adults. This beneficial outcome was linked to a corresponding increase in the differentiation of activity

in the hippocampus and more positive autobiographical sentiment at the time of retrieval. By strengthening connections between the present and past self, this application presents a non-invasive approach to mitigating real-world age-related memory decline. More generally, to the extent that autobiographical memory makes important contributions to other aspects of cognition and the maintenance of meaningful interpersonal relationships, this intervention has potential to promote graceful aging.

## Materials and Methods

**Participants.** ***Experiment 1.*** Twenty-two neurologically healthy older adults (mean age = 69.64 years ± 0.89 SEM, range = 62-76 years, 16 women) participated in Experiment 1. Two participants in Experiment 1 were unable to complete a Time 2 autobiographical memory test due to personal scheduling constraints. All participants obtained a passing score on the Montreal Cognitive Assessment (MoCA) (mean score = 27.10 ± 0.26 SEM, range = 26-30), suggesting that these individuals were cognitively healthy at the time of testing (58). Of this sample, 13 individuals also participated in the fMRI experiment (mean age = 68.84 years ± 1.19 SEM, range = 62-76 years, 10 women, mean MoCA = 27.62 ± 0.35 SEM). ***Experiment 2.*** Twelve neurologically healthy older adults participated in Experiment 2 (mean age = 66.77 years ± 0.81 SEM, range = 61-71, 6 women, mean MoCA score = 26.58 ± 0.85 SEM). Four of these individuals failed the MoCA (scores of 20, 24, 25, and 25) but had no documented history of neurological or cognitive disorder. For illustrative purposes, data from these participants are depicted with open markers in Results figures. The research protocol for both experiments was reviewed and approved by the Research Ethics Board at The University of Toronto. Written informed consent was obtained from all participants prior to DMA use and again before fMRI data collection.

**HippoCamera Smartphone Application**. We developed the *HippoCamera* application using a participatory design approach aimed at optimizing ease of use and enjoyability in older adults. The application supports two key functions: recording and replaying autobiographical memory cues.

*Recording Cues with HippoCamera:* Cues are recorded in a four-step process, with automated transitions between steps (Fig. 1*A*). First, participants intentionally make the decision to record an ongoing event. Second, they capture an 8-second audio recording that is a self-generated verbal description of the target event. Third, they record a 24-second high-definition video. Fourth, they rate the significance of the event using a 1-5 scale. Meta-data are also automatically recorded, including time, date, and GPS co-ordinates, when available. Upon completing a recording, the application 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 file containing the 8-second verbal description. A notification system can be toggled on to encourage participant compliance. For the current study, these notifications reminded participants to record five cues per day in Experiment 1 and one cue per day in Experiment 2. Note that most record parameters can be customized to suit the specific research question at hand.

*Replaying Cues with HippoCamera:* Replay takes place within sessions that consist of up to five sequentially presented cues that are automatically selected (Fig. 1*B*). Cues are separated by a lead-in screen on which the date and approximate age of the event are shown in text. Each cue consists of the previously recorded verbal description (8s, real speed) played concurrently with the speeded video (24s accelerated by a factor of 3). Within a session, cues are replayed in reverse chronological order. The application is designed to select cues for replay in a manner that achieves balance between distributed learning and the prioritization of recent, highly significant events. For the current research, notifications encouraged participants to replay 6 times per day in Experiment 1 and once per day in Experiment 2. Many of the parameters that govern replay can be customized to reflect varying research demands.

*Assignment of Cues to Experimental Conditions:* For the purpose of the current research, cues were randomly assigned to either the Replayed or Baseline condition on a per-cue basis in Experiment 1. In Experiment 2, assignment was blocked in an ABAB manner such that all cues recorded in a given week were assigned to the Replayed condition and

cues recorded in the next week to the Baseline condition. Condition assignment procedures support multiple kinds of research through probabilistic assignment, fixed schedules established at intake, or remote real-time management by a research team.

The studies described herein were conducted using a beta version of the *HippoCamera* application that was developed by our research team. This software was subsequently updated to improve stability, enhance visualizations, enable cloud-based storage, and permit researchers to remotely access content recorded by participants. These improvements were implemented by Tactica Interactive (Winnipeg, Manitoba). This version of the application can be obtained from Apple's App Store and Google Play by researchers interested in using this application for scientific purposes. As of the time of writing, this is a research-dedicated application that can only be unlocked with an access code. We encourage interested individuals to contact a corresponding author to obtain an access code and administrator privileges.

**Behavioral Task.** Behavioral performance was assessed using an adapted version of the Autobiographical Interview (8) (SI, Behavioral Methods). In Experiment 1, the Time 1 autobiographical memory test was administered twice, once after the first seven days of *HippoCamera* use and a second time after the second seven days (Fig. 1*C*). Data from these two test sessions were collapsed for all statistical analyses. In Experiment 2, the Time 1 memory test was completed one week after the end of *HippoCamera* use and divided over two consecutive days. We probed memory for Replayed and Baseline memories that were captured over the 10-week application use period (Fig. 1*D*). Time 2 memory tests were completed three months after fMRI scanning in both Experiment 1 and Experiment 2.

Trial order was randomized in our autobiographical memory tests, and experimenters were blind to the condition of each cue. Responses were recorded, transcribed, and then quantified by a blinded experimenter using an adapted version of the scoring protocol developed for the Autobiographical Interview (43) (SI, Behavioral Methods, Autobiographical Memory Tests). Specifically, each recalled detail was scored as being either Internal or External in nature. Recalled details were not counted if they were apparent based on the contents of the cue, i.e., either the speeded video or verbal

description of the event. In other words, we conservatively discounted details that a naïve observer could also describe based on having seen only the cue, but not having experienced the event.

**Stimulus Selection.** Anecdotally, the quality of cues varied within and across participants and experiments. Some cues corresponded to interesting and complex events (e.g., attending an outdoor concert at a summer festival), whereas others captured more mundane moments from daily life (e.g., preparing lunch). On average, participants in Experiment 1 recorded a total of 66.9 cues over their 14-day use period and participants in Experiment 2 recorded a total of 66.75 cues over their 70-day use period. Because of the extensive nature of our autobiographical memory tests, we selected up to 40 of these cues for the purpose of constructing our behavioral and fMRI assessments (up to 20 Replayed and up to 20 Baseline). In some cases, fewer than 40 cues were selected based on three criteria. First, we aimed to match the events for which we were testing memory at the level of event frequency, event significance, and memory age. Second, we selected cues that sampled broadly from the range of recorded behaviors and events to ensure that we were probing memory for experiences that were representative of our participants' lives. Cues were excluded from testing if they received low significance ratings (i.e., a rating of 1 or 2 out of 5). Third, in Experiment 1, multiple cues that corresponded to the same event (e.g., a birthday party with one cue of the cake and another of presents being opened), but were randomly assigned to different conditions (i.e., one cue was Replayed whereas the other was Baseline), were not tested in either the behavioral or fMRI experiments.

Using this approach we successfully matched Experiment 1 events across the Replayed and Baseline conditions at the level of event frequency ($M_{Replayed}$ = 2.52 on a 5-point scale, $M_{Baseline}$ = 2.60; paired $t(21) = 0.72$, $P = .48$) and event significance ($M_{Replayed}$ = 3.13 on a 5-point scale, $M_{Baseline}$ = 3.13; paired $t(21) = 0.01$, $P = .99$). There was a statistically significant difference between Replayed and Baseline events at the level of memory age (Time 1 $M_{age}$: Replayed = 4.3 days ± .16 SEM, Baseline = 4.0 days ± .20 SEM, paired $t(20) = 2.49$, $P = .02$, $d = 0.54$; Time 2 $M_{age}$: Replayed = 123.8 days ± 4.92 SEM, Baseline = 123.4 days ± 4.90 SEM, paired $t(18) = 2.17$, $P = .04$, $d = 0.50$). We note,

however, that this difference was rather small in practical terms and that its direction (Replayed older than Baseline) works against our hypotheses regarding enhanced memory in the Replayed condition.

In Experiment 2, Replayed and Baseline memories were matched at the levels of event significance ($M_{Replayed}$ = 3.32 on a 5-point scale, $M_{Baseline}$ = 3.24; paired $t(11) = 1.08$, $P = .30$), event frequency ($M_{Replayed}$ = 2.52 on a 5-point scale, $M_{Baseline}$ = 2.28; paired $t(11) = 2.01$, $P = .06$), and memory age (Time 1 $M_{age}$: Replayed = 43.35 days ± 2.31 SEM, Baseline = 44.98 days ± 1.93 SEM, paired $t(11) = 0.54$, $P = 0.59$; Time 2 $M_{age}$: Replayed = 144.55 days ± 4.51 SEM, Baseline = 146.16 days ± 4.11 SEM, paired $t(11) = 0.26$, $P = 0.79$).

**Sentiment Analysis.** Cued-recall transcripts were processed using VADER (Valence Aware Dictionary and sEntiment Reasoner), a lexicon and rule-based sentiment analysis tool that systematically identifies and quantifies affective states communicated in natural language (44). The polarity and intensity scores of the 9000 words comprising the VADER lexicon reflect sentiment ratings from human observers. VADER returns scores that reflect positive sentiment, negative sentiment, neutral sentiment, and a normalized weighted composite score that ranges between -1 (extremely negative) and 1 (extremely positive). We used composite scores as dependent measures, as they provide a single unidimensional measure of sentiment.

**MRI Acquisition.** MRI data were recorded on a 3T Siemens Magnetom Prisma system at the Toronto Neuroimaging facility using a 32-channel head coil. High-resolution anatomical images were acquired with a 3D-MPRAGE T1-weighted sequence with oblique axial slices covering the whole brain (TR = 2000 ms, TE = 2.4 ms, flip angle = 9°, voxel size = 1 $mm^3$, matrix size = 192 x 256 x 160). Functional images were recorded using a gradient echo EPI sequence with 56 oblique axial slices oriented parallel to the hippocampus (TR = 1000 ms, TE = 30 ms, flip angle = 45°, voxel size = 3.4 x 3.4 x 3.0 mm, matrix size = 70 x 70 x 56). The number of functional volumes acquired per run varied across participants (M = 298.25, range = 265-327), reflecting the fact that some participants had more memories tested in the autobiographical interview than others.

**fMRI Task.** Data for Experiment 1 were collected across 4 functional runs. Data from one run could not be collected for one participant due to a technical error. Data for Experiment 2 were collected across eight functional runs. Three participants were unable to complete all eight runs due to physical discomfort: one completed four runs, two completed six runs.

**fMRI Data Preprocessing.** All neuroimaging data were preprocessed using FSL 6.00 (FMRIB software library, https://fsl.fmrib.ox.ac.uk/fsl/fslwiki). Images were skull-stripped using BET (63), and data were corrected for slice-acquisition time, high-pass temporally filtered using a 50-second period cu-off, and motion corrected using MCFLIRT (64). Each participant's functional data were smoothed using a 5mm FWHM kernel and registered to their high-resolution anatomical image using FLIRT boundary-based registration. The resulting data were analyzed using first-level FEAT. Parameter estimates of BOLD response amplitude were computed using FILM, with a general linear model that included temporal autocorrelation correction and six motion parameters as nuisance covariates. Each task component of each trial (Watch Cue, Mentally Relive, and Episodic Probe) was modeled with a boxcar function corresponding to the event onset and then convolved with a double-gamma hemodynamic response function. Separate t-statistic images were created for each task component on each trial, which were then normalized to MNI space. Memory-specific t-images were then averaged across repetitions, resulting in a single t-image for each memory. These data were used for the purpose of our pattern-based similarity analyses.

**fMRI ROI Definition.** All fMRI analyses were completed using data that were normalized to MNI space. Accordingly, one hippocampal ROI was created in each hemisphere using an MNI template. For the purpose of our first exploratory analysis, we used the uncal apex as an anatomical marker to create anterior hippocampus ROI that was distinct from a posterior hippocampus ROI, bilaterally (61). For the purpose of our second exploratory analysis, a vmPFC ROI was created using criteria established in previous research focused on memory consolidation (62). This ROI encompassed Broadmann's Area (BA) 14, BA 25, ventral parts of BA 24 and BA 32, the caudal part of BA 10, and the medial part of BA 11.

**Representational Similarity Analysis.** Representational similarity analyses were performed using the CoSMoMVPA Matlab toolbox (http://www.cosmomvpa.org/) (63). Analyses focused on activity in the hippocampus, including exploratory analyses that examined the anterior and posterior extent separately, were performed using multivoxel patterns extracted from our ROIs bilaterally.

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**Conflict of Interests Statement**

C.B.M, B.H., R.N.N., A.X., C.J.H., 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 conduct the research described herein, but has given Dynamic Memory Solutions the rights to commercialize. No person, nor organization 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.

## Supplementary Information

## Behavioral Methods

### Autobiographical Memory Tests

*Administration*

We assessed memory performance in Experiment 1 and Experiment 2 using an adapted version of the autobiographical interview (AI) (1). Typical administration of the AI involves asking participants to verbally describe their memory for self-selected events from five different life periods. Following a free-recall response in the typical AI, participants respond to a general probe intended to encourage retrieval of additional information without providing specific guidance. They are then asked to respond to a series of specific probes designed to elicit further detail corresponding to events, time, time integration, place, sensory information, emotions, and thoughts. In our adapted version of the AI, participants were instructed to recall events for which they had previously recorded an autobiographical cue. Memory for each event was tested by first having the participant view the event-specific cue and then provide a verbal description of what they remembered based on the following instructions:

*"Please tell me as much as you can remember about the event that was just cued. Try to restrict your description to the specific event that was the subject of the recording. It is important that your description goes beyond the contents of the video and verbal description that you recorded. In other words, do not simply narrate the video, tell me about the entirety of the event."*

The length of event-specific verbal descriptions elicited by this approach varied across events and participants. Time 1 cued-recall responses ranged from 15 seconds to 20 minutes per event. Given that we were probing memory for up to 40 distinct events, rather than five as is typical in the AI, we did not consistently administer general or specific probes. As such, all data described in this report reflect details described in initial cued-recall responses.

*Scoring*

All raters completed the AI training protocol (1). In this context, our raters scored closely to skilled raters. We omitted details that were apparent in the cue from all trial-specific detail counts. For example, if a cue included video footage of a dinner partner who was wearing a red dress and eating chicken, any mention of the red dress or specific comments about the chicken dish were not counted for the purpose of our statistical analyses. This strategy ensured that our dependent measure reflected episodic reliving rather than mere recall of content from the multi-modal cue. Cued-recall responses were quantified using an adapted version of the AI scoring protocol that specifies criteria for distinguishing between Internal and External details, as well as different types of External details (2). For our purposes, we did not discriminate between different types of Internal details. External details were further parsed according to the subtypes outlined in Renoult et al. (2):

- *External Event* details: recall of information that is episodic in nature but pertains to non-target events.
- *General Semantic* details: culturally shared knowledge of facts, public events, people, and concepts.
- *Personal Semantic* details: semantic knowledge of one's personal past, which is further divided into three subtypes.
    - *Autobiographical Facts*: basic units of knowledge about one's personal past, such as the name of the street on which you lived as a child, or your dog's name.
    - *Self-Knowledge*: awareness of one's disposition and preferences, such as claiming that you are hot tempered or noting that you dislike spicy food.
    - *Repeated Events*: descriptions of features that are common to multiple instances of an episode, such as mentioning that you and a friend always order the same cobbler for dessert when you get together for dinner on Saturdays.
- *Repeated Details*: information provided multiple times while describing memory for a specific event.

- *Other*: utterances that could not otherwise be scored as Internal or any of the above External subtypes (e.g., “Give me a moment to think about this”, “I don’t remember this event very well”).

**Linear Mixed Modeling with Autobiographical Memory Test Data**

Detail counts form the autobiographical memory tests were analyzed using multilevel modeling in R 4.1.0 (R Core Team, 2021) with the *lme4* package (3). The *performance* package was used to obtain intraclass correlations (ICC) and both conditional and marginal coefficients of determination ($R^2_C$ and $R^2_M$, respectively) to determine model fits (4, 5). To test hypotheses related to autobiographical memory test detail counts, we used 2-level multilevel generalized Poisson models with individual trials nested within participants. Poisson models were used to best account for the count-based nature of the number of details recollected (6). For both Experiment 1 (2-Week Intervention) and Experiment 2 (10-Week Intervention), individual models were specified for both Internal and External details to obtain separate estimates for each detail type. Multilevel modeling was appropriate given the degree of variance explained by individual participants in Experiment 1 and Experiment 2 (Table S1). For all models, we first fit the model with the maximal random effects structure (7). To investigate the effect of Condition and Test Session, this entailed estimating fixed effects for Condition (Replayed vs. Baseline), Test Session (Time 1 vs. Time 2), and their interaction, as well as a random intercept estimated for each participant and a random slope estimated for each fixed effect. Condition and Test Session were effect coded (Condition: Baseline = -1, Replayed = 1; Test Session: Time 1 = -1, Time 2 = 1). In the situation that the maximal model failed to converge due to overparameterization, we employed a backward-selection heuristic (8). To probe for any significant interactions, simple effects tests were conducted with the Tukey adjustment for pairwise comparisons using the *emmeans* package (9)—adjusted *P*-values are reported for simple effects. To compare the total number of details recalled across both experiments, the maximal model predicting the total number of details recalled on a trial with a fixed effect for Experiment (Experiment 1 vs Experiment 2), a random slope for Experiment, and a random intercept for each participant was first specified—Experiment was effect coded (Experiment 1 = -1, Experiment 2 = 1). Model

selection was performed in the same fashion as described above. All models were estimated with an unstructured covariance matrix.

## Behavioral Results

### Autobiographical Memory Test External Detail Counts

*Overall External Details*

As noted in the main body of our report, we did not have specific hypotheses regarding the effect of replaying autobiographical memory cues on recall of External details. In an effort to provide a comprehensive picture of our data, we performed an exploratory analysis focused on External details in cued-recall responses (Fig. S1, Table S1-S2). In our first analysis, we examined External details without considering different detail subtypes. A Poisson generalized linear mixed model revealed no significant main effect of either Condition (Replayed vs. Baseline: b = -0.0275, SE = 0.0182, z = -1.513, *P* = .130) or Test Session (Time 1 vs. Time 2: b = -0.0660, SE = 0.0410, z = -1.608, *P* = .108). There was also no significant interaction between Condition and Test (b = 0.0318, SE = 0.0166, z = 1.921, *P* = .0548).

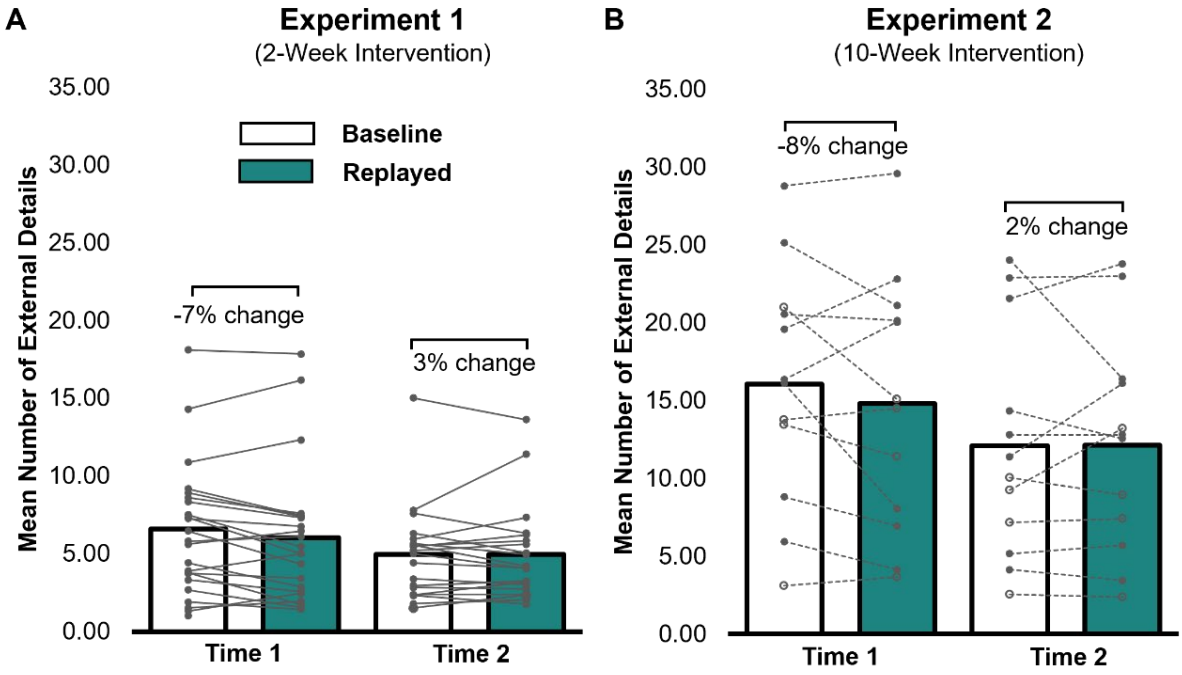

**Fig. S1. Behavioral Results – Overall External Detail Counts.** Mean number of External details for Experiment 1 and Experiment 2. Time 1 corresponds to behavioral performance measured during (Experiment 1) and shortly after (Experiment 2) *HippoCamera* use. Time 2 corresponds to behavioral performance after a 3.25-month delay, during which time participants did not have access to their memory cues. Percent change values are included for illustrative rather than inferential purposes. Open markers denote Experiment 2 participants who failed the Montreal Cognitive Assessment.

*External Details by Subtype*

In a second exploratory analysis, we examined External detail counts for seven different detail subtypes (Fig. S2, Table S3-S4).

*External Event:* For Experiment 1, we did not find a significant main effect of Condition (Replayed vs. Baseline: b = 0.327, SE = 0.0797, z = 0.411, *P* = .681), Test Session (Time 1 vs. Time 2: b = -0.0160, SE = 0.0832, z = -0.192, *P* = .847), or interaction between the two (b = -0.0934, SE = 0.0652, z = -1.434, *P* = .152) on the average number of External Event details recalled. For Experiment 2, we did not find a significant main effect of Condition (Replayed vs. Baseline: b = -0.0933, SE = .0640, z = -1.457, *P* = .145). However, we did find a significant main effect of Test Session (Time 1 vs. Time 2: b = -0.252, SE = 0.0720, z = -3.508, *P* < .001), such that participants provided more External Event details during the Time 1 memory test than the Time 2 memory test. In addition, we found a significant interaction between Condition and Test Session (b = 0.195, SE = 0.0966, z = 2.019, *P* = .0435), where participants provided fewer External Event details for Replayed compared to Baseline events at the Time 1 memory test (b = -0.577, SE = 0.232, z = -2.483, *P* = .0130), but not during the Time 2 memory test (b = 0.204, SE = 0.231, z = 0.880, *P* = .379).

*General Semantics:* For Experiment 1, we did not find a significant main effect of Condition (Replayed vs. Baseline: b = 0.0643, SE = 0.0647, z = 0.995, *P* = .320) on the average number of General Semantic details recalled. However, we did find a significant main effect of Test Session (Time 1 vs. Time 2: b = -0.228, SE = 0.0380, z = -6.009, *P* < .001), such that participants provided more General Semantic details during the Time 1 memory test than the Time 2 memory test. In addition, we found a significant interaction between Condition and Test Session (b = 0.192, SE = 0.0377, z = 5.107, *P* < .001), such that participants provided more General Semantic details for Replayed compared to

Baseline events during the Time 2 memory test (b = 0.513, SE = 0.160, z = 3.205, *P* = .0013), but not during the Time 1 memory test (b = -0.256, SE = 0.138, z = -1.849, *P* = .0645). For Experiment 2, we did not find a significant main effect of Condition (b = 0.0145, SE = 0.0535, z = 0.271, *P* = .787), Test Session (b = -0.0889, SE = 0.0498, z = -1.786, *P* = .0741), or interaction between the two (b = 0.0329, SE = 0.0238, z = 1.383, *P* = .167).

*Autobiographical Facts:* For Experiment 1, we did not find a significant main effect of either Condition (Replayed vs. Baseline: b = -0.00526, SE = 0.0366, z = -0.144, *P* = .886) or Test Session (b = -0.132, SE = 0.0895, z = -1.472, *P* = .141) on the on the average number of Autobiographical Facts recalled. However, there was a significant interaction between Condition and Test Session (b = 0.0769, SE = 0.0241, z = 3.192, *P* = .00141), such that participants provided fewer Autobiographical Facts for Replayed compared to Baseline events during the Time 1 memory test (b = -0.164, SE = 0.0828, z = -1.985, *P* = .0472), but not during the Time 2 memory test (b = 0.143, SE = 0.0921, z = 1.555, *P* = .120). For Experiment 2, we did not find a significant main effect of Condition (Replayed vs. Baseline: b = 0.0228, SE = 0.0448, z = 0.510, *P* = .610). However, there was a significant main effect of Test Session (b = -0.211, SE = 0.0506, z = -4.166, *P* < .001), with participants providing more Autobiographical Facts during Time 1 memory tests compared to Time 2 memory tests. There was no significant interaction between Condition and Test Session (b = 0.0456, SE = 0.0467, z = 0.978, *P* = .328).

*Self-Knowledge:* For Experiment 1, we did not find a significant main effect of either Condition (Replayed vs. Baseline: b = 0.0276, SE = 0.0641, z = 0.431, *P* = .666) or Test Session (b = -0.203, SE = 0.116, z = -1.745, *P* = .0810) on the on the average number of Self-Knowledge details recalled. However, there was a significant interaction between Condition and Test Session (b = -0.122, SE = 0.0461, z = -2.647, *P* = .00812), where participants provided more Self-Knowledge details for Replayed compared to Baseline events during the Time 1 memory test (b = 0.299, SE = 0.144, z = 2.079, *P* = .0376), but not during the Time 2 memory test (b = -0.189, SE = 0.171, z = -1.105, *P* = .269). For Experiment 2, we did not find a significant main effect of Condition (Replayed vs. Baseline: b = -0.0253, SE = 0.0323, z = -0.783, *P* = .434). However, there was a significant main effect of Test Session (b = -0.162, SE = 0.0556, z = -2.909, *P* = .00362),

with participants providing more Self-Knowledge details during Time 1 memory tests compared to Time 2 memory tests. There was no significant interaction between Condition and Test Session (b = 0.0229, SE = 0.0323, z = 0.710, *P* = .478).

*Repeated Events:* For Experiment 1, we did not find a significant main effect of Test Session (b = -0.147, SE = 0.133, z = -1.104, *P* = .270). However, we did find a significant main effect of Condition (Replayed vs. Baseline: b = -0.149, SE = 0.0722, z = -2.061, *P* = .0393) and a significant interaction between Condition and Test Session (b = -0.170, SE = 0.0721, z = -2.351, *P* = .0187) on the number of Repeated Event details provided. This pattern of results is driven by participants providing fewer Repeated Event details for Replayed events compared to Baseline events at Time 2 memory tests (b = -0.637, SE = 0.233, z = -2.735, *P* = .0062), but not at Time 1 memory tests (b = 0.0418, SE = 0.170, z = 0.245, *P* = .806). For Experiment 2, we found a significant main effect of Condition (Replayed vs. Baseline: b = -0.168, SE = 0.0657, z = -2.561, *P* = .0104), with participants providing fewer Repeated Event details for Replayed compared to Baseline events. We did not find a significant main effect of Test Session (b = -0.0725, SE = 0.0940, z = -0.771, *P* = .440), or a significant interaction between Condition and Test Session (b = 0.0629, SE = 0.0617, z = 1.019, *P* = .308).

*Repeated Details:* For Experiment 1, we did not find a significant main effect of Condition (Replayed vs. Baseline: b = -0.0420, SE = 0.0442, z = -0.952, *P* = .341), Test Session (b = -0.144, SE = 0.0839, z = -1.718, *P* = .0859), or interaction between the two (b = 0.00369, SE = 0.0358, z = 0.103, *P* = .918) on the average number of Repeated details recalled. For Experiment 2, we did not find a significant main effect of Condition (Replayed vs. Baseline: b = 0.0427, SE = 0.0323, z = 1.320, *P* = .187). However, there was a significant main effect of Test Session (b = -0.214, SE = 0.0684, z = -3.120, *P* = .00181), with participants providing more Repeated details during Time 1 memory tests compared to Time 2 memory tests. There was no significant interaction between Condition and Test Session (b = 0.0204, SE = 0.0272, z = 0.749, *P* = .454).

*Other Details:* For Experiment 1, we did not find a significant main effect of Condition (Replayed vs. Baseline: b = -0.0185, SE = 0.0400, z = -0.463, *P* = .643), Test Session (b = -0.0621, SE = 0.0577, z = -1.075, *P* = .282), or interaction between the two (b = 0.0395,

SE = 0.0471, z = 0.838, *P* = .402) on the average number of Other details recalled. We found the same pattern in Experiment 2, with no evidence for a significant main effect of Condition (Replayed vs. Baseline: b = -0.0282, SE = 0.0346, z = -0.814, *P* = .416), Test Session (b = 0.00651, SE = 0.0396, z = 0.164, *P* = .870), or interaction between the two (b = -0.00802, SE = 0.0196, z = -0.409, *P* = .682).

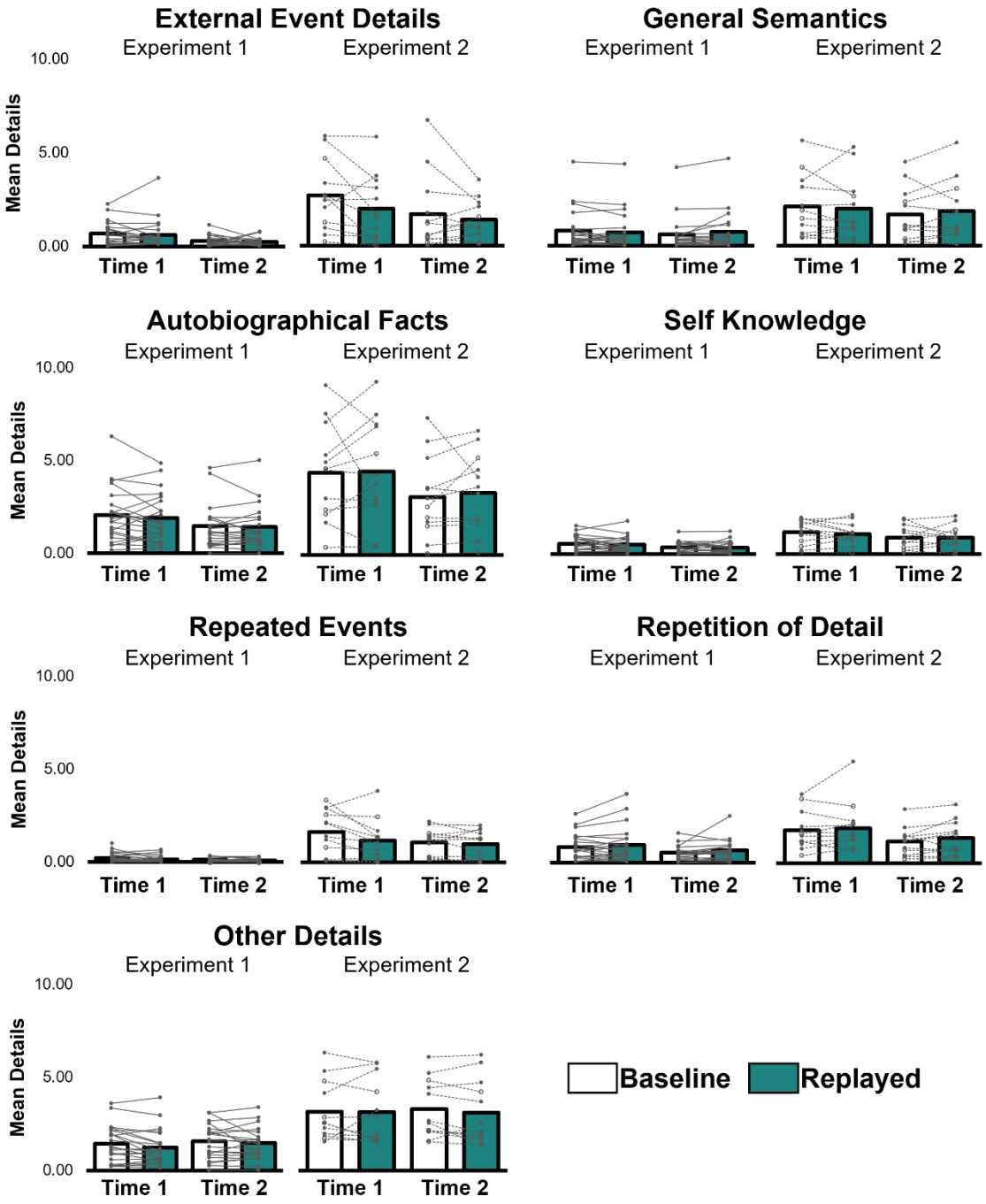


**Fig. S2. Behavioral Results – External Details by Subtype.** Mean number of External details by subtype for Experiment 1 and Experiment 2. Time 1 corresponds to behavioral performance measured during (Experiment 1) and shortly after (Experiment 2) *HippoCamera* use. Time 2 corresponds to behavioral performance after a 3-month delay, during which time participants did not have access to their memory cues. Open markers denote Experiment 2 participants who failed the Montreal Cognitive Assessment.

## fMRI Methods

### Linear Mixed Modeling with fMRI Data

Data were analyzed using multilevel modeling in R 4.1.0 (R Core Team, 2021) using the same tools implemented in our behavioral analyses. We used 2-level multilevel linear models with individual trials nested within participants. Individual models were specified for the entire hippocampus, the anterior hippocampus, posterior hippocampus, and ventromedial prefrontal cortex (vmPFC). Multilevel modeling was appropriate given the degree of variance explained by individual participants for differentiation scores across all regions of interest, as assessed by their ICCs (Table S6). For all models, we would first always fit the model with the maximal random effects structure, according to Barr et al. (7). To investigate the effect of Condition and task component, this entailed estimating fixed effects for Condition (Baseline vs. Replayed), Task (Episodic Probe vs. Mentally Relive vs. Watch Cue), and their interaction; a random intercept estimated for each participant; and a random slope estimated for each fixed effect. Both Condition and Task were effect coded (Condition: Baseline = -1, Replayed = 1; Task: Episodic Probe = 1, Mentally Relive = 0, Watch Cue = -1; for second task component effect code: Episodic Probe = 0, Mentally Relive = 1, Watch Cue = -1). In the situation that the maximal model failed to converge due to overparameterization, we employed the backward-selection heuristic (8). To probe any significant interactions, simple effects tests were conducted with the Tukey adjustment for pairwise comparisons using the emmeans package (9)—adjusted P-values are reported for simple effects. The lmerTest package in R was used to obtain *P*-values corresponding to each fixed effect using likelihood ratio tests with the Satterthwaite approximation for degrees of freedom (10). The best fitting models described using Wilkinson notation, their corresponding model fit statistics, and ANOVA tables assessing the significance of fixed-effects parameters for the above analyses are summarized in Table S6. All models were estimated with an unstructured covariance matrix.

In addition, we performed an exploratory analysis to investigate whether differentiation scores differed across the long axis of the hippocampus. Specifically, we added an additional fixed effect for hippocampal ROI (Anterior vs. Posterior).

Hippocampal ROIs were effect coded (Anterior = 1, Posterior = -1). Model specification was otherwise performed in the same fashion as described above.

## fMRI Results

### Pattern Differentiation in the Anterior versus Posterior Hippocampus

Our main set of fMRI pattern-based similarity analyses focused on the hippocampus in its entirety, which revealed greater differentiation (i.e., pattern dissimilarity) among memories in the Replayed condition than among memories in the Baseline condition. A substantial body of evidence suggests that the hippocampus is neither anatomically nor functional homogeneous along its anterior-posterior extent and that the functional distinction may be captured by differences between gist-based and detail-based memory representations (11, 12). Within this framework, the activity in the anterior hippocampus is thought to support gist-based memory, whereas the posterior hippocampus is thought to support detail-based memory. To investigate whether replay-related increases in pattern differentiation differed between the anterior and posterior extent of the hippocampus, we performed an exploratory analysis that used the uncal apex as an anatomical marker separating the anterior from the posterior extent (13).

A linear mixed model revealed a significant main effect of ROI, such that anterior hippocampus showed increased differentiation in activity patterns overall compared to posterior hippocampus (b = $6.143\times10^{-3}$, SE = $2.855\times10^{-3}$, $t(4597) = 2.152$, $P = .0351$). However, we did not find evidence for any interactions involving ROI and any other predictor for differentiation in activity patterns (all $P$'s > .05).

We did find a significant main effect of Condition (Replayed vs. Baseline: b = $2.587\times10^{-2}$, SE = $2.855\times10^{-3}$, $t(4597) = 9.060$, $P < .001$) and a significant interaction between Condition and Task ($F(2, 4597) = 22.337$, $P < .001$). This was driven by increased differentiation in hippocampal activity patterns for Replayed compared to Baseline events during the Episodic Probe task (b = 0.0886, SE = $8.54\times10^{-3}$, $t(4597) = 10.378$, $P < .001$) and the Mentally Relive task (b = 0.0582, SE = 0.0122, $t(4597) = 4.791$, $P < .001$) tasks. The difference between Replayed and Baseline differentiation during the Watch Cue task

was not significant (b = $8.37\times10^{-3}$, SE = $8.54\times10^{-3}$, $t(4597) = 0.980$, $P = .327$). Lastly, we did not find evidence for a significant main effect of Task ($F(2, 13) = 0.161$, $P = .853$).

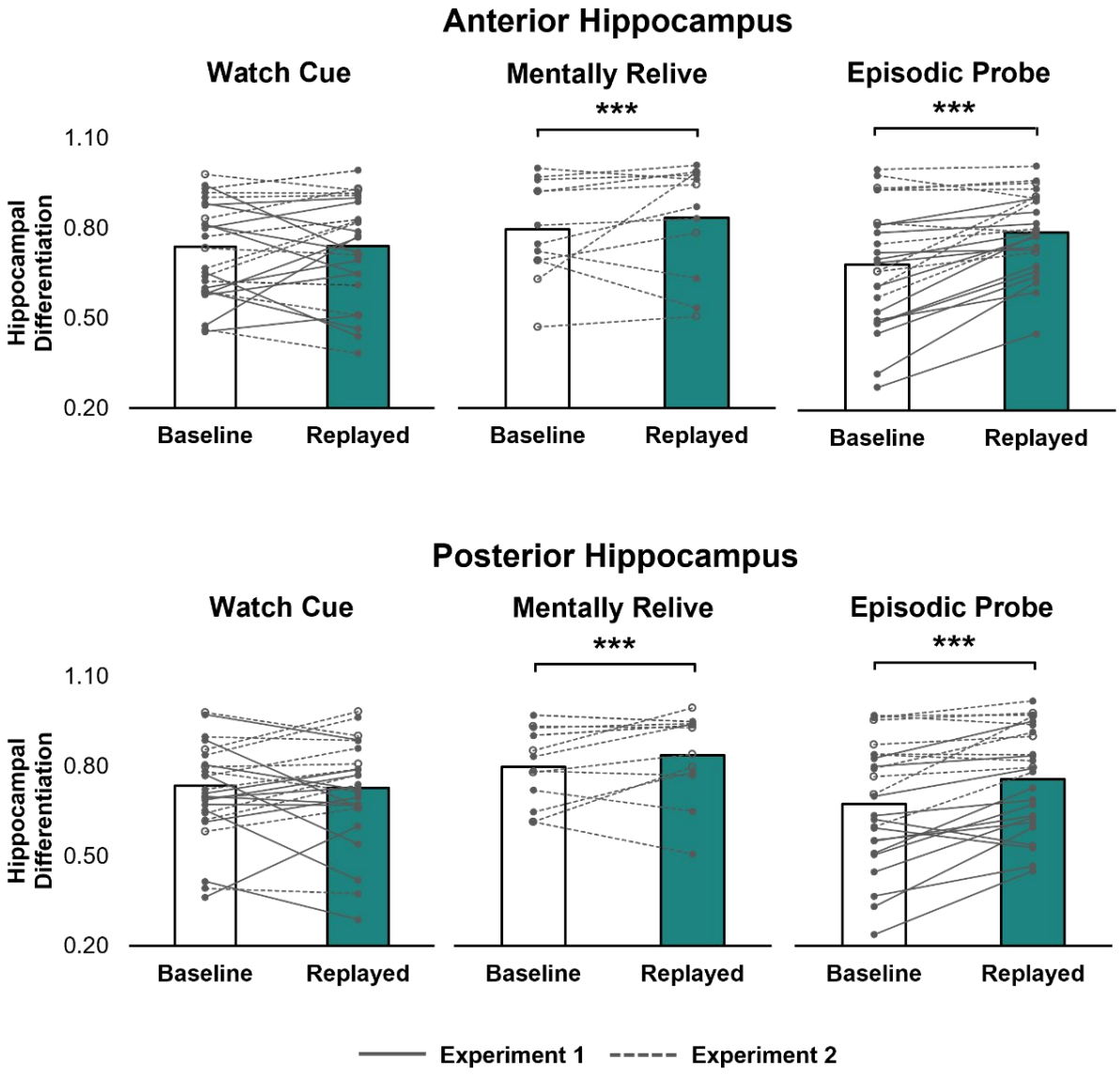


**Fig. S3. Differentiation of Anterior and Posterior Hippocampus Activity.** We quantified within condition measures of differentiation (1 – Pearson's r) using activity patterns obtained from the anterior and posterior hippocampus during each component of the fMRI task. Solid lines depict data from Experiment 1 and dashed lines depict data from Experiment 2. Open markers denote Experiment 2 participants who failed the Montreal Cognitive Assessment. *** = $P < .001$.

### Pattern Differentiation in Ventromedial Prefrontal Cortex (vmPFC)

In addition to the well-established role of the hippocampus in the encoding and retrieval of memory for recent events, previous neuroimaging research has also revealed important contributions of vmPFC (14-16). To investigate whether distributed replay of detail-rich autobiographical memory cues would promote differentiation of memory-related activity in vmPFC, we performed an exploratory pattern analysis focused on an vmPFC ROI.

Results are presented in Fig. S4. We found a significant main effect of Condition (Replayed vs. Baseline: b = $6.033\times10^{-3}$, SE = $2.628\times10^{-3}$, $t(2304) = 2.296$, $P = .0218$) and a significant interaction between Condition and Task ($F(2, 2303) = 3.048$, $P = .0476$). This pattern of results is driven by increased differentiation in vmPFC activity patterns for Replayed as compared to Baseline events during the Episodic Probe task (b = 0.0283, SE = $7.86\times10^{-3}$, $t(2304) = 3.603$, $P = .0003$), but not during the Mentally Relive (b = $5.63\times10^{-3}$, SE = 0.0112, $t(2304) = 0.503$, $P = .615$) or Watch Cue (b = $2.26\times10^{-3}$, SE = 7.86×10-3, $t(2304) = 0.287$, $P = .774$) tasks. We did not find evidence for a significant main effect of task component ($F(2, 2309) = 1.566$, $P = .209$).

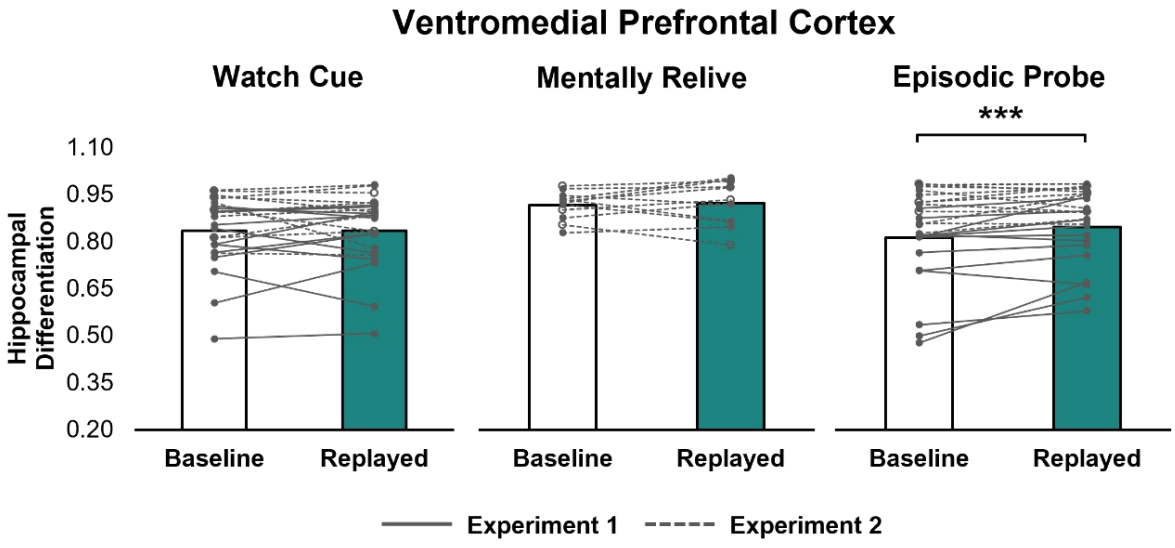


**Fig. S4. Differentiation of vmPFC Activity.** We quantified within condition measures of differentiation (1 – Pearson's r) using activity patterns obtained from vmPFC during each component of the fMRI task. Solid lines depict data from Experiment 1 and dashed lines depict data from Experiment 2. Open markers denote Experiment 2 participants who failed the Montreal Cognitive Assessment. *** = $P < .001$.

## Relationship Between Pattern Differentiation in vmPFC and Recollection of Internal Details

We next asked whether pattern differentiation in vmPFC was positively correlated with retrieval of Internal details from the Time 1 and Time 2 autobiographical memory tests (Fig. S5). Here, we focused specifically on the Episodic Probe component of the fMRI experiments given that it was the only task that showed greater differentiation among activity patterns for events in the Replayed as compared to the Baseline condition. A one-sample *t*-test against a mean of zero revealed that the group averaged correlation values were indeed significantly greater than chance when Time 1 behavioral measures were considered ($t(24) = 2.23$, $P = .02$). The same analysis with Time 2 Internal detail counts was not significant ($t(22) = -1.06$, $P = .85$).

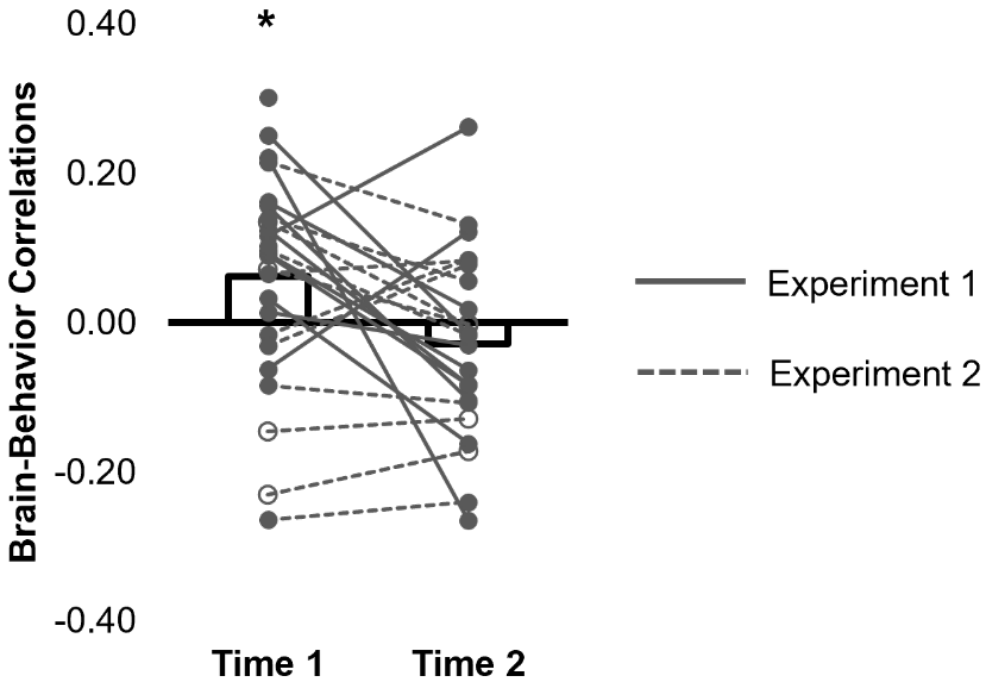


**Fig. S5. Correlation Between Differentiation Scores in vmPFC and Retrieval of Internal Details.** Pearson's correlation values obtained between vmPFC differentiation in the Episodic Probe component of the fMRI task and number of Internal details recalled at Time 1 and Time 2. Subject-level correlations are denoted by solid lines for Experiment 1 and dashed lines for Experiment 2. Open markers denote Experiment 2 participants who failed the Montreal Cognitive Assessment. Significance values indicate correlations great than chance, i.e., correlation of zero, at the group level. * = $P < .05$.

## Relationship Between Pattern Differentiation in the Hippocampus and Recall of External Details

In a final set of exploratory analyses, we correlated differentiation scores from the hippocampus and number of External details recalled in our Time 1 and Time 2 behavioral assessments (Fig. S6). Whereas hippocampal differentiation was significantly correlated with number of Internal details recalled (Fig. 5 in main text), we did not find evidence for any such relationship with External details. A one-sample t-test against a mean of zero revealed that the group averaged correlation values did not differ from chance during any of the task components or test sessions (Watch Cue and Time 1 ($t(24) = -1.52$, $P = .14$), Watch Cue and Time 2 ($t(22) = -0.69$, $P = .49$), Mentally Relive and Time 1 ($t(11) = 0.57$, $P = .58$), Mentally Relive and Time 2 ($t(11) = -1.05$, $P = .32$), Episodic Probe and Time 1 ($t(24) = -0.26$, $P = .80$), or Episodic Probe and Time 2 ($t(22) = 0.68$, $P = .50$).

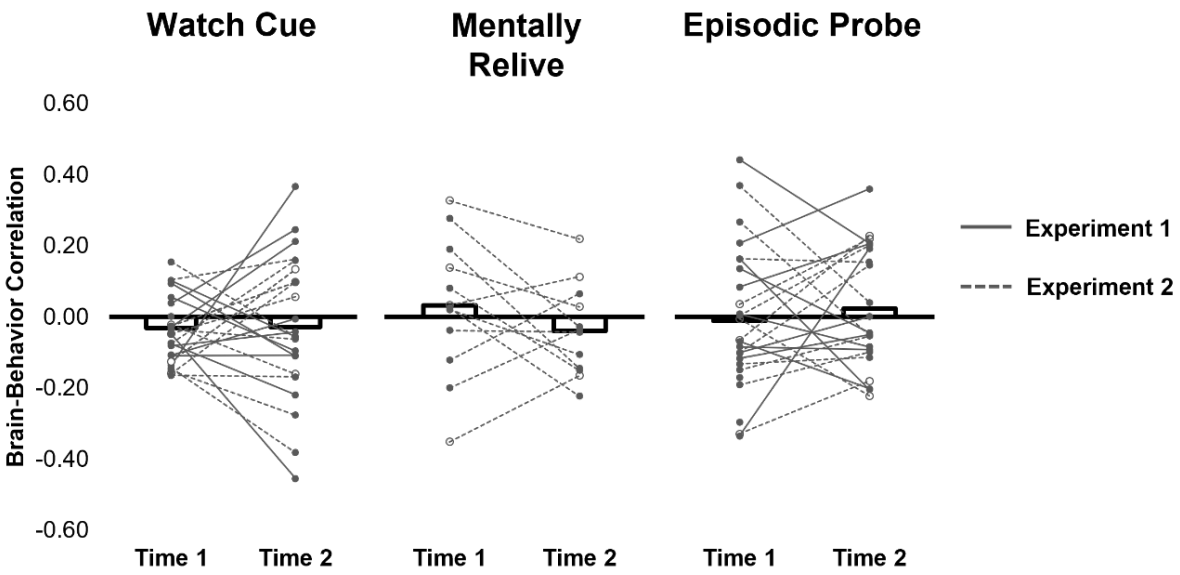


**Fig. S6. Correlation Between Differentiation Scores in the Hippocampus and Retrieval of External Details.** Pearson's correlation values obtained between hippocampal differentiation and overall number of External details recalled at Time 1 and Time 2. Subject-level correlations are denoted by solid lines for Experiment 1 and dashed lines for Experiment 2. Open markers denote Experiment 2 participants who failed the Montreal Cognitive Assessment.

**Table S1.** Intraclass correlations for intercept-only models of Internal and External detail counts.

| Analysis | Detail Type | ICC |
|---|---|---|
| Experiment 1 | Internal | .422 |
| | External | .660 |
| Experiment 2 | Internal | .697 |
| | External | .832 |

**Table S2.** Fit statistics and fixed-effects parameters for best fitting models for Internal and External detail counts.

| Experiment | Detail Type | Model Formula | $R^2_C$ | $R^2_M$ | Fixed Effect | Estimate (b) | SE | z | *P* |
|---|---|---|---|---|---|---|---|---|---|
| Experiment 1 | Internal | ~ Condition × Test Session + (Condition + Test Session \| Participant) | .481 | .232 | Intercept | 1.617 | 0.0612 | 26.429 | < 2e-16 *** |
| | | | | | Condition | 0.144 | 0.0196 | 7.336 | 2.19e-13 *** |
| | | | | | Test Session | -0.271 | 0.0320 | -8.476 | < 2e-16 *** |
| | | | | | Condition × Test Session | -0.0136 | 0.0124 | -1.090 | .276 |
| Experiment 1 | External | ~ Condition × Test Session + (Condition × Test Session \| Participant) | .654 | .011 | Intercept | 1.566 | 0.124 | 12.617 | <2e-16 *** |
| | | | | | Condition | -0.0275 | 0.0182 | -1.513 | .130 |
| | | | | | Test Session | -0.0660 | 0.0410 | -1.608 | .108 |
| | | | | | Condition × Test Session | 0.0318 | 0.0166 | 1.921 | .0548 |
| Experiment 2 | Internal | ~ Condition × Test Session + (Condition × Test Session \| Participant) | .828 | .162 | Intercept | 2.183 | 0.144 | 15.114 | < 2e-16 *** |
| | | | | | Condition | 0.222 | 0.0264 | 8.407 | < 2e-16 *** |
| | | | | | Test Session | -0.120 | 0.0312 | -3.840 | 0.000123 *** |
| | | | | | Condition × Test Session | -0.0369 | 0.0142 | -2.607 | 0.009143 ** |
| Experiment 2 | External | ~ Condition × Test Session + (Condition × Test Session \| Participant) | .893 | .041 | Intercept | 2.434 | 0.185 | 13.133 | < 2e-16 *** |
| | | | | | Condition | -0.0278 | 0.0181 | -1.536 | .124 |
| | | | | | Test Session | -0.138 | 0.0323 | -4.288 | 1.8e-05 *** |
| | | | | | Condition × Test Session | 0.0314 | 0.0289 | 1.087 | .277 |

Legend: $R^2_C$ = conditional coefficient of determination, $R^2_M$: marginal coefficient of determination, SE: standard error, ** *P* < .01, *** *P* < .001. Note: models specified here are multilevel generalized Poisson models to best account for the count-based nature of the number of details recollected.

**Table S3.** Intraclass correlations for intercept-only models External detail counts by subtype.

| Analysis | External Detail Subtype | ICC |
|---|---|---|
| Experiment 1 | External event | .345 |
| | General semantic | .472 |
| | Autobiographical fact | .387 |
| | Self-knowledge | .272 |
| | Repeated event | .177 |
| | Repeated detail | .326 |
| | Other | .374 |
| Experiment 2 | External event | .644 |
| | General semantic | .578 |
| | Autobiographical fact | .713 |
| | Self-knowledge | .455 |
| | Repeated event | .624 |
| | Repeated detail | .361 |
| | Other | .366 |

**Table S4.** Fit statistics and fixed-effects parameters for best fitting models for External detail counts by subtype.

| Experiment | Detail Type | Model Formula | $R^2_C$ | $R^2_M$ | Fixed Effect | Estimate (b) | SE | z | *P* |
|---|---|---|---|---|---|---|---|---|---|
| Experiment 1 | External Event | ~ Condition × Test Session + (Condition × Test Session \| Participant) | .363 | .005 | Intercept | -1.0857 | 0.176 | -6.152 | 7.66e-10 *** |
| | | | | | Condition | 0.0327 | 0.0797 | 0.411 | .681 |
| | | | | | Test Session | -0.0160 | 0.0832 | -0.192 | .847 |
| | | | | | Condition × Test Session | -0.0934 | 0.0652 | -1.434 | .152 |
| Experiment 1 | General Semantic | ~ Condition × Test Session + (Condition \| Participant) | .485 | .040 | Intercept | -0.871 | 0.217 | -4.017 | 5.88e-05 *** |
| | | | | | Condition | 0.0643 | 0.0647 | 0.995 | .320 |
| | | | | | Test Session | -0.228 | 0.0380 | -6.009 | 1.87e-09 *** |
| | | | | | Condition × Test Session | 0.192 | 0.0377 | 5.107 | 3.28e-07 *** |
| Experiment 1 | Autobiographical Fact | ~ Condition × Test Session + (Condition + Test Session \| Participant) | .462 | .023 | Intercept | 0.314 | 0.118 | 2.654 | .00796 ** |
| | | | | | Condition | -0.00526 | 0.0366 | -0.144 | .886 |
| | | | | | Test Session | -0.132 | 0.0895 | -1.472 | .141 |
| | | | | | Condition × Test Session | 0.0769 | 0.0241 | 3.192 | .00141 ** |
| Experiment 1 | Self-Knowledge | ~ Condition × Test Session + (Condition + Test Session \| Participant) | .378 | .026 | Intercept | -1.176 | 0.174 | -6.757 | 1.41e-11 *** |
| | | | | | Condition | 0.0276 | 0.0641 | 0.431 | .666 |
| | | | | | Test Session | -0.203 | 0.116 | -1.745 | .0810 |
| | | | | | Condition × Test Session | -0.122 | 0.0461 | -2.647 | .00812 ** |

| **Experiment** | Detail Type | Model Formula | $R^2_C$ | $R^2_M$ | Fixed Effect | Estimate (b) | SE | z | *P* |
|---|---|---|---|---|---|---|---|---|---|
| Experiment 1 | Repeated Event | ~ Condition × Test Session + (Test Session \| Participant) | .230 | .023 | Intercept | -2.263 | 0.174 | -13.038 | <2e-16 *** |
| | | | | | Condition | -0.149 | 0.0722 | -2.061 | .0393 * |
| | | | | | Test Session | -0.147 | 0.133 | -1.104 | .270 |
| | | | | | Condition × Test Session | -0.170 | 0.0721 | -2.351 | .0187 * |
| Experiment 1 | Repeated Detail | ~ Condition × Test Session + (Condition + Test Session \| Participant) | .344 | .015 | Intercept | -0.554 | 0.140 | -3.968 | 7.25e-05 *** |
| | | | | | Condition | -0.0420 | 0.0442 | -0.952 | .341 |
| | | | | | Test Session | -0.144 | 0.0839 | -1.718 | .0859 |
| | | | | | Condition × Test Session | 0.00369 | 0.0358 | 0.103 | .918 |
| Experiment 1 | Other | ~ Condition × Test Session + (Condition × Test Session \| Participant) | .443 | .006 | Intercept | 0.183 | 0.132 | 1.388 | .165 |
| | | | | | Condition | -0.0185 | 0.0400 | -0.463 | .643 |
| | | | | | Test Session | -0.0621 | 0.0577 | -1.075 | .282 |
| | | | | | Condition × Test Session | 0.0395 | 0.0471 | 0.838 | .402 |
| Experiment 2 | External Event | ~ Condition × Test Session + (Condition × Test Session \| Participant) | .698 | .056 | Intercept | 0.144 | 0.307 | 0.471 | .637 |
| | | | | | Condition | -0.0933 | 0.0640 | -1.457 | .145 |
| | | | | | Test Session | -0.252 | 0.0720 | -3.508 | 4.52e-04 *** |
| | | | | | Condition × Test Session | 0.195 | 0.0966 | 2.019 | .0435 * |

| **Experiment** | Detail Type | Model Formula | $R^2_C$ | $R^2_M$ | Fixed Effect | Estimate (b) | SE | z | *P* |
|---|---|---|---|---|---|---|---|---|---|
| Experiment 2 | General Semantic | ~ Condition × Test Session + (Condition + Test Session \| Participant) | .586 | .007 | Intercept | 0.286 | 0.256 | 1.117 | .264 |
| | | | | | Condition | 0.0145 | 0.0535 | 0.271 | .787 |
| | | | | | Test Session | -0.0889 | 0.0498 | -1.786 | .0741 |
| | | | | | Condition × Test Session | 0.0329 | 0.0238 | 1.383 | .167 |
| Experiment 2 | Autobiographical Fact | ~ Condition × Test Session + (Condition × Test Session \| Participant) | .876 | .041 | Intercept | 0.884 | 0.275 | 3.218 | .00129 ** |
| | | | | | Condition | 0.0228 | 0.0448 | 0.510 | .610 |
| | | | | | Test Session | -0.211 | 0.0506 | -4.166 | 3.10e-05 *** |
| | | | | | Condition × Test Session | 0.0456 | 0.0467 | 0.978 | .328 |
| Experiment 2 | Self-Knowledge | ~ Condition × Test Session + (Test Session \| Participant) | .455 | .017 | Intercept | -0.249 | 0.246 | -1.011 | .312 |
| | | | | | Condition | -0.0253 | 0.0323 | -0.783 | .434 |
| | | | | | Test Session | -0.162 | 0.0556 | -2.909 | .00362 ** |
| | | | | | Condition × Test Session | 0.0229 | 0.0323 | 0.710 | .478 |
| Experiment 2 | Repeated Event | ~ Condition × Test Session + (Condition × Test Session \| Participant) | .589 | .014 | Intercept | -0.305 | 0.346 | -0.882 | .378 |
| | | | | | Condition | -0.168 | 0.0657 | -2.561 | .0104 * |
| | | | | | Test Session | -0.0725 | 0.0940 | -0.771 | .440 |
| | | | | | Condition × Test Session | 0.0629 | 0.0617 | 1.019 | .308 |

| **Experiment** | Detail Type | Model Formula | $R^2_C$ | $R^2_M$ | Fixed Effect | Estimate (b) | SE | z | *P* |
|---|---|---|---|---|---|---|---|---|---|
| Experiment 2 | Repeated Detail | ~ Condition × Test Session + (Condition + Test Session \| Participant) | .440 | .049 | Intercept | 0.228 | 0.171 | 1.337 | .181 |
| | | | | | Condition | 0.0427 | 0.0323 | 1.320 | .187 |
| | | | | | Test Session | -0.214 | 0.0684 | -3.120 | .00181 ** |
| | | | | | Condition × Test Session | 0.204 | 0.0272 | 0.749 | .454 |
| Experiment 2 | Other | ~ Condition × Test Session + (Condition + Test Session \| Participant) | .399 | .002 | Intercept | 0.914 | 0.130 | 7.044 | 1.87e-12 *** |
| | | | | | Condition | -0.0282 | 0.0346 | -0.814 | .416 |
| | | | | | Test Session | 0.00651 | 0.0396 | 0.164 | .870 |
| | | | | | Condition × Test Session | -0.00802 | 0.0196 | -0.409 | .682 |

Legend: $R^2_C$ = conditional coefficient of determination, $R^2_M$: marginal coefficient of determination, SE: standard error, ** *P* < .01, *** *P* < .001. Note: models specified here are multilevel generalized Poisson models to best account for the count-based nature of the number of details recollected.

**Table S5.** Intraclass correlations for intercept-only models of fMRI differentiation by region of interest

| **Analysis (ROI)** | **ICC** |
|---|---|
| Hippocampus | .391 |
| Anterior/Posterior Hippocampus | .349 |
| Ventromedial Prefrontal Cortex | .475 |

**Table S6.** Fit statistics and fixed-effects parameters for best fitting models of fMRI differentiation by region of interest

| Analysis (ROI) | Model Formula | $R^2_C$ | $R^2_M$ | Fixed Effect | SS | MS | $df_N$ | $df_D$ | F | *P* |
|---|---|---|---|---|---|---|---|---|---|---|
| Hippocampus | ~ Condition × Task Component + (Condition + Task Component \| Participant) | .500 | .022 | Condition | 0.0479 | 0.479 | 1 | 24 | 17.508 | .000330 *** |
| | | | | Task Component | 0.0838 | 0.0419 | 2 | 11 | 1.532 | .257 |
| | | | | Condition × Task Component | 0.762 | 0.381 | 2 | 2186 | 13.933 | 9.71e-07 *** |
| Anterior/Posterior Hippocampus | ~ Condition × Task Component × Region of Interest + (Task Component \| Participant) | .423 | .018 | Condition | 2.800 | 2.800 | 1 | 4597 | 82.076 | <2.2e-16 *** |
| | | | | Task Component | 0.0110 | 0.00549 | 2 | 13 | 0.161 | .853 |
| | | | | Region of Interest | 0.158 | 0.158 | 1 | 4597 | 4.629 | .0315 * |
| | | | | Condition × Task Component | 1.524 | 0.762 | 2 | 4597 | 22.337 | 2.22e-10 *** |
| | | | | Condition × Region of Interest | 0.0305 | 0.0305 | 1 | 4597 | 0.863 | .345 |
| | | | | Task Component × Region of Interest | 0.0645 | 0.0322 | 2 | 4597 | 0.945 | .389 |
| | | | | Condition × Task Component × Region of Interest | 0.00402 | 0.00201 | 2 | 4597 | 0.0589 | .943 |
| ventromedial Prefrontal Cortex | ~ Condition × Task Component + (1 \| Participant) | .473 | .004 | Condition | 0.0762 | 0.0762 | 1 | 2303 | 5.272 | .0218 * |
| | | | | Task Component | 0.0452 | 0.0226 | 2 | 2309 | 1.566 | .209 |
| | | | | Condition × Task Component | 0.0881 | 0.0440 | 2 | 2303 | 3.048 | .0476 * |

Legend: $R^2_C$ = conditional coefficient of determination, $R^2_M$: marginal coefficient of determination, SS: sum of squares, MS: mean squares, dfN: numerator degrees of freedom, dfD: denominator degrees of freedom, * $P < .05$, ** $P < .01$, *** $P < .001$.

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