Evidence supporting a time-limited hippocampal role in retrieving autobiographical memories

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The necessity of the human hippocampus for remote autobiographical recall remains fiercely debated. The standard model of consolidation predicts a time-limited role for the hippocampus, but the competing multiple trace/trace transformation theories posit indefinite involvement. Lesion evidence remains inconclusive, and the inferences one can draw from functional MRI (fMRI) have been limited by reliance on covert (silent) recall, which obscures dynamic, moment-to-moment content of retrieved memories. Here, we capitalized on advances in fMRI denoising to employ overtly spoken recall. Forty participants retrieved recent and remote memories, describing each for approximately 2 min. Details associated with each memory were identified and modeled in the fMRI time-series data using a variant of the Autobiographical Interview procedure, and activity associated with the recall of recent and remote memories was then compared. Posterior hippocampal regions exhibited temporally graded activity patterns (recent events > remote events), as did several regions of frontal and parietal cortex. Consistent with predictions of the standard model, recall-related hippocampal activity differed from a non-autobiographical control task only for recent, and not remote, events. Task-based connectivity between posterior hippocampal regions and others associated with mental scene construction also exhibited a temporal gradient, with greater connectivity accompanying the recall of recent events. These findings support predictions of the standard model of consolidation and demonstrate the potential benefits of overt recall in neuroimaging experiments.

autobiographical memory | fMRI | hippocampus | parietal cortex | spoken recall

Episodic memory refers to a collection of processes that support the retrieval of information about a spatially and temporally specific occurrence (1). A hallmark of this ability is a sense of mental time travel—of leaving the here and now to re-experience detailed aspects of a prior event (2). Neuropsychological and neuroimaging studies have identified a distributed collection of brain regions that support the retrieval of episodic memories, including regions within the medial temporal lobe, medial and superior prefrontal cortex, medial parietal cortex, and angular gyrus (3–5). Of particular importance is the interaction of the hippocampus—a medial temporal lobe structure strongly associated with memory encoding and retrieval (6–8)—and these other regions of cortex.

Over the last several decades, a debate has arisen regarding the nature of hippocampal–neocortical interaction during the retrieval of recent, as compared to remote, events. On one hand, clinicians have long noted a pattern by which temporally distant memories are the best retained and the first recovered following insults such as brain injury (9, 10). Similarly, neuropsychology studies in humans (6) and lesion experiments in nonhuman primates (11) and rodents (12) often find temporally graded retrograde amnesia following hippocampal damage; recently acquired memories are lost, while remote or more distant memories are spared. To account for these observations, a popular hypothesis known as the standard model of consolidation (SMC; refs. 13 and

14) asserts that a process of consolidation (possibly driven by hippocampal replay; ref. 15) results in a migration of retrieval routes from the hippocampus to the neocortex, such that over time, the hippocampus is no longer required for successful retrieval of a given event.

Others have argued that the critical determinate to hippocampal involvement is not time, but memory contents and detail. The multiple trace and more recent trace transformation (MT/TT) hypotheses—so named because they predict that each retrieval of an event is accompanied by another memory trace being formed and stored more broadly across the hippocampus—posit that the hippocampus is always required for vividly recalling memories (16, 17); memories recalled without a hippocampus are schematic and lack specific detail. Furthermore, the MT/TT hypotheses stipulate that hippocampal activity will scale as a function of the amount of information retrieved. Although the ideas behind, and predictions of, MT/TT and SMC differ substantially, distinguishing between the two models is complicated by the tendency for memories to become more schematic and less detailed over time (18, 19). That is, a memory's age and the subjective detail or vividness with which it is re-experienced are typically confounded.

A number of functional MRI (fMRI) studies in neurologically healthy participants have been conducted that speak to the

Significance

The hippocampus is central to healthy memory function, yet its necessity for remembering events from the distant past remains unclear. Prominent hypotheses alternatively suggest a time-limited or an indefinite role. fMRI evidence, typically based on silent in-scanner recall, has been equivocal, possibly because it provides sparse information of the content being remembered. Here, we asked fMRI participants to verbally describe recent and remote memories. After accounting for neural activity associated with the moment-to-moment memory content of recalled memories, we observed a temporally graded pattern of activity within the posterior hippocampus and found that recent—but not remote—event recall significantly activated the hippocampus relative to a non-autobiographical control task. Our findings support a time-limited hippocampal role in autobiographical memory.

question of how recent and remote events are retrieved. However, evidence has been mixed, and recent large-scale reviews have arrived at conflicting—and frankly incompatible—conclusions. For example, in a recent large-scale meta-analysis, Boccia et al. (5) found support for temporally graded activity, both in the hippocampus and neocortical regions, whereas a recent review from Yonelinas et al. (20) concluded that neuroimaging provides "little support for the [SMC] assumption that the hippocampus becomes less involved in retrieval as episodic memories become more remote" (p. 369). In part, Yonelinas et al. cited the potential confounding of memory age and vividness in reaching their conclusions. In a separate recent review, Sekeres et al. (17) argued that neuroimaging evidence "decidedly favors the positions taken by [MT/TT]: detailed or vivid episodic memories activate the hippocampus no matter how long ago the memories were acquired." (p. 42). Thus, over the past few years, reviews of the evidence seem to somehow simultaneously support and reject the SMC.

The debate for and against temporally graded activity in the hippocampus seems to rest largely on the subjective phenomenology of retrieved memories. From this perspective, fMRI studies of autobiographical memory have suffered in particular because of their reliance upon covert, or silent, recall. Covert recall is employed to reduce in-scanner head motion, but comes at the cost of knowing the moment-to-moment content of recalled memories. In lieu of overtly recalled details, Likert-type rating scales are employed to provide a summary rating for the subjective detail and/or vividness with which a given memory was re-experienced. Although vividness ratings are thought to reflect the amount of overall detail recalled (ref. 21; see also ref. 22), they provide no specific information relating to the nature of the recalled content. As a consequence, unaccounted-for differences in the number or types of details associated with recent and remote memories may obscure (or spuriously produce) effects associated with the age of a memory, contributing to the confused situation that currently characterizes the literature.

Here, we capitalized on recent advances in fMRI denoising (23) to employ *overtly spoken* in-scanner recall. Forty participants (23 female; 24.2 ± 2.8 y old) described memories from three Recall Periods: earlier on the day of scanning, a period of 6–18 mo prior, and a period of 5–10 y prior. Each memory was cued by using photographs of scenes and subsequently described aloud for a period of approximately 2 min (Fig. 1*A*). A non-autobiographical control (baseline) task involving a description of the same type of images was included to equate for narrative processes and possible re-encoding of details as they were being recalled and described (24). Memory contents were labeled by using an adapted version of the Autobiographical Interview procedure (24, 25) (Fig. 1*B*), and, after synchronizing the spoken audio and fMRI time series (Fig. 1*C*), contents were converted to event-related regressors to capture variance associated with every recalled detail (Fig. 1*D*). By separately modeling details within events from the temporal distance of an event, the basic question could be asked of how the recency or remoteness of a memory, per se, altered retrieval-related activity. Support for the SMC would be obtained if hippocampal activity was graded over time and differed from a control task for recent, but not remote, events. On the other hand, the MT/TT hypotheses would predict no difference in activity for recent and remote memories after accounting for detail-related recall effects, with consistent activation above levels observed in the control task.

Results

Overt Response Scoring Revealed Complex Event Descriptions across All Recall Periods. Overt recall enabled a detailed labeling and quantification of the contents of each memory, from each condition, for each participant. Each response was scored by using a variant of the Autobiographical Interview, which seeks to separate episodic and semantic contributions to memory retrieval (25). At a broad level, a given detail might be "Internal" to the event (i.e., spatially and temporally specific to the occurrence; an "episodic" detail) or it might be "External" (i.e., not specifically related to the event being described). Details were then broken
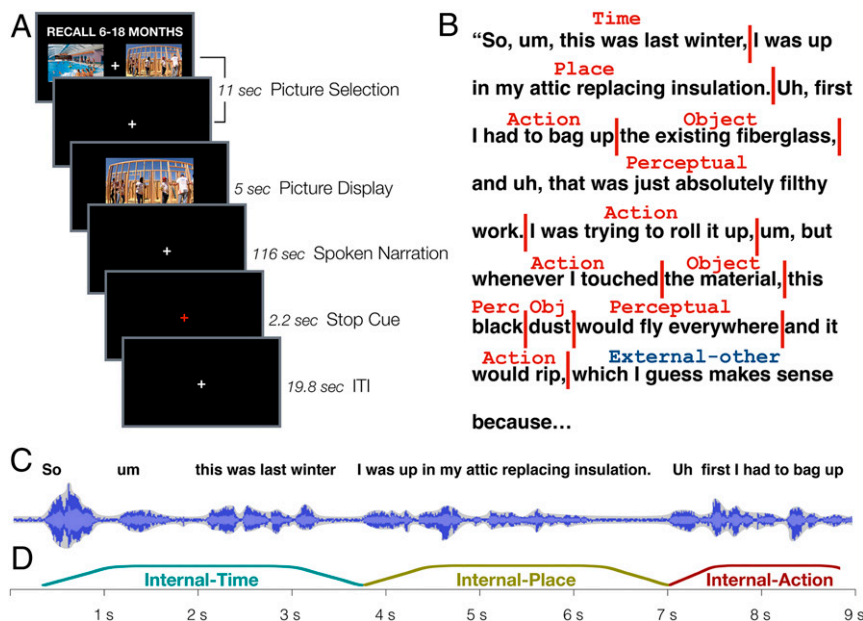
Fig. 1. Trial structure and approach. (*A*) Autobiographical memories were cued from three different recall periods (same-day, 6–18 mo ago, and 5–10 y ago), and participants selected their preferred picture cue for each trial. After viewing an enlarged version of their selected cue, participants described the memory as vividly as possible. A stop cue signaled the end of each trial. (*B*) Transcripts of each description were labeled and scored for content. (*C* and *D*) Transcript text was realigned with the original audio recording (*C*) and resynchronized with the BOLD time series (*D*) so that each detail could be converted to an event-related regressor. This allowed separate modeling of details and recall period effects.

down by subtype: Internal details might refer to a specific person, place, and so on, whereas External details might refer to general semantic knowledge or repetitions of previously stated information (see *SI Appendix*, Table S1 for a full list of categories). Here, comparisons at both levels (Internal vs. External, as well as the subcategories within each) were compared across Recall Periods.

Average counts of Internal and External details were subjected to a repeated measures ANOVA with factors of Detail Type (Internal or External) and Recall Period (Today, 6–18 mo, or 5–10 y). Overall, participants were quite detailed in their responses for all Recall Periods, and a main effect of Detail Type reflected the greater number of Internal versus External details, $F(1, 39) = 106.02$, $P < 0.001$, $\eta_p^2 = 0.731$ (Fig. 2A). A main effect of Recall Period was also observed, reflecting temporally graded reductions in both Internal and External detail types, $F(1, 39) = 68.09$, $P < 0.001$, $\eta_p^2 = 0.193$. No interaction between the factors was observed, $F(2, 78) = 2.15$, $P = 0.123$, $\eta_p^2 = 0.052$. Planned comparisons of Internal detail counts indicated that a slight reduction in details was present for the most remote time period relative to the earlier conditions [6–18 mo vs. 5–10 y: $t(39) = 2.73$, $P = 0.009$, $d = 0.445$; Today vs. 5–10 y: $t(39) = 2.02$, $P = 0.051$, $d = 0.319$], while an examination of External detail counts found that the most recent events contained more nonspecific details than did those of later Recall Periods [Today vs. 6–18 mo: $t(39) = 2.81$, $P = 0.008$, $d = 0.445$; Today vs. 5–10 y: $t(39) = 1.92$, $P = 0.062$, $d = 0.292$].

The ratio of Internal-to-External details was also compared, as this may better capture broader qualitative differences across conditions. If remote memories were more schematic in the current sample, then one would expect to see proportionally more External details as a function of Recall Period, which may be difficult to appreciate from raw counts alone. However, no significant effect was observed, $F(2, 78) = 2.377$, $P = 0.10$, $\eta_p^2 = 0.057$ (Fig. 2B). Thus, although small numeric differences in Internal detail counts were present between recent and remote events, the extent to which this represented a shift in subjective memory detail over time depends on how one asks the question.

Internal and External details are composed of numerous subcategories, and the frequency of each of these categories over time was also examined. This analysis revealed a complex pattern of differences, with some categories, such as Activity and Object details, appearing more frequently in recent memories, but others, such as Thought/Emotion or Person details, appearing more frequently for remote memories (Fig. 2C). For still others, no effect of temporal distance was present. Thus, it was not the case that there was an across-the-board reduction in all types of Internal/episodic details, as one might conclude if only looking at the coarse Internal vs. External category level. Instead, these results stress that—consistent with earlier work (18, 19)—recent and remote memories differ in the composition of their overall content.
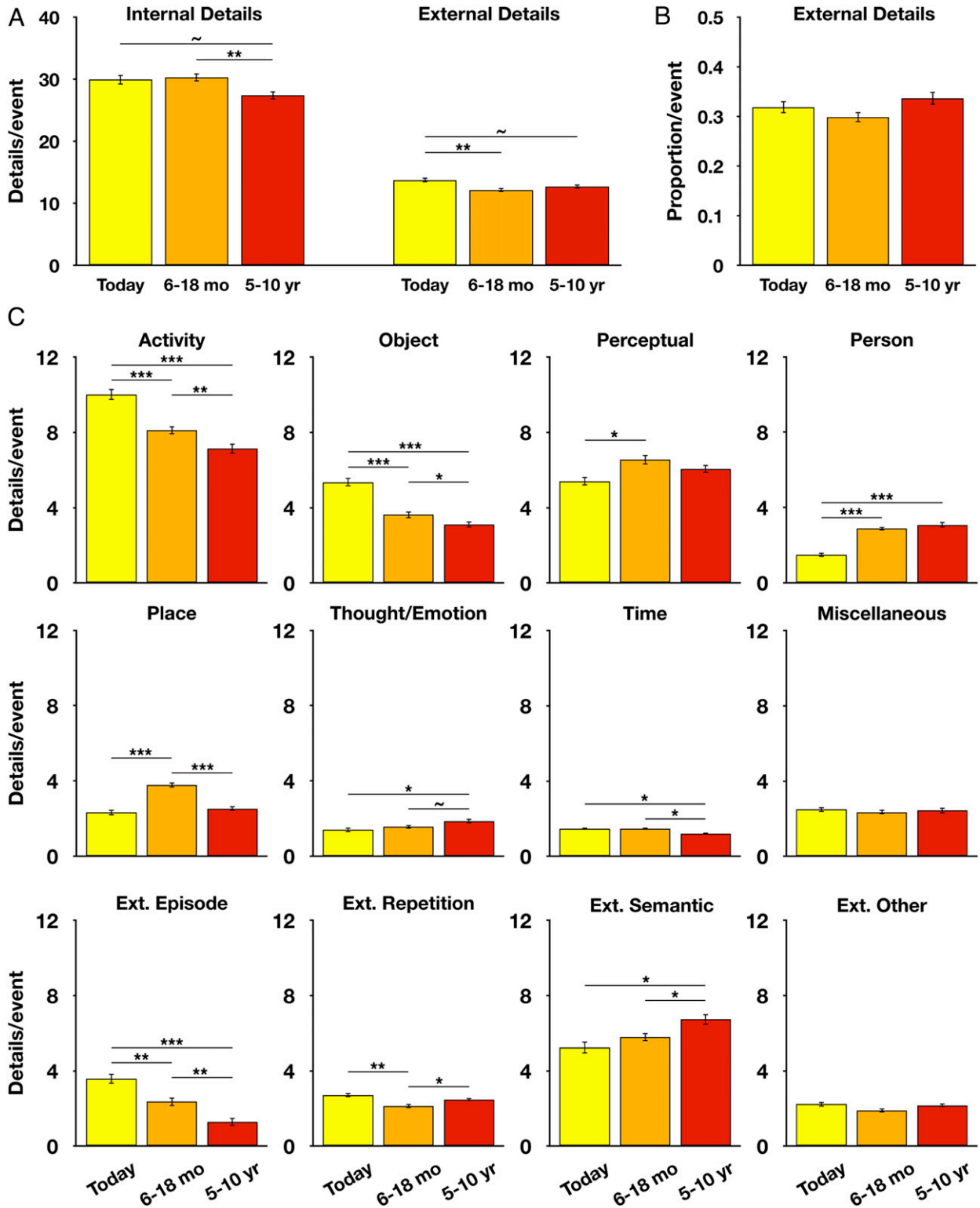
Descriptions from Different Recall Periods Did Not Differ in Rated Vividness or Detail. The prior analyses suggested that either no or minor differences in detail were present across Recall Periods, but their mapping to a broader change in the vividness of recall remained unclear. To rule out spurious causes of an apparent temporal gradient in neural activity in the current data (16, 17), a separate experiment was conducted in which memory descriptions were deidentified and subsequently rated by independent readers using Amazon's Mechanical Turk. If differences were present across Recall Periods, then separate raters should consistently differ in their ratings of recent and remote memories. In a first online experiment, participants ($n = 129$) were asked to rate one event description from each condition on its overall vividness on a Likert-type scale ranging from 1 ("very generic") to 6 ("very vivid"). No differences were observed across conditions, $F(2, 256) = 0.779$, $P = 0.460$, $\eta_p^2 = 0.006$ (*SI Appendix*, Fig.

S2A). In a follow-up experiment, participants ($n = 144$) instead rated event descriptions in terms of their overall detail, with the scale ranging from 1 ("very generic") to 6 ("very detailed"). Once again, no subjective differences were observed across conditions, $F(2, 286) = 1.78$, $P = 0.17$, $\eta_p^2 = 0.012$. Both experiments were then combined into a single model; there was no effect of Experiment number, $F(1, 271) = 1.14$, $P = 0.286$, $\eta_p^2 = 0.004$; no effect of Recall Period, $F(2, 542) = 1.53$, $P = 0.216$, $\eta_p^2 = 0.006$; and no interaction of Experiment number and Recall Period, $F(2, 542) = 1.04$, $P = 0.355$, $\eta_p^2 = 0.004$ (*SI Appendix*, Fig. S2B). Thus, although the types of details associated with recalled memories differed as a function of temporal distance (Fig. 2), raters naïve to the hypotheses of the experiment were unable to detect any significant shift in how recent or remote events were described in the current data.
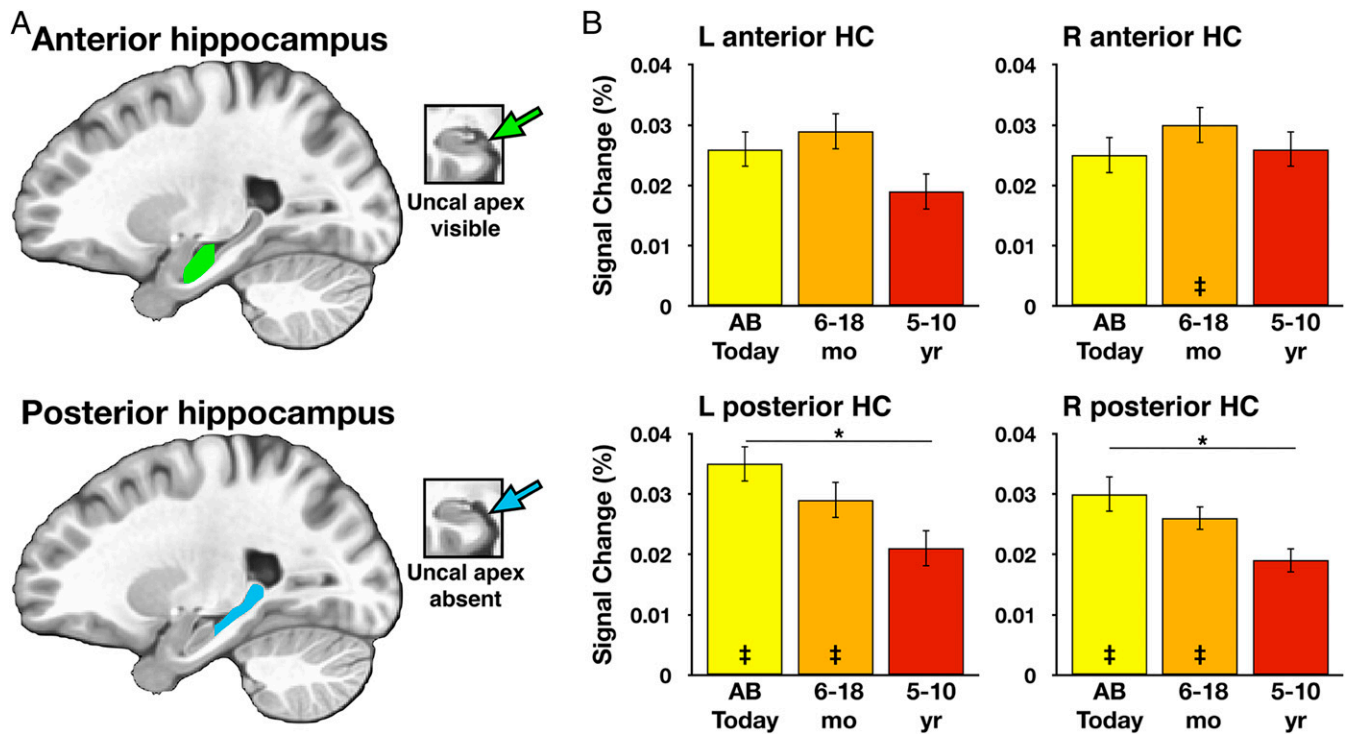
Graded Univariate Activity Was Observed in the Posterior Hippocampus. The results of the behavioral analyses highlight the shortcomings of a covert recall procedure. Without a description of how a memory is re-experienced, dynamic activity associated with the recall of various event details (Internal or External) cannot be accounted for in an fMRI time series (and, thus, would be aliased into regressors meant to capture activity associated with each Recall Period). Herein lies the main benefit of an overt recall paradigm: Each recalled detail can be labeled and time-locked with the BOLD time series for each event so that transient activity associated with naturalistically recalled content can be modeled and accounted for (as described by ref. 26). This separation should provide a purer estimate of how retrieval-related activity is affected by the recency or remoteness of a memory than was previously achievable.

Having separately modeled transient effects in the data related to the dynamically recalled content of memories, activity associated with each Recall Period was then compared in the hippocampus. Subject-specific anterior and posterior hippocampal regions—separated to reflect known functional and connectional heterogeneity across the long axis of the hippocampus (17, 27, 28)—were interrogated for each Recall Period (Fig. 3A). Effects were tested by using a repeated-measures ANOVA with factors of Subregion (Anterior or Posterior), Hemisphere (Left or Right), and Recall Period (Today, 6–18 mo prior, or 5–10 y prior). No main effects were observed [largest F-statistic: $F(1, 39) = 2.11$, $P = 0.128$, $\eta_p^2 = 0.051$, obtained for Recall Period; Other F's < 1]. However, this must be qualified by a significant Subregion × Recall Period interaction, $F(2, 78) = 6.76$, $P = 0.002$, $\eta_p^2 = 0.148$; and a marginally significant Hemisphere × Recall Period interaction, $F(2, 78) = 2.84$, $P = 0.065$, $\eta_p^2 = 0.068$. The Subregion × Recall Period interaction reflects temporally graded activity differences in Posterior [Today vs. 5–10 y ago: $t(39) = 2.91$, $P = 0.006$, $d = 0.460$; 6–18 mo vs. 5 –10 y ago: $t(39) = 1.97$, $P = 0.056$, $d = 0.311$], but not Anterior Subregions (Today vs. 5–10 y ago: $t(39) = 0.717$, $P = 0.478$, $d = 0.113$; 6–18 mo vs. 5–10 y ago: $t(39) = 1.41$, $P = 0.168$, d = 0.222] (Fig. 3B). Differences took the form of greater activity for recent than for remote events. The marginal Hemisphere × Recall Period interaction reflected a slightly smaller difference in BOLD activity between the Today and 5–10 y Recall Periods in the right hemisphere [$t(39) = 1.22$, $P = 0.231$, $d = 0.192$], as compared to left hemisphere [$t(39) = 2.30$, $P = 0.027$, $d = 0.364$]. No significant three-way interaction of Recall Period, Subregion, and Hemisphere was observed, $F(2, 78) = 0.813$, $P = 0.447$, $\eta_p^2 = 0.020$.

To address the possibility that the univariate gradient was a result of activity associated with the recall of various details aliasing into sustained activity associated with recall, a control analysis was conducted in which the mean BOLD activity for each trial was correlated with the number of Internal details recalled. This analysis used a modified set of general linear models

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Fig. 2. Internal and External (Ext.) details generated across temporal distances. (*A*) Events from 5–10 y ago had fewer Internal details than more recent events, whereas events from the Today condition had more External details than did other Recall Periods. (*B*) However, the overall proportion of External details did not significantly differ across Recall Periods. (*C*) Considerable variability was present across subtypes of details, suggesting that a simple "semanticizing account" of older memories may not accurately depict changes over time. Error bars denote within-subject SE (76). *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ~$P < 0.07$ (nonsignificant). For detail counts related to the Picture Description control task, see *SI Appendix*, Fig. S1.

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Fig. 3. Analysis of a priori, subject-specific hippocampal ROIs. (*A*) Anterior and posterior hippocampal ROIs were manually segmented for each subject using the uncal apex as a division landmark (27). (*A*, *Insets*) Example anterior and posterior boundary slices. (*B*) Posterior, but not anterior, hippocampal subregions exhibited a temporal gradient across the overt recall period, with more recent memories eliciting stronger activations than remote memories. Effects are plotted relative to the Picture Description baseline. Activity significantly differed from the baseline control task for the Today and 6–18 mo ago, but not 5–10 y ago, conditions in posterior HC regions, but anterior effects were largely indistinguishable from the control baseline (*SI Appendix*, Fig. S3). Error bars denote within-subject SE. *$P < 0.05$; ‡Significant one-sample test vs. baseline Picture Description task (FDR, $q < 0.05$). AB, autobiographical; HC, hippocampus; L, left; R, right.
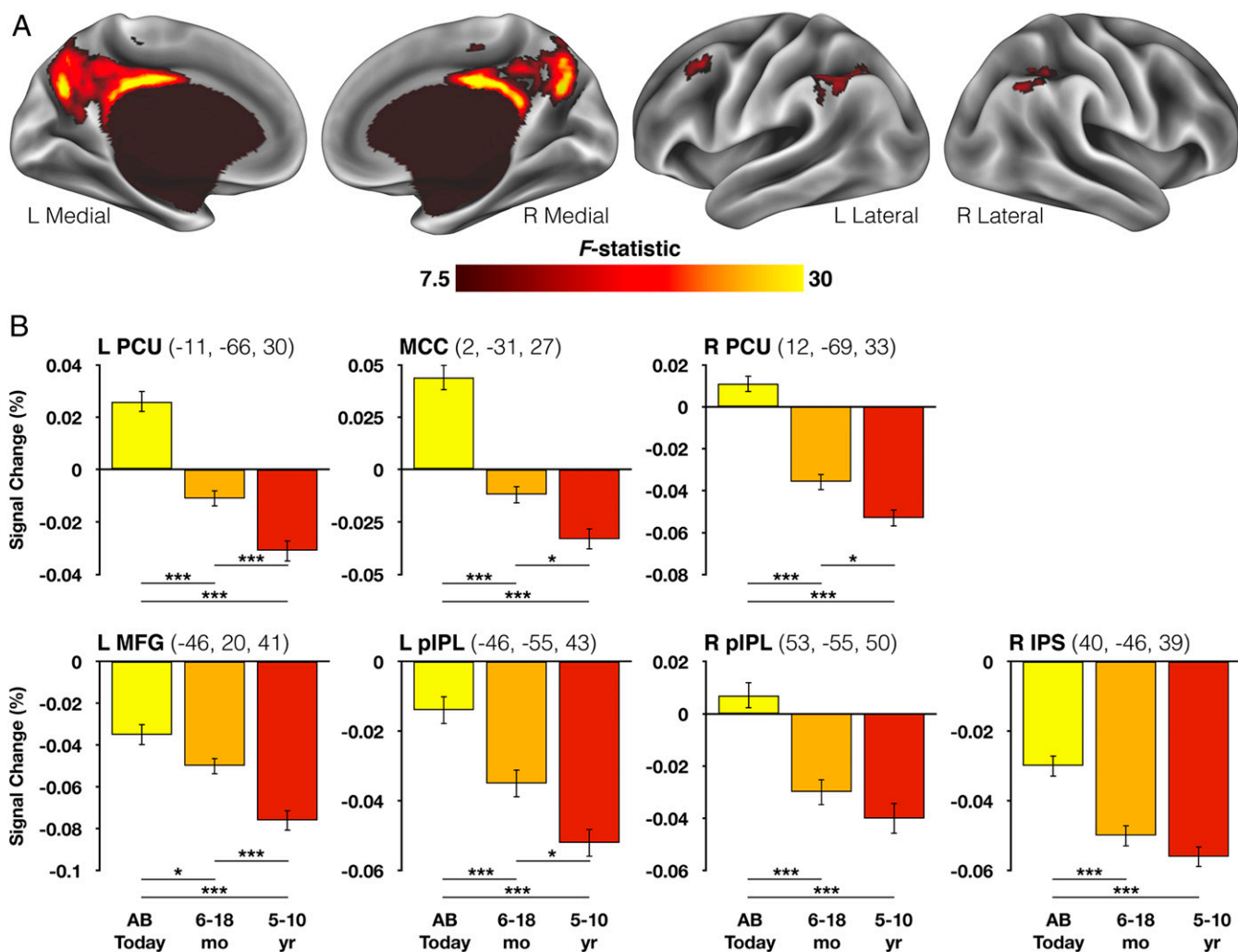
(GLMs) that modeled transient detail recall effects, but not sustained effects associated with each recall period (*SI Appendix, Supplementary Methods*). No trial-wise correlation of residual BOLD activity with the number of Internal details was observed at the group level in either the left or right posterior hippocampus ($t < 0.5$, $P > 0.7$; *SI Appendix*, Fig. S4). The temporally graded pattern therefore supports predictions of the SMC, as it cannot be accounted for by lingering effects of recalled details.

Comparing Autobiographical Recall and Picture Description Tasks Suggests a Time-Limited Hippocampal Role in Retrieval. Although graded univariate activity was observed in the posterior hippocampus, that need not imply that its role in retrieval was time-limited, as suggested by the SMC. Activity in each Recall Period in each hippocampal subregion was therefore compared to the active baseline task directly, as by definition, the latter lacked a long-term episodic memory component. Qualitatively different patterns emerged in anterior and posterior subregions (Fig. 3*B* and *SI Appendix*, Fig. S3). Both posterior hippocampal regions of interest (ROIs) differed from the baseline task for Today and 6–18 mo Recall Periods [left posterior hippocampus "Today," $t(39) = 3.38$, $P = 0.033$, $d = 0.534$; left posterior hippocampus "6–18 mo ago," $t(39) = 3.12$, $P = 0.034$ $d = 0.494$; right posterior hippocampus "Today," $t(39) = 3.90$, $P = 0.02$, $d = 0.616$; right posterior hippocampus "6–18 mo ago," $t(39) = 3.33$, $P = 0.033$ $d = 0.525$; P values corrected for multiple comparisons], but, crucially, did not differ from the baseline task in the (remote) 5–10 y ago condition (corrected p's > 0.10). In contrast, only a single significant difference was observed in anterior hippocampal regions [right anterior hippocampus "6–18 mo ago," $t(39) = 3.21$, $P = 0.034$, $d = 0.059$; other corrected $P > 0.07$

in right and > 0.13 in left anterior hippocampus]. This pattern held both for the applied false discovery rate (FDR) correction, as well as a more stringent Bonferroni correction. Posterior hippocampal effects were therefore consistent with predictions of the SMC: temporally graded, with retrieval-related activity observed for recent, but not remote, events. In contrast, anterior hippocampal activity was largely indistinguishable from that observed in the Picture Description control task.

Whole-Brain Univariate Effects of Temporal Distance. Effects of temporal distance were also tested at a whole-brain level. A voxel-wise repeated-measures ANOVA, with the within-subject factor of Recall Period, identified regions in bilateral medial and lateral parietal cortex and the left middle frontal gyrus (Fig. 4*A* and *SI Appendix*, Table S2). Post hoc comparisons indicated that in all of the seven identified peaks, significantly greater activity for recent as compared to remote events was observed (Fig. 4*B*). No identified regions exhibited greater activity for remote than for recent events.

Temporally Graded Task-Based Connectivity Was Observed between Regions Exhibiting Univariate Effects and Regions Associated with Scene Construction. To complement the univariate analyses, task-based connectivity for all significant univariate ROIs (two hippocampal and seven neocortical) was compared for recent and remote events. These analyses took advantage of the long recall periods present in the current experiment (~2 min), thus providing a large number of data points for each trial. SMC would predict a temporally graded connectivity pattern that mirrors univariate effects in hippocampal regions, whereas MT/TT would predict sustained connectivity across recall periods, as the

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Fig. 4. Voxel-wise whole-brain analysis of temporal distance effects. (*A*) Regions exhibiting significant main effects of temporal distance were identified in medial and lateral parietal cortex and the left superior frontal gyrus. (*B*) Subsequent pairwise contrasts revealed that events from earlier in the same day always elicited greater activity than did more distant events, and in all cases a monotonic reduction in activity accompanied increasing temporal distance. Results are depicted on a partially inflated human brain surface (77), and effects are plotted relative to the Picture Description baseline. Coordinates are listed in MNI152 space and refer to centers of mass for each region. Error bars denote within-subject SE. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$. AB, autobiographical; IPS, intraparietal sulcus; L, left; MCC, midcingulate cortex; MFG, middle frontal gyrus; PCU, precuneus; pIPL, posterior inferior parietal lobule; R, right.

hippocampus should always be involved in reactivating prior experiences. Task-based connectivity might also inform interpretation of the univariate whole-brain results, as identified regions have been associated with recognition memory performance and familiarity-related processing more than autobiographical recall (29–32).

Head motion is a possible concern when conducting any connectivity analysis (33). In the current case, connectivity was being compared during periods of continuous natural speech, further exacerbating potential motion effects. However, a repeated-measures ANOVA examining frame-to-frame motion during periods of speech found no significant effect of Recall Period, $F(2, 78) = 2.25$, $P = 0.112$, $\eta_p^2 = 0.055$. Similarly, whole-brain signal variability, which is proportional to temporal signal-to-noise ratio and serves as an omnibus measure of artifactual sources of variance (34), did not differ across conditions, $F(2, 78) = 1.70$, $P = 0.189$ $\eta_p^2 = 0.042$. Nevertheless, to ensure that no subtle effects related to motion might bias comparisons of connectivity across conditions, the linear mixed-effect (LME) approach taken to compare whole-brain connectivity patterns across Recall Periods included covariates for both the motion and signal-

variability measures for each trial for each participant (see also ref. 35).

Significant differences in connectivity between recent and remote events were observed for five of the task-based connectivity seeds. These manifested in a remarkably stereotyped pattern across the whole brain (Fig. 5*A* and *SI Appendix*, Fig. S5). Consistency was quantified by using a conjunction analysis approach (*SI Appendix*, Table S3). The strongest overlap (≥4 maps) fell in regions of the parahippocampal cortex, the retrosplenial cortex/parieto-occipital sulcus (sometimes referred to as the "retrosplenial complex"), the posterior angular gyrus, and the superior frontal cortex (Fig. 5*B*). These regions have been strongly associated with mental time travel (and episodic simulation) in general (36), and autobiographical recall in particular (36–38). With the exception of the superior frontal gyrus, these regions are also associated with both the active visual perception of scenes and mental scene construction (39, 40), the latter of which has been argued to be a core component of vivid event recall (41–43).

The conjunction analysis results therefore led to the formulation of the final key hypothesis to be tested in this report: If autobiographical recall becomes less reliant upon the hippocampus
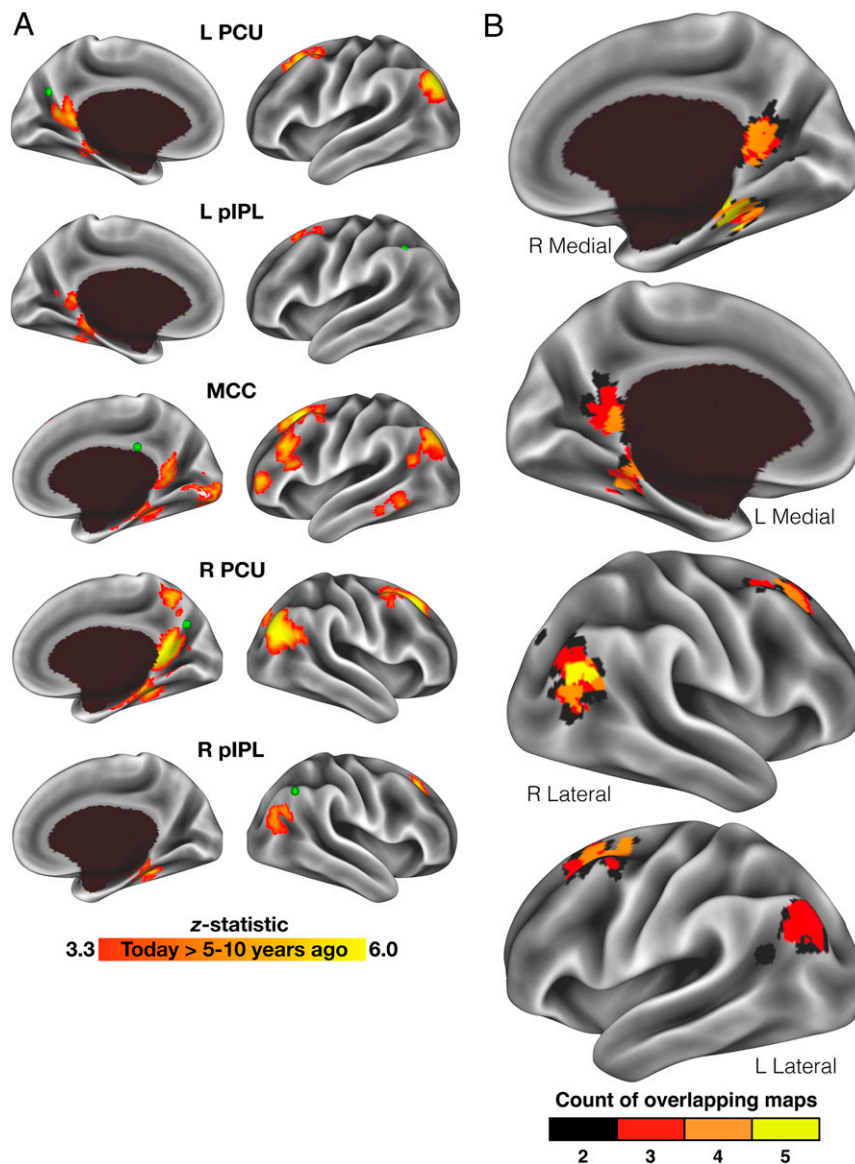
Fig. 5. Temporally graded connectivity was observed across seed regions. (*A*) Regions identified in the univariate whole-brain analysis served as seeds whose connectivity was compared for recent (Today) and remote (5–10 y ago) events. Green nodes depict centers of mass for each seed. (*B*) Maps were binarized and summed across the whole brain. Effects were consistently observed (present in four or more seed maps) in the right angular gyrus and retrosplenial cortex/parieto-occipital sulcus, parahippocampal cortex, and superior frontal cortex bilaterally. L, left; MCC, midcingulate cortex; PCU, precuneus; pIPL, posterior inferior parietal lobule; R, right.

over time, then the hippocampus should exhibit a temporally graded pattern of connectivity with regions thought to mentally construct the scenes or contexts in which the events occur. As a means of independently identifying cortical scene-selective/scene construction regions, a multicategory localizer dataset was collected in a separate scanning session for approximately half of the participants (*n* = 22; *Materials and Methods*). This procedure involved the visual presentation of 11 different stimulus categories, and a contrast of activity during blocks of scenes against all other categories identified a group-level mask of scene-selective cortex, which includes—and extends beyond—the regions consistently observed in the conjunction analysis (40) (Fig. 6*A*). The time series of all voxels within the scene-selective mask was correlated with each posterior hippocampal seed region and averaged in a trial-wise fashion. As before, an LME approach was taken, with motion and signal variability covariates associated with each specific trial in each condition for each participant.

The contrast of connectivity strength for recent and remote events revealed a significant difference for the Today vs. 5–10 y ago Recall Periods in the right posterior hippocampus, $t(611) = 2.51$, $P = 0.012$, as well as a significant difference between the Today and 6–18 mo ago conditions, $t(611) = 2.13$, $P = 0.033$. A similar, but nonsignificant, tendency was observed in the left posterior hippocampus for the Today vs. 5–10 y ago Recall Periods, $t(611) = 1.43$, $P = 0.154$ (Fig. 6*B*). Thus, just as univariate effects within the hippocampus were identifiable following a targeted analysis, so, too, were temporally graded hippocampal–cortical interactions, with the latter occurring in regions of cortex thought to process the mental construction of scenes. Importantly, the observed pattern does not appear explainable by univariate BOLD activity difference across voxels in the scene construction mask, as no significant differences in activity were observed between the Today and 5–10 y ago Recall periods, $t(39) = 0.26$, $P = 0.795$, $d = 0.042$.
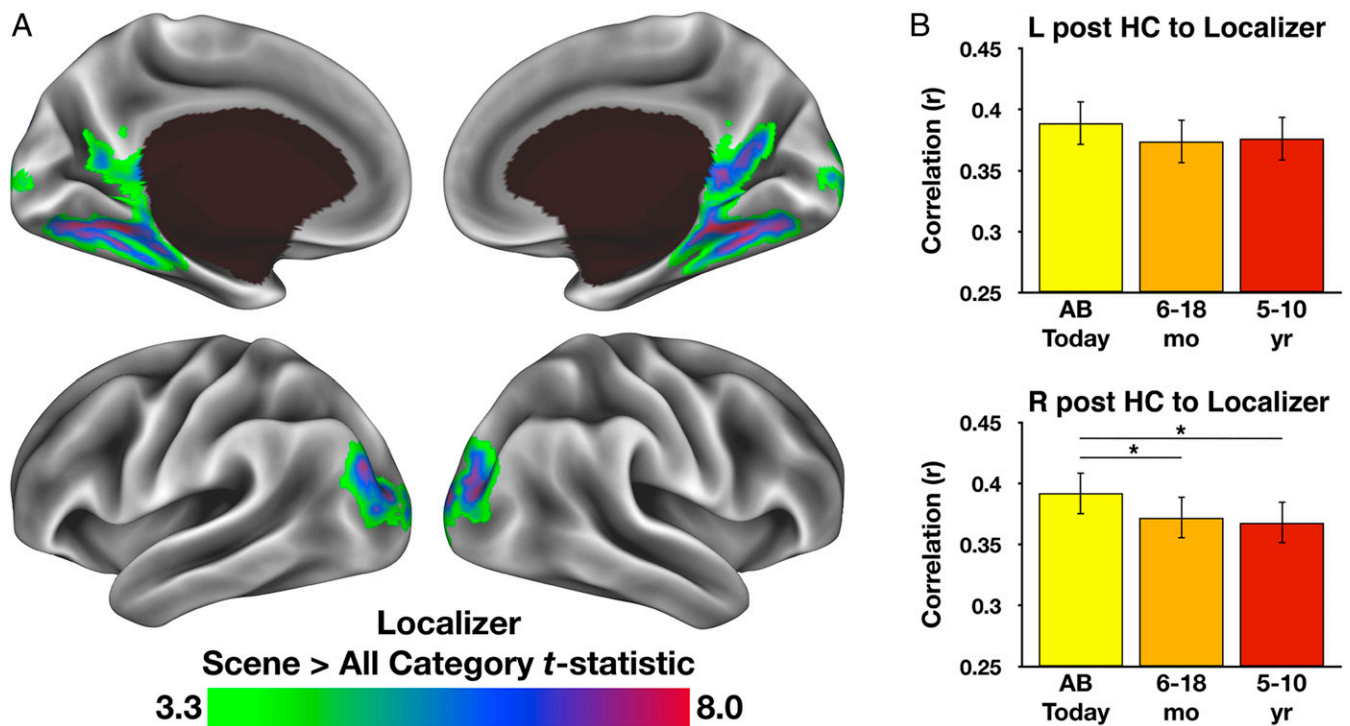
Fig. 6. Scene-selective cortex exhibits a temporal gradient in task-based connectivity to the posterior hippocampus. (*A*) Independent localizer data were used to define scene-selective regions. (*B*) A significant difference in task-based connectivity in the right posterior hippocampus (R post HC) and a nonsignificant tendency in the left posterior hippocampus (L post HC) were observed across Recall Periods. Error bars reflect SEM. *P < 0.05. AB, autobiographical.

Discussion

The work in this report used spoken in-scanner recall to investigate the nature of recent and remote memory retrieval. After identifying the moment-to-moment content of recalled memories using an established scoring approach (24, 25), we observed temporally graded activity emerge in posterior hippocampal ROIs, as well as in a cortical network often associated with the processing of stimulus familiarity. Regions exhibiting temporal gradients also showed a graded correlation during recall with regions thought to support the mental construction of scenes. Taken as a whole, the results of this study help to clarify an ambiguous literature, lending support to the SMC hypothesis, and emphasizing the utility of overt recall in the cognitive neuroscientific study of autobiographical memory.

Overt Recall Provides Insights into Retrieved Content. The subjective experience of mental time travel is a critical aspect of an episodic memory (1). To date, fMRI studies of autobiographical recall—even those that have manipulated the remoteness or recency of recalled events— have relied upon covert retrieval, typically with something like a Likert-type rating scale indicating the subjective vividness or richness of the recalled memory. Such ratings can be efficiently collected, but necessarily provide an impoverished view into the rich phenomenology of episodic recall. In contrast, the current approach goes beyond this simple rating scale in that it uses overt, recordable descriptions to assess phenomenology. This approach does not, of course, provide a direct window into the minds of participants—such a capability remains sorely awaited by psychologists and neuroscientists alike—yet it provides a means of accounting for, at least to some degree, dynamic effects associated with the recollection of different event details (26). By accounting for such activity, the current approach provides a means of separating the content of memories from their temporal distance in a manner not previously possible, and certainly in a manner that exceeds the variance that can be accounted for by using a trial-

level Likert rating. Similarly, the current approach also extends beyond what was possible based on previous back-sorting approaches. For instance, Spiers and Maguire (44) collected detailed postscan narration following a memory-guided navigation task and used these narratives to code certain behaviors at decision points along the route. This approach was remarkably clever, yet restricted time-locking only to specific decision points and, thus, could not account for the rich variety of thoughts that accompany the recall of a past episode.

Temporal Distance Effects Were Specific to Posterior Hippocampal Regions. Having labeled, quantified, and modeled the dynamic moment-to-moment content of recalled experiences (complete with the tangents and nonlinear narration associated with naturalistic recall), and after testing for—but failing to observe—broader qualitative differences across event descriptions, we could then ask how recent and remote events might be differently retrieved at the neural level. Within the hippocampus, posterior regions exhibited temporally graded activity that differed from a baseline task in recent, but not the most remote, Recall Periods. This behavior is consistent with predictions of the SMC, although it should be noted that the SMC does not distinguish between posterior and anterior hippocampal subregions in its predictions. However, the current data echo recent meta-analytic findings of posterior (not anterior) hippocampal regions exhibiting temporally graded activity during autobiographical recall (5).

The behavioral results obtained through overt recall appear to rule out an alternative "semanticizing" account of the fMRI results (all recall was highly detailed, and changes over time were appreciably more complicated than a general reduction in Internal details; Fig. 2 and *SI Appendix*, Fig. S2). Although this may appear surprising, given the strong concerns raised by proponents of the MT/TT framework, the current pattern is not without precedent, and prior fMRI studies have also reported a similar number of total details for recent and remote events (e.g.,

refs. 45 and 46). The most straightforward explanation is therefore that there is at least some effect of temporal distance on hippocampal activity during the recall of autobiographical events and that this effect is consistent with predictions made by Squire and others over the past several decades in the form of the SMC framework (13, 14).

On the Importance of an Active Control Condition in Testing for a Temporal Gradient. A challenge in studying hippocampal contributions to retrieval is that the hippocampus is always actively encoding one's ongoing experiences (47), including information that is recalled during retrieval (48). Indeed, such re-encoding is central to the MT/TT framework (16, 17). A natural problem thus becomes the separation of activity related to retrieving event details from the re-encoding of the same details. Importantly, the nature of the control task used in this experiment— and the results of comparisons between the control and Autobiographical recall tasks—suggests that re-encoding is unlikely to explain the current findings. As has been noted in prior behavioral work that used the same control task (24, 49), visual processing of picture cues and required verbal outputs are well-matched across the Autobiographical Recall and Picture Description control conditions. In both cases, these aspects of each trial need to be (re)encoded (see also ref. 50 for related reasoning using a conceptually similar control). However, what is necessarily absent from the Picture Description condition is an existing episodic memory representation. Differences in activity between the baseline and Autobiographical Recall conditions should therefore be attributable to retrieval-related processing. Within posterior hippocampal regions, activity differed from this encoding baseline in two of the three Recall Periods (Fig. 3B)—those associated with the more recent conditions. It was only in the most temporally remote condition that significant differences between the Picture Description and Autobiographical Recall conditions were not observed. These results fit predictions of the SMC hypothesis.

What About the Anterior Hippocampus? One might look at the "flat" activity profile in the anterior hippocampus (Fig. 3B) and conclude that it supports the MT/TT hypotheses just as strongly as the posterior hippocampal results support the SMC framework. However, before reaching such a conclusion, it is important to consider not just the overall gradient pattern, but also the significance of autobiographical recall effects relative to the nonautobiographical control. If the hippocampus were always required for recall, then it should always produce greater activity during the Autobiographical Recall than the Picture Description task. This was not the pattern observed in the current data (Fig. 3B and *SI Appendix*, Fig. S3). Thus, the anterior effects no more support one model than they do argue against another in the present data.

Cortical Signatures of Temporal Distance during Overt Recall. Beyond effects within the hippocampus, temporal distance effects were also observed in a small collection of neocortical regions. Effects manifested in the form of greater activity accompanying recent, rather than remote, memories—a pattern not cleanly predicted by either the SMC or MT/TT models. SMC would predict either no change or greater univariate activity for remote events (complementing reduced activity in/reliance on the hippocampus), whereas MT/TT predicts that activity should be based on retrieved event features rather than temporal distance. However, the identified cortical regions have all been associated with recognition memory (cf. ref. 51), and those in parietal cortex align particularly well with the parietal memory network, which sits adjacent to default network regions and is thought to support the recognition of, and orientation toward, familiar stimuli (31, 52, 53). If one assumes that objective recency is accompanied by a strong subjective familiarity when recalling an event, then the current observations coincide well with prior work, both with studies involving externally presented stimuli (e.g., refs. 52–54) as well as those requiring repeatedly imagining complex events (e.g., refs. 55 and 56). Furthermore, the foundation of parietal memory network knowledge consists of laboratory studies that typically involve very short (minutes-long) delays between subsequent exposures. It is an intriguing possibility that this same network may support a sense of familiarity for complex events that occurred hours, months, or even years ago, and follow-up work may offer a mechanistic explanation for a means by which temporal distance estimates are made when thinking back to past episodes.

There is evidence of univariate (57) or multivariate (58, 59) effects of temporal distance in ventromedial prefrontal cortex (vmPFC)—sometimes manifesting as nonmonotonic shifts in activity over time (60). However, temporal distance effects were not reliably observed in recent meta-analyses (5), nor were any observed in this report. Thus, while it seems clear that vmPFC is important for autobiographical memory recall in general (e.g., refs. 3, 30, 61, and 62), the precise conditions under which it exhibits a temporally graded activity pattern require further clarification.

Interactivity between the Hippocampus and Scene Construction Regions during Recall. It is thought that scene construction is a core process underlying episodic autobiographical recall (41–43). Indeed, a memory without a spatial context fails to meet the basic criteria of an episodic memory (1), and lesions to regions associated with scene construction reliably produce memory impairments and amnesia (63). Given the centrality of scene construction to autobiographical recall, one might expect to see a similar engagement of regions that support scene construction across temporal distance, assuming detailed recollections in each case. Consistent with this expectation, BOLD activity within scene construction regions did not significantly differ between the most recent and most remote conditions. However, the data also demonstrate that connectivity between scene construction regions (localized independently within a subset of the overall sample) and the posterior hippocampus is reduced in a temporally graded fashion. In other words, although the scene construction regions themselves seem to be similarly engaged when recalling recent or remote events, the nature of the interactions between scene construction regions and the posterior hippocampus differs. As in prior analyses, these results support predictions of the SMC model.

Conclusion

The present data reveal that overt, in-scanner recall provides evidence that supports predictions made by the SMC hypothesis: The hippocampus exhibits temporally graded reductions in activity during autobiographical recall, does not differ from baseline activity when recalling remote events, and exhibits reduced hippocampal–cortical interactivity with regions thought to serve a core aspect of autobiographical memory retrieval. At the same time, regions thought to be important for the recognition of familiar stimuli also appear sensitive to the recency or remoteness of memories that occurred months or even years ago, suggesting an important phenomenological role for these regions in retrieval processes in general. Finally, these data encourage the utilization of overt in-scanner recall to study human cognition and demonstrate that technical concerns related to motion need not hold researchers back from collecting larger and richer datasets.

Materials and Methods

fMRI Participants. The fMRI sample consisted of 40 healthy, right-handed, young adult participants (23 female; 24.2 ± 2.8 y old). Informed consent was obtained from all participants prior to their participation, and the experiment was approved by the NIH institutional review board (NIH Clinical Study

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Protocol 93-M-0170; clinical trials no. NCT00001360). All participants were monetarily compensated for their time. For further details, see *SI Appendix, Supplementary Methods*.

Online (Mechanical Turk) Participants. The sample for Online Experiment 1 consisted of 129 participants (50 female) aged 35.8 ± 12.1 y of age. Online Experiment 2 consisted of 144 participants (60 female) aged 36.6 ± 10.5 y. Additional participant information is presented in *SI Appendix, Supplementary Methods*. All participants had to acknowledge participation before beginning the experiment, following guidelines set by the NIH Office of Human Subjects Research Protections. Participants were monetarily compensated for their time.

fMRI Stimuli. Autobiographical and Picture Description stimuli consisted of 48 pictures depicting people in different locations undertaking various activities (e.g., ordering at a café). Some of these images have been described (24, 49); the remainder were newly acquired via internet search. Images were presented in color against a black background and were sized at 525×395 pixels.

Multicategory localizer task stimuli consisted of 120 images of 10 different categories (abstract shapes, animals, body parts, static dots, faces, nonmanipulable objects, scenes, phase-scrambled images, tools, and words), as well as 5 images that cued different movements, from a larger described collection (64). Images were 600×600 pixels and were gray-scaled.

Stimuli for all tasks were presented by using PsychoPy2 software (65) (Resource Research Identifier [RRID]: SCR_006571) on an HP desktop computer running Windows 10 (display resolution: $1,920 \times 1,080$ pixels).

Online Experiment Stimuli. Stimuli used in both Online Experiments were modified verbal reports from the main fMRI experiment. A total of 210 de-identified event descriptions were selected from each Recall Period. Event descriptions were presented in black, 12-point Arial type against a white background.

Autobiographical Recall Task. In this task, participants overtly retrieved autobiographical memories of different ages in response to picture cues. Participants were oriented to a specific recall period for each trial (earlier in the same day, 6–18 mo ago, and 5–10 y ago), and provided with two different picture cues (Fig. 1) to reduce event recall failures. Participants had 11 s to select via button press the picture they preferred to use as a memory cue. Image pairings were shuffled pseudorandomly, with a subset of more typical scenes reserved for the "Today" condition. Following their selection, the images were removed until the end of the 11-s selection period, when an enlarged version of the selected image was centrally presented for 5 s. Participants were instructed during this time to use the picture to help remember an event from the cued time period.

Following the 5-s presentation, the image was replaced with a white crosshair for 116 s. During this time, participants were instructed to narrate the cued memory with as much detail as possible for the full duration of the trial. Participants were instructed that events should be unique (i.e., the same event should not be described multiple times) and should be specific in time and place (i.e., should reflect unique episodes rather than routine recurrences). In cases where participants ceased early in the trial (e.g., with ≥ 20 s remaining), they were given a general prompt by the experimenter. This took the form of the question "Are there any other details that come to mind?" as described by Levine et al. (25). Such prompts were rare (averaging less than one occurrence per individual). At the end of the narration period, the white fixation cross changed to a red color for 2.2 s, which signaled the end of the trial. Trials were separated by 19.8 s of fixation, and three trials (one per Recall Period) were included per scan run. Six autobiographical task runs were collected for each participant. The order of Recall Periods was counterbalanced across runs and participants.

Picture Description Task. This control task required descriptions of complex photographs and was modeled after Autobiographical Recall trials. Participants were cued to describe what was occurring in their choice of two photographs. The selected image was enlarged and presented briefly (5 s), after which it was replaced with a white fixation cross for a 116-s narration period. Participants were instructed to describe the image with as much detail as possible for the full duration of the trial. A red 2.2-s stop cue ended the trial, and the same verbal prompts were given if a verbal description ended early. Trials were separated by 19.8 s of fixation, with three trials per scan run. Two runs of the Picture Description task were collected for each participant and were interleaved with the Autobiographical Recall scan runs.

Ordering was counterbalanced such that an equal number of Autobiographical Recall runs preceded or followed Picture Description scans.

Prior to scanning, participants were instructed on, and practiced engaging in, both types of tasks. They were given additional instruction/practice cycles if autobiographical events were not initially specific in time and place or otherwise episodic in nature.

Multicategory Localizer Task. In a separate session, 22 participants completed a one-back task meant to serve as a multicategory functional localizer. Participants were presented with blocks of images from each included category and were directed to press a button when they noticed a repetition of the same image (see *SI Appendix, Supplementary Methods* for additional details). Six localizer runs were collected for each participant.

Audio Recording and In-Scanner Speech. Participants spoke their descriptions into an Optoacoustics FOMRI-III NC MRI-compatible microphone. Audio was passed through an M-Audio FastTrack Ultra 8-R Universal Serial Bus audio/MIDI interface (inMusic) and recorded using Adobe Audition CS6 on a Dell Precision M4400 laptop. A secondary track captured a square wave pulse marking the onset of each stimulus presentation to allow precise syncing of audio tracks and scan onset times. Participants practiced speaking in the scanner prior to beginning data collection to help reduce head motion (*SI Appendix, Supplementary Methods*).

Alignment of Spoken Responses to BOLD Time-Series Data. Spoken response tracks were processed in Audacity 2.3 (https://www.audacityteam.org/) to reduce background noise. All spoken responses were transcribed and checked against the original audio to ensure that they were free of typographical errors. A Python-based text-to-speech alignment tool (p2fa; ref. 66) synchronized the text and spoken audio for each event; outputs were manually edited to correct misalignments using Praat (67) version 6.0.48 (RRID: SCR_016564). Onset times and durations were then calculated for every spoken word and phrase to convert them to event-related regressors (discussed below). Technical problems with recording caused two scan runs to be dropped from one participant and one to be dropped from two others.

Transcript Scoring. Transcribed autobiographical memories and picture descriptions were scored using an adapted version of the Autobiographical Interview scoring system (25), modified to accommodate picture descriptions (24). Briefly, this approach segmented different details provided by participants as either being "Internal" (i.e., episodic details related to the central event being described) or "External" (i.e., other types of details or repetitions of previously described details). Additional scoring information is described in *SI Appendix, Supplementary Methods*, and a full list of detail types is presented in *SI Appendix*, Table S1.

Across the three Recall Periods, the overall frequency of Internal and External detail types, as well as the subtypes within each broad category, were compared using repeated-measures ANOVAs and follow-up pairwise comparisons (two-tailed). Given the large number of ANOVAs conducted in investigating this aspect of the data, an FDR approach was selected for multiple comparison correction, requiring $q < 0.05$.

fMRI Data Acquisition and Preprocessing. Scanning was performed using a General Electric Discovery MR750 3.0-T scanner, with a 32-channel head coil. Scan acquisition parameters are described in *SI Appendix, Supplementary Methods*. fMRI data were preprocessed using AFNI (68) (RRID: SCR_005927) to reduce noise and facilitate across-subject comparisons. Preprocessing included both standard and multiecho preprocessing using multiecho independent components analysis (69) as described in *SI Appendix, Supplementary Methods*.

GLM-Based fMRI Data Analysis. All task scans consisted of 210 MR frames (214 before initial frame discarding) and lasted 7 min, 51 s. Any runs with average motion >0.2 mm/TR (calculated using AFNI's @1dDiffMag) were excluded. Two autobiographical task runs were excluded from four participants based on this motion criterion, and one autobiographical task run was excluded from five participants. In addition, one run was dropped from three participants due to technical problems with the scanner.

fMRI data were analyzed using a GLM approach (3dDeconvolve). The initial picture selection period was modeled using a single hemodynamic response function (HRF) convolved with a boxcar of 11-s duration. The subsequent Picture Display period was modeled with a single HRF convolved with a boxcar of 5-s duration. The analysis of recall effects utilized a mixed

block/event-related design (70–72). Separate regressors (four total) modeled sustained effects (118.2 s in duration) related to the narration periods of each Autobiographical Recall and the Picture Description condition. Twelve additional regressors coded for transient effects associated with the type of detail being described throughout each narration period. This provided a means to account for activity differences associated with the recall of different types of content for any given memory (26). By modeling transient effects, estimations of sustained effects should more accurately reflect basic differences associated with the temporal distance of an event. Three translational and three rotational motion parameters were also included in the GLM.

Hippocampal ROI Definition. Subject-specific hippocampal masks were generated with Freesurfer (version 6.0; RRID: SCR_001847), and each mask was manually segmented into anterior and posterior subregions using the uncal apex as a landmark of separation (27). Masks for each region for each subject were then resampled to the resolution of the echo-planar imaging data.

Calculating Effects of Temporal Distance. Univariate activity was averaged for each recall condition across all voxels in each hippocampal ROI in each subject's native space, with the Picture Description task serving as a baseline comparison condition. A repeated-measures ANOVA with a single factor of Recall Period (three levels: Today, 6–18 mo ago, and 5–10 y ago) was conducted for each of the four hippocampal subregions. Where significant, ANOVAs were followed up with paired-sample, two-tailed t tests. One-sample t tests were subsequently conducted to compare the significance of each response versus the baseline Picture Description condition (FDR correction, $q < 0.05$). The analysis was then repeated at the voxel-wise whole-brain level (see *SI Appendix, Supplementary Methods* for additional details).

Task-Based Connectivity Analysis. Task-based connectivity was compared across the different Recall Periods. For each subject, 53-TR (116.6 s) windows for each event were notched out of the residual time series (i.e., with condition effects regressed out as described), beginning the TR after the description period began and ending at the stop cue for each trial. Trial-wise motion and signal-variability covariates were derived from this same window.

Regions exhibiting significant univariate temporal distance effects served as seed regions in a whole-brain analysis. The time course of activity for each seed was correlated with all voxels in the brain for each trial of each condition. The resulting correlation maps were Fisher-transformed and entered into an LME model using AFNI's 3dLME (73), with one within-subjects factor (Recall Period) and two trial-level covariates (motion and signal variability) serving as explanatory variables. Random intercepts were estimated for each participant. Separate models were built for each seed region with the goal of identifying voxels whose correlations to a given seed exhibited a linear trend across the three Recall Periods (contrast weights: +1, 0, −1). Whole-brain correction for multiple comparisons was achieved for each map ($P < 0.05$) by setting a voxel-wise $P < 0.001$, $k \geq 18$ (determined using 3dClustStim). Maps were binarized and summed to quantify overlap.

Independent Definition of Scene-Related Cortical Regions. Regions associated with scene processing were defined by using a contrast of Scenes > all other task blocks in the localizer dataset, corrected to a whole-brain $P < 0.05$ (voxel-wise $P < 0.001$; $k \geq 18$). Voxels within a 1-voxel radius of any participants' hippocampus were excluded from the scene mask. The average correlation of scene-selective voxels was compared across conditions for the left and right posterior hippocampus using the same LME modeling approach described previously, implemented in R using the lme4 (74) and lsmeans (75) packages.

Online Experiment 1. Participants were instructed to read three event descriptions and rate each on the vividness of its description using a six-point Likert-type scale (for more details, see *SI Appendix, Supplementary Methods*). A repeated-measures ANOVA with the single factor of Recall Period assessed differences in ratings across the three temporal distances.

Online Experiment 2. Online Experiment 2 was identical to Online Experiment 1, with the exception that participants rated events on their overall level of "detail," rather than "vividness."

Data Availability. Anonymized MRI data and associated analysis code have been deposited in OpenNeuro, https://openneuro.org/ (DOI: 10.18112/openneuro.ds003511.v1.0.0) (78). Behavioral recall data are available upon request.

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