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Functional anatomy of temporal organisation and domain-specificity of episodic memory retrieval

Sze Chai Kwok[a,*], **Tim Shallice**[b,c], and **Emiliano Macaluso**[a]

[a]Neuroimaging Laboratory, Santa Lucia Foundation, Via Ardeatina 306, 00179 Rome, Italy

[b]Cognitive Neuroscience Sector, SISSA, Trieste, Italy

[c]Institute of Cognitive Neuroscience, University College London, London, UK

Abstract

Episodic memory provides information about the "when" of events as well as "what" and "where" they happened. Using functional imaging, we investigated the domain specificity of retrieval-related processes following encoding of complex, naturalistic events. Subjects watched a 42-min TV episode, and 24 h later, made discriminative choices of scenes from the clip during fMRI. Subjects were presented with two scenes and required to either choose the scene that happened earlier in the film (Temporal), or the scene with a correct spatial arrangement (Spatial), or the scene that had been shown (Object). We identified a retrieval network comprising the precuneus, lateral and dorsal parietal cortex, middle frontal and medial temporal areas. The precuneus and angular gyrus are associated with temporal retrieval, with precuneal activity correlating negatively with temporal distance between two happenings at encoding. A dorsal fronto-parietal network engages during spatial retrieval, while antero-medial temporal regions activate during object-related retrieval. We propose that access to episodic memory traces involves different processes depending on task requirements. These include memory-searching within an organised knowledge structure in the precuneus (Temporal task), online maintenance of spatial information in dorsal fronto-parietal cortices (Spatial task) and combining scene-related spatial and non-spatial information in the hippocampus (Object task). Our findings support the proposal of process-specific dissociations of retrieval.

Keywords

What-where-when; Precuneus; Hierarchical structure; Cinematographic material; fMRI

1. Introduction

Episodic memory provides information about our personal experiences of "when" and "where" events occur as well as "what" happens. In order to simulate the complexity of the processes involved in autobiographical memory, recent studies on episodic memory retrieval have endeavoured to employ real-life-like materials for learning. These range from photographs taken from a first-person perspective (St. Jacques, Rubin, LaBar, & Cabeza, 2008), to documentary videos of people engaged in everyday life activities (Fujii et al., 2004; Mendelsohn, Chalamish, Solomonovich, & Dudai, 2008; Mendelsohn, Furman, & Dudai, 2010), to videos showing navigation through a house (Hayes, Ryan, Schnyer, & Nadel, 2004), or navigating in virtual environments (Burgess, Maguire, Spiers, & O'Keefe,

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[*]Corresponding author. Tel.: +39 06 5150 1459; fax: +39 06 5150 1213. sc.kwok@hsantalucia.it (S.C. Kwok). .

2001; Ekstrom & Bookheimer, 2007; Ekstrom, Copara, Isham, Wang, & Yonelinas, 2011; King, Hartley, Spiers, Maguire, & Burgess, 2005).

A defining characteristic of episodic memories is that they allow us to relive our past as it has unfolded over extended time windows (Tulving, 1985). In order to be accessible for future retrieval, the different elements of an event have to be associatively linked into a durable memory trace (Staresina & Davachi, 2009). The organisation of temporal memory can be classified in “distance”, “location”, and “relative times” theories (Friedman, 1993). For example, distance-based explanations are dependent on processes that are correlated with the time between encoding and retrieval. A subgroup of distance-based theories, namely “chronological organisation theories”, holds that representations of events are organised in the memory store by their order of occurrence. Friedman (1993) reasoned that if memory is organised according to the order of occurrence, memories laid down at adjacent points in time would prime one another (see also Estes, 1985). Behavioural findings in long-term memory recall support this prediction (Barsalou, 1988; Bruce & Van Pelt, 1989; Huttenlocher, Hedges, & Prohaska, 1988; Linton, 1986). In these studies, subjects frequently reported having thought of other events that were close to the target event in time (Friedman, 1987; Friedman & Wilkins, 1985). Similarly, serial position recall experiments (on a time scale of minutes) provide evidence that even when unordered recall is required, subjects show a strong unprompted tendency to recall temporally adjacent items together (e.g., Laming, 1999). These findings are consistent with the proposal that memories are laid down and recalled according to the order of occurrence.

However, a large body of behavioural evidence gave the opposite pattern of results. Studies on serial recall and free recall have found that items that are near to one another in time are more confusable (Brown & Chater, 2001; Yntema & Trask, 1963). Behavioural experiments that manipulated the temporal distance between items by increasing or decreasing the rate of presentation of items in a list showed that temporally adjacent items tend to have their positions recalled in the wrong order after short delays (e.g., Neath & Crowder, 1990, 1996), and even after 24 h (Nairne, 1992). Neuropsychological studies associated deficits in temporal order retrieval with damage to the prefrontal cortex (e.g., Butters, Kaszniak, Glisky, Eslinger, & Schacter, 1994; McAndrews & Milner, 1991; Shimamura, Janowsky, & Squire, 1990). Specifically, Milner, Corsi, and Leonard (1991) reported demand for temporal order retrieval was greater when the temporal distance of a stimuli pair was shorter.

Functional neuroimaging techniques provide an additional means to assess the neural correlates of temporal memory and the effect of temporal distance. Behavioural measures (i.e., accuracy and RT) provide us with the end result of a set of processes. This set is likely to engage multiple brain regions, each of which may contribute differentially to temporal retrieval performance. Previous fMRI studies on temporal distance have found that the higher difficulty for items closer in time is associated with activation of prefrontal cortex. For example, in temporal order judgements prefrontal activations increased with decreasing temporal distance between word pairs [with 3 vs. 8 intervening words] (Konishi et al., 2002), between line-drawing pictures [within vs. across lists] (Suzuki et al., 2002) or in verbal recency judgements (Zorrilla, Aguirre, Zarahn, Cannon, & D’Esposito, 1996).

Unlike these previous studies, in this investigation we adopted a paradigm that employed rich stimuli entailing a large amount of interrelated events (i.e., happenings within a TV episode). We investigated whether the parameterised temporal distance between encoded events led to a modulatory effect on brain activity which can be associated with the retrieval of such temporal information. Of particular relevance is St. Jacques et al. (2008) study when subjects made temporal order judgements to pairs of photographs they had personally taken.

They found that events separated by shorter temporal distance led to activations in left prefrontal, parahippocampal, precuneus, and visual cortices. Given the effect of temporal distance on retrieval performance, St. Jacques et al. (2008)'s parametric analysis controlled for task difficulty by taking into account subject-specific accuracy as a potential confounding effect. However, this procedure only copes with between-subject performance differences but not for the critical difference between trial-types (i.e., shorter vs. longer distances). This makes it harder to interpret their parametric effects given that retrieval demands tend to increase with shorter temporal distances (Christoff et al., 2001; Konishi et al., 2002).

Together with these temporal aspects, episodic memories are characterised by complex content experiences that typically involve multiple types of elements. According to Tulving (1972), this construct can be conceptually broken down into the three elements: “when”, “what” and “where”, each of which can be assessed behaviourally. As loss of the connections between the different elements of an event is commonplace (Burgess & Shallice, 1996), it is possible that processes related to the retrieval of these different elements may be subserved by dissociable anatomical structures of a wider retrieval network. Several previous studies made use of fMRI or PET to disentangle the functional contributions of these elements (Burgess et al., 2001; Ekstrom & Bookheimer, 2007; Ekstrom et al., 2011; Fujii et al., 2004; Hayes et al., 2004; Nyberg et al., 1996). For example, in a spatial navigation paradigm, Ekstrom and Bookheimer (2007) had subjects play a taxi-driver game, in which they freely searched for passengers and delivered them to specific landmark stores. Subjects were then scanned with fMRI as they retrieved landmarks, spatial, and temporal associations from their navigational experience. The authors attributed perirhinal cortex activations to landmark retrieval, hippocampal/striatal activations to temporal order retrieval, and parahippocampal activations to spatial association retrieval, respectively. In a subsequent study, Ekstrom et al. (2011) dissociated brain regions involved in the retrieval of spatial and temporal information. Again, participants first navigated a virtual city, experiencing unique routes in a specific temporal order and learning about the spatial layout of the city. At retrieval, subjects made discrimination judgments either about the spatial distance between two landmarks or about the temporal order in which they came across the two. fMRI analyses revealed comparable hippocampal activity during these two tasks, and confirmed greater parahippocampal activity during spatial retrieval, and greater prefrontal activity during temporal order retrieval.

We aimed to address several issues with respect with these earlier studies. First, these studies have focussed on probing temporal order (or recency) judgements of two independent events, which did not occur one after the other among a string of similar events (e.g., “which store did you visit first?”). Second, they have not directly compared spatial (“where”) and temporal (“when”) and object (“what”) retrieval tasks following the encoding of a single experience (here, the viewing of the TV episode). Third, the durations between encoding and retrieval in these studies, which ranged from seconds (e.g., Ekstrom et al., 2011) to an average of 83 min in Fujii et al. (2004), were considerably shorter than the one-day period used in our current study.

In light of these considerations, our experiment was designed to employ rich, semantically contiguous/continuous stimuli for encoding (cinematic material) and to require a longer retention period (24 h). Given the advantages of naturalistic cinematic material (e.g., Hasson, Furman, Clark, Dudai, & Davahi, 2008), we employed a specific TV series involving complex features characteristic of real-life-like events. The choice of a long movie with a very large amount of interrelated events differs from other studies that have chosen to use short, action/goal-oriented clips (e.g., Swallow et al., 2011; Swallow, Zacks, & Abrams, 2009). As critically, the 42-min episode contained one hour of movie plot that related to real-world events, and accordingly provided an almost one-to-one temporal correspondence between the time of the events in the movie plot and the “real” time experienced by the viewer. Twenty-four hours after encoding, subjects were tested with a two-choice discrimination test of scenes extracted from the film, while undergoing functional magnetic resonance imaging. On each trial, the subject was either required to choose the scene that happened earlier in the film (Temporal trials), or the scene with a correct spatial arrangement when it was contrasted with a mirror-image foil (Spatial trials), or the scene that had been shown in the film as opposed to a novel scene (Object trials).

This study had two main aims. First, within our paradigm we asked whether decreasing the temporal distance between encoded events would improve (e.g., Friedman, 1993) or weaken (e.g., Konishi et al., 2002) retrieval performance on temporal trials, and so enable us to assess the effect of temporal distance on retrieval-related brain activity. Second, we examined whether the domain-specificity of the components of “what”, “where” and “when” would lead to different patterns of activation during the retrieval tasks.

2. Materials and methods

2.1. Subjects

Fifteen right-handed native Italian speakers participated in this study (mean age: 25.9, 18–37 years; 9 females). All had normal or corrected-to-normal (contact lenses) visual acuity and were screened by their naivety about the TV series utilised in the study. No participants reported neurological impairments and all gave written informed consent. The study was approved by the Fondazione Santa Lucia (Scientific Institute for Research Hospitalization and Health Care) Independent Ethnics Committee, in accordance with the Declaration of Helsinki.

2.2. Experimental procedure

The experimental design consisted of two main phases, encoding and testing, organised across two consecutive days. On day 1, subjects were asked to watch one single 42-min episode of a TV series (encoding, unscanned). The following day, they were asked to make discriminative choices, during fMRI scanning, of still scenes extracted from the film. Before encoding (day 1), subjects were instructed to concentrate on the film and memorise as much of it as possible. They were made aware of the intention to test their memory of the film the following day; however, they were not informed about what type of information they would be tested on. Before retrieval (day 2), subjects received detailed task instructions (Temporal, Spatial or Object trials; cf. *Memory tasks* section, below) with examples of the different screen displays and familiarised themselves with using the MRI compatible keyboard for making choices.

2.3. Stimuli

At encoding, subjects watched one episode of the American TV series “24”. The episode contained five concurrent storylines portraying different characters at disparate locations (plot A: depiction of the president and his team in the White House; plot B: interactions of inmates in a detention centre; plot C: happenings in the office of the Counter Terrorism Unit; plot D: depiction of Agent Jack on the move; plot E: a middleman working for the terrorists and his girlfriend). The 42-min episode represents one hour of happenings; hence, from a temporal perspective, watching it can be viewed as mimicking “real life” events unfolding over time.

For the retrieval test we generated static images from the film. These were selected on the basis of a content analysis of the episode. The episode was first divided into 89 epochs on the principle that each of the epochs contained a depiction of a disparate setting. Twenty five epochs were reserved for the Spatial trials, another 25 epochs were used for the Object trials, and the remaining 39 epochs were for the Temporal trials, with the three types of trials being ordered in a pseudorandom manner across the 89 epochs. By this means we sought to avoid any possible effect of repeating the presentation of the same stimulus/picture under different task instructions. For example, seeing the same scene twice may – upon the second presentation – result in proactive interference/facilitation that could affect decisions in a Spatial trial, or impair reconstruction during a Temporal trial. To avoid these potential artefacts, different stimuli/pictures were presented in the different tasks, without any counterbalancing. Nonetheless, the randomisation process involved in allocating epochs to trial-type made it most unlikely any idiosyncrasies that could produce the selective patterns of activation that we report here (cf. parametric modulation of activity in the precuneus, see Results).

The 25 Spatial trials were generated by pairing each of the spatial target scenes with its own mirror image; whereas the 25 Object trials were generated by pairing each of the object target scenes with a novel scene extracted from a different episode of the same series (hence unseen to the subjects). From the remaining 39 epochs, 100 pairs of scenes were randomly extracted and paired-up for the Temporal task based on two criteria: (1) the two scenes had to be extracted from the same storyline and (2) the pairings were extracted from two different epochs, the latter criterion thus guaranteed at least one change of settings between the two selected scenes. This manner of pairing permitted sampling of extensive range of temporal distances between the two chosen scenes across Temporal trials.

2.4. Memory tasks

Subjects were scanned during the retrieval test. The retrieval test included three experimental conditions: Temporal trials (100 trials), Spatial trials (25) and Object trials (25) (Fig. 1 panel 1). All trials carried an identical structure consisting of a pair of scenes, one of which was designated as the target. The left-right positions of the target scenes were balanced across 150 trials. To minimise task-switching requirements, the three tasks were presented in blocks of 5 consecutive trials. By contrast, on Temporal trials, the temporal distance (i.e., the time between the two scenes at encoding) was randomly assigned within and across blocks. Accordingly, from the perspective of the temporal distance differential contrast (parametric modulation, see below), our fMRI protocol conformed to the established procedure of intermixing the different trial types (i.e., short/medium/long).

Before each block, written instructions specified what task the subject had to perform with the forthcoming 5 trials. Each trial was presented on the screen for 5 s and then the screen was blanked for a further 2 s. Subjects were instructed to recall events from their memory and to respond with an MRI compatible keyboard as accurately as possible during the 5 s period. Subjects indicated the left/right target stimulus by pressing either one of the two keys with the right hand. Between each block, trials were separated by fixations of variable duration (12–15 s).

Temporal trials (T)—There were 100 Temporal trials. Dictated by the selection criteria, the temporal distances of the happenings of the two scenes varied across the 100 trials on a wide spectrum, ranging from 0.5 min apart to 31.7 min apart. At retrieval subjects were instructed to reconstruct the order of occurrences so as to choose the scene that had happened at an earlier time point in the film. It should be noted that this also approximately matched to the subject's own temporal experience while watching the film, because of the correspondence between the "movie plot" time and "real" time.

Spatial trials (S)—There were 25 Spatial trials, each of them was generated by a target spatial scene and its mirror image. Subjects were instructed to focus on the spatial layout of the scenes and recall which one of the two scenes had the identical spatial arrangement as the film at encoding.

Object trials (O)—There were 25 Object trials, each of them was generated by a target object scene and a novel scene extracted from a different episode (hence unseen by the subjects). Subjects were instructed to focus on the content of the scenes and to identify the scene they had seen the day before. Here, the term "Object" was chosen as a label of the "what" component of "What-Where-When" memory tasks that have been previously used across diverse experimental settings (e.g., Clayton & Dickinson, 1998; Tulving, 1972). However, note that the "Object" task could involve a wider range of elements than just "objects", such as memory for settings, people, or actions, broadly representing the "what" element of the "What-Where-When" classification.

2.5. Eye tracking

Eye position during fMRI scanning was monitored using an ASL Eye-Tracking System with remote optics, custom-adapted for use in the scanner (Applied Science Laboratories, Bedford, United States; Model 504, sampling rate=60 Hz). Good quality eye-tracking data throughout the entire scanning session were available for 10 participants. For these subjects, we computed the frequency and path-length of saccades made during each trial (i.e., in a 5-s window). Saccades were identified as shifts of gaze-position of at least 1 deg, followed by at least 100 ms fixation. Median frequencies and mean path-lengths of eye movements across subjects were then computed according to condition (*T*, *S*, *O*) and used as covariates of no interest in the fMRI control analyses (see below).

2.6. Image acquisition

A Siemens Allegra (Siemens Medical Systems, Erlangen, Germany) 3T scanner equipped for echo-planar imaging (EPI) was used to acquire functional magnetic resonance (MR) images. A quadrature volume head coil was used for radio frequency transmission and reception. Head movement was minimised by mild restraint and cushioning. Thirty-two slices of functional MR images were acquired using blood oxygenation level-dependent imaging (3×3 mm in-plane, 2.5 mm thick, 50% distance factor, repetition time=2.08 s, echo time=30 ms, flip angle=70 deg, FOV=192 mm, acquisition order=continuous, ascending), covering the entirety of the cortex.

2.7. Data analysis

Data pre-processing was performed with SPM8 (Wellcome Department of Cognitive Neurology) as implemented on MATLAB 7.4. A total of 783 fMRI volumes for each subject were acquired in a single fMRI-session which lasted for approximately 30 min. After having discarded the first 4 volumes, images were realigned in order to correct for head movements. Slice-acquisition delays were corrected using the middle slice as a reference. Images were then normalised to the MNI EPI template, re-sampled to 2 mm isotropic voxel size and spatially smoothed using an isotropic Gaussian kernel of 8 mm FWHM (full-width half-maximum).

We carried out four sets of analyses. The first analysis ("main analysis") sought to identify brain areas that activated during retrieval in a domain-specific manner (temporal, spatial or object). The second set of analyses ("temporal distance") considered specifically processes related to the retrieval of temporal information. For this we tested for co-variation between the temporal distance of two occurrences at encoding and brain activity during retrieval of the same events. The third set of analyses ("controls for the Spatial task") utilised eye-movements data recorded in the scanner to assess the influence of overt orienting behaviour on brain activity associated with the Spatial task. Moreover, as the behavioural data revealed that spatial information was most difficult to retrieve (Fig. 2 panel 1), these control analyses re-assessed the effect of the Spatial task but now including reaction times (RTs) as a covariate of no interest. Finally, the fourth set of analyses ("controls for recollection success") probed the issue of whether domain-related activations were process- or content-specific by contrasting correct vs. incorrect trials, as a function of task.

2.7.1. Domain-specific retrieval—Data were analysed with SPM8 following a standard two-levels procedure (Penny & Holmes, 2004). First-level multiple regression models (i.e., single-subject analyses) included the 3 conditions of interest (Temporal, Spatial, Object trials), plus Errors and movement parameters (cf. realignment pre-processing step, above) as effect of no-interest. Each trial was modelled as an event, time-locked to the presentation of the two scenes and with duration=5 s. Event-related modelling (despite the design that the *T*/*S*/*O*-task was blocked for 5 trials) enabled us to discard error trials and, most importantly, to include trial-specific modulatory effects related to temporal distance (Delta*T*) and reaction times (RTs), see also below. Time series at each voxel were high-pass filtered at 256 s and pre-whitened by means of autoregressive model AR(1). The parameter estimates of each subject and condition of interest were then assessed at the second-level for random effect statistical inference. Note that because of the relatively long inter-blocks intervals (12–15 s), the parameter estimate of each condition essentially represents "activation vs. rest".

The second-level analysis consisted of a within-subjects ANOVA modelling the three effects of interest: *T*, *S* and *O* conditions, considering only correct trials. Correction for non-sphericity was used to account for possible differences in error variance across conditions and any non-independent error terms for the repeated measures (Friston et al., 2002). *T*-contrasts were used to assess the effect of each condition vs. rest (e.g., [T>0]), and – most importantly – to directly compare the different retrieval conditions. A conjunction analysis (Nichols, Brett, Andersson, Wager, & Poline, 2005; Price & Friston, 1997) highlighted areas activated during all 3 retrieval conditions (null-conjunction: [T>0] and [S>0] and [O>0]; *p*-FWE<0.05, whole-brain corrected at cluster level, cluster size estimated at *p*-unc.=0.001). For the identification of task-specific effects, *T*-contrasts compared each condition vs. the mean of the other two conditions (e.g., [T>(S+O)/2]). For this main contrast, the statistical threshold was set to *p*-FWE<0.05, whole brain corrected at cluster level (cluster size estimated at *p*-unc.=0.001). To further ensure the specificity of these condition-specific effects, the main differential contrast was inclusively masked with 3 additional contrasts. These were: activation for the critical condition vs. rest (e.g., [T>0]) and activation for the critical condition vs. each of the two other conditions (e.g., [T>S] and [T>O]). For these additional, not independent, masking contrasts the threshold was set to *p*-unc.=0.05. These procedures led us to identify areas specifically activated by one of the three retrieval conditions (see also signal plots in Fig. 1).

2.7.2. Effect of temporal distance during the temporal task (DeltaT)—Behaviourally, subjects were slower (and less accurate) in trials with short temporal distance (short Delta*T*) compared to those with long temporal distance (long Delta*T*). For this analysis, we took advantage of the large pool of Temporal trials (100 trials, vs. 25 for each of the other two tasks) further selecting a subset of trials in which most subjects responded correctly. We called these trials "high consistency Temporal trials" (*T*-high, as opposed to "low consistency *T* trials": *T*-low). By applying a cut-off criterion to selecting trials in which at least 13 out of 15 subjects responded correctly, we obtained 67 high consistency trials for the analysis. For these 67 trials the correlation between reaction times and Delta *T* was significant (see results section, and Fig. 2 panel 1).

We re-constructed all first-level fMRI models now considering separately *T*-high and *T*-low trials, and including Delta *T* as a trial-specific modulator of the *T*-high responses (Delta *T*-covariate). Moreover, because of the correlation between RTs and Delta *T* (see above), trial-specific RTs averaged across subjects were used as an additional modulator of the *T*-high trials (RTs-covariate). Accordingly, any significant co-variation between BOLD and Delta *T* cannot be explained by RTs differences (e.g., short temporal distance trials being just more difficult than long distance trials). For completeness, these new first-level models included also the corresponding RTs-covariates for Spatial and Object trials. The random effects analysis consisted of a one-sample *t*-test assessing the significance of Delta *T*-covariate at the group level. The statistical threshold was set to *p*-FWE=0.05, considering the precuneus and the right angular gyrus (i.e., the areas activated for Temporal trials in the main analysis, cf. Table 2) as the volume of interest (Worsley et al., 1996).

The effect of temporal distance in the precuneus was also tested with an additional analysis that categorically compared short vs. long trials (cf. St. Jacques et al., 2008) and included performance at the subject-specific level, rather than using performance consistency across subjects. We reconstructed all first-level models, dividing the Temporal trials into “short” and “long” Delta *T* trials (cf. St. Jacques et al., 2008), and further into correct and incorrect trials. We obtained 4 conditions for the Temporal task (short/long×correct/incorrect), plus 2 for Space (correct/incorrect) and 2 for Object (correct/incorrect). Because subjects differed in their individual accuracy, the cut-off separating “short” vs. “long” trials was set specifically for each subject. This ensured a well balanced number of short and long trials for each individual. At the group level, we tested the effect of short vs. long trials, with the aim of replicating the effect of temporal distance in the precuneus, now using a categorical rather than parametric comparison.

2.7.3. Control analyses for the spatial task—Our main analysis showed that the Spatial task activated a large network of brain areas including oculo-motor circuits in dorsal fronto-parietal regions. Moreover, the behavioural data indicated that this task was more difficult than the other two retrieval conditions (Fig. 2 panel 1). Accordingly, we ran two additional control analyses. The first analysis consisted of a within-subject ANOVA that was identical to the main analysis (15 subjects, 3 conditions: *T*, *S*, *O*), but now including subject-specific RTs, that is, an average RT (across repetitions of the same condition) for each subject and each condition, as a covariate of no interest. In this way, the inherent differences in task difficulty across conditions were accounted for. Within this we tested again for activation associated with the Spatial task ([$S>(T+O)/2$], inclusively masked with (i) [$S>0$], (ii) [$S>T$] and [$S>O$]), but now accounting for the influence of RT differences. The second control analysis made use of the eye-movement data recorded during fMRI. Because good quality eye-tracking data were available only in a subgroup of subjects, this ANOVA included 10 subjects, 3 conditions, plus subject- and condition-specific saccadic frequency and path-length as additional covariates of no interest. Again we tested for activations associated with the Spatial task ([$S>(T+O)/2$], masked with (i) [$S>0$], (ii) [$S>T$] and (iii) [$S>O$]), in this case excluding any contribution of differential patterns of eye-movements between conditions. These additional, not-independent, analyses were restricted to regions/voxels showing activation for the Spatial task in the main analysis (cf. Tables 2 and 3).

2.7.4. Control analyses for retrieval success—In order to examine whether the domain-specific activations were due to putative task-related retrieval processes or the retrieval of specific diagnostic content, we investigated the effect of task and temporal distance including incorrect trials as well as correct ones. Operationally, we associated task-related processes to activations independently of retrieval success (i.e., showing task-related effects for incorrect trials too), while content-components were tested as effects specific for correct retrieval only (task by accuracy interactions). Accordingly, we reconstructed all subject-specific first-level GLM including error trials separately for each of the 3 Tasks. These now included 6 conditions given by the crossing of Tasks (*T*, *S*, *O*) and Accuracy (correct, incorrect). For these additional analyses, at the group level, we considered only Time and Space (×Accuracy), because the Object condition had too few error trials (mean=1.8 error/subject; range=0–5 errors).

3. Results

3.1. Behavioural results

Subjects performed better than chance level in all three retrieval conditions (all ps<0.001). They performed significantly better in Object condition (error rate: 7.47±1.40%) than Temporal condition [error rate: 16.40±0.75%; $t(14)=5.58$, $p<0.001$] and Spatial condition [error rate: 32.27±2.11%; $t(14)=10.28$, $p<0.001$]. On Temporal trials subjects were more accurate than Spatial trials [$t(14)=7.42$, $p<0.001$]. A similar pattern was observed with the reaction times on correct trials. Subjects responded significantly faster in Object condition [2048±162 ms] than in Temporal condition [2614±181 ms; $t(14)=8.02$, $p<0.001$] and Spatial condition [3038±192 ms; $t(14)=9.34$, $p<0.001$], and the RTs in Temporal condition were faster than Spatial condition [$t(14)=5.69$, $p<0.001$] (see Fig. 2 panel 1, leftmost plot).

For the Temporal task, we assessed whether there was some relationship between RTs (at retrieval) and the temporal distance (at encoding) between two occurrences/scenes that subjects were asked to judge (i.e., the Delta *T*). We found a significant correlation between RTs and Delta *T* (Pearson $r=-0.25$, $p=0.045$), but only when the analysis was constrained to trials that were recalled in a reliable manner (i.e., the 67 Temporal trials correctly judged by at least 13 out of 15 subjects). This negative correlation indicates that subjects were faster to access/judge temporal information stored in episodic memory, when the temporal distance between the two events increased (Fig. 2 panel 1, central plot). This accords with the view that memory traces are organised in some structured manner that facilitates judgements of events separated by long temporal distances compared with short distances. As an additional control, we tested whether there was any systematic relationship between the absolute position of the scenes in the film (averaging the time of the two frames) and reaction times. This did not reveal any significant correlation ($p>0.1$), reflecting the specificity of the Delta *T* effect, regardless of the segment's temporal position in the film.

With the eye-movement data available (10 subjects), subjects made significantly more saccades (median number of saccades per second) in the Temporal condition (1.78±0.08) and in the Spatial condition (1.81±0.09) than in the Object condition [1.55±0.08; compared to Temporal: $t(9)=6.70$, $p<0.001$; com pared to Spatial: $t(9)=4.33$, $p=0.002$], and there was no difference between Temporal and Spatial conditions [$t(9)<1$]. The mean path-length executed during 5-s retrieval periods (in visual degree) was significantly larger in the Temporal condition (46.46±2.79) than in either Spatial [42.58±3.48; $t(9)=3.19$, $p=0.011$] or Object conditions [41.30±2.31; $t(9)=7.36$, $p<0.001$], and there was no difference between Spatial and Object conditions [$t(9)<1$] (Fig. 2 panel 1, rightmost plots).

3.2. Domain-specific retrieval from episodic memory

Before testing for any domain-specific effect, we used a conjunction analysis across the three retrieval conditions (*T*, *S* and *O*) to highlight the brain regions engaged during memory retrieval vs. rest, irrespective of retrieval task. This revealed activation of a widespread network that included large sections of the occipital cortex, regions in the dorsal fronto-parietal network, plus motor, pre-motor and prefrontal areas bilaterally in the frontal lobe (Table 1). Most of these activations can be attributed to the visual stimulation, motor performance and general task-requirements. However, this analysis also revealed that all three retrieval conditions activated the posterior part of the hippocampus, and that was dissociated from a more anterior region that responded selectively during object retrieval task (see below, and Fig. 1 panel 4).

Temporal retrieval task—The direct comparison of the Temporal task with the other two retrieval conditions revealed two clusters of significant activation (Table 2). One cluster was located medially and included the precuneus bilaterally. The second cluster was on the lateral surface of the right hemisphere and involved primarily the angular gyrus. The signal plots in Fig. 1 panel 2 show that activity in these two regions was highly specific for the temporal retrieval task (see bar in red).

Spatial retrieval task—The fMRI analysis concerning the retrieval of spatial memories highlighted activation of the superior parietal gyrus, the intraparietal sulcus and frontal eye-fields in the dorsal fronto-parietal network, the middle frontal gyrus, anterior insula, plus regions in occipital visual cortex (Fig. 1 panel 3, and Table 2). We performed two control analyses to assess the possible role of task difficulty (indexed using RTs) and overt spatial behaviour (indexed using saccade frequency and path-lengths) for the activation of this network. The analysis including RTs as a covariate of no interest confirmed that the Spatial task activated the posterior nodes of the dorsal fronto-partial network (superior parietal gyrus and intraparietal sulcus) with activation also in the right superior frontal gyrus (Table 3, and Figure 2.3 central panel). In the control analysis including saccade frequency and path-lengths as confounding effects, we found activation in superior parietal and superior frontal gyrus bilaterally, plus the left intraparietal sulcus (Table 3, and Figure 2.3 rightmost panel). Thus, the activation of dorsal frontoparietal regions for the Spatial retrieval task cannot be merely explained by overall task difficulty and/or oculo-motor behaviour.

Object retrieval task—The object retrieval task was selectively associated with the symmetrical activation the left and right anterior hippocampus (see Fig. 1 panel 4, and Table 2), extending to the parahippocampal cortex. Probabilistic cytoarchitectonic maps (Amunts et al., 2005) revealed that 47.5% of the left cluster could be assigned to the hippocampal formation, including the CA and subiculum areas, whereas, in the right hemisphere, 32.2% of the cluster was assigned to the hippocampal formation, with a further 16.7% assigned to the entorhinal cortex (see Table 4). The signal plots in Fig. 1 (panel 4) show that these activations were selective for the Object task with spatial and temporal tasks leading, if anything, to a de-activation of these regions. The sagittal section in this panel highlights that the object-specific effect was more anterior than the hippocampus activation observed irrespective of retrieval condition (common activation for *T*, *S*, and *O* tasks; see Table 1, and signal plot for the right anterior hippocampus in Fig. 1 panel 4).

3.3. Effect of temporal distance (DeltaT)

Next, we turned to the issue of whether modulation of temporal distance had any impact on functional activities within the areas activated selectively during the Temporal task. On a trial-by-trial basis, we assessed the relationship between BOLD activation at retrieval and the temporal distance between the two relevant events at encoding (Delta*T*). This showed a significant modulation of the precuneus response associated with Temporal trials (*T*-high) as a function of temporal distance (x, y, z=6, −70, 44; p-FWE<0.007). Specifically, the retrieval-related activation of the precuneus increased with decreasing temporal distance between the two events at encoding, providing support to the notion of structurallyorganised memory traces. It should be noted that this analysis accounted, on a trial-by-trial basis, for the changes of RTs as a function of temporal distance. Thus, mere task difficulty is unlikely to explain this additional time-related modulatory effect in the precuneus (Fig. 2 panel 2; note also that the most difficult retrieval condition – i.e., the Spatial task – activated this region less than the Temporal task). For completeness, we also tested whether Delta T modulated activity in Spatial- and Object-related areas. As expected, this did not reveal any significant effect of temporal distance in these regions.

With a non-independent additional analysis, we tested the effect of temporal distance re-categorising all temporal trials as “short” or “long” distance trials (cf. St. Jacques et al., 2008). The direct comparison of “short minus long” trials replicated the effect of temporal distance in the precuneus, albeit only at an uncorrected level of significance ($x, y, z = -10, -60, 48$; p-unc.<0.001). This analysis included accuracy as a factor, allowing us to test for the interaction between distance and accuracy (see also next section). No interaction was found in the precuneus, even at an uncorrected level of significance.

3.4. Process- vs. content-specific retrieval

Finally, we tested whether the activations associated with the Temporal and the Spatial tasks (cf. Fig. 1, panels 2 and 3) were selective for correct trials or they were independent of retrieval success. Using incorrect trials only, we replicated the activations of the precuneus and the right angular gyrus for the Temporal task ($T>S$: both p-FWE<0.05, at the whole-brain level) and the dorsal fronto-parietal cortex for the Spatial task ($S>T$; including posterior and intra-parietal cortex bilaterally and the right superior frontal gyrus, all p-FWE<0.05, at the whole-brain level). The task×accuracy interactions did not reveal any significant activation. These results speak in favour of a process-based rather than content-based account of our domain-specific results (see Discussion).

4. Discussion

We obtained two main sets of findings. First, at both behavioural and neural levels we found a modulatory effect on retrieval of the parameterised temporal distance between encoded events, in that both RTs and activity in the precuneus showed a negative correlation with temporal distance between two events at encoding (i.e., longer RTs and a greater activation for shorter distances). These findings are more consistent with search processes operating on episodic details within an organised memory structure, than with serial search between temporally organised adjacent memory traces. Second, dissociations in the functional anatomy of domain-specific retrieval were exhibited by different specific comparisons: retrieval of the temporal order of events led to the activation of the precuneus and the right angular gyrus. The dorsal frontal and parietal cortices were engaged during recall of spatial information. Activations within the hippocampal formation were found in object-based retrieval. These task-specific effects occurred independently of retrieval success. We discuss the implications of these patterns of activation with respect to the underlying processes that are involved during retrieval of complex, naturalistic memories, primarily in the context of how memory is organised temporally.

4.1. Retrieval of temporal components in the precuneus

Compared to the possible selectivity of medial temporal structures for specific retrieval processes (e.g., Diana, Yonelinas, & Ranganath, 2007; Hassabis, Kumaran, Vann, & Maguire, 2007), less is known about the specific role of parietal cortex during retrieval (cf. Cabeza & Nyberg, 2000; Nyberg et al., 2000; Vilberg & Rugg, 2008). In a general framework of parietal functions, activation during episodic retrieval has been associated with attention-related processes (Ciaramelli, Grady, & Moscovitch, 2008; Wagner, Shannon, Kahn, & Buckner, 2005). However, Sestieri, Shulman, and Corbetta (2010) reported a dissociation between these two cognitive functions in parietal cortex (see also Hutchinson, Uncapher, & Wagner, 2009). They found a specific involvement of the angular gyrus, precuneus and posterior cingulate cortex during memory-search, but of intraparietal sulcus (IPS) and the superior parietal lobule for perceptually-related processes. Our findings are in agreement with this distinction showing retrieval-related activation in the precuneus and the right angular gyrus (Fig. 1 panel 2).

Unlike the Spatial and Object tasks, which could be accomplished by retrieving a single “snapshot” of the memorised episode, the Temporal task required the subject to access multiple (at least two) instances of the storyline. According to chronological organisation theory (Friedman, 1993), this can be done by retrieving the time position of one of the two test scenes in the film, and then scanning through the rest of the episode looking for the second scene (i.e., serial temporal search). However, if memory is organised in this fashion, we would expect that memories laid down at adjacent points in time would prime one another. Thus, when remembering some past event, it should be easy to order events that occurred at about the same time. Here, we found that reaction times (Fig. 2 panel 1) and activity in the precuneus (Fig. 2 panel 2) increased with decreasing temporal distances between the two test scenes/events. RTs could reflect more than one process (e.g., not only retrieval times, but also decision times which could reflect a greater uncertainty about relative recency, when the two pictures were close in time). However, as far as the role played by the precuneus, the key structure in the temporal task, is concerned, these effects appear to speak against it being involved in any form of serial search along temporally organised memory traces, if retrieval of the second event were to arise by scanning backward or forward from the first on some “time-line”. In accord with studies which required subjects to make recency judgements of less complex stimuli (Konishi et al., 2002; Suzuki et al., 2002), and with the results of St. Jacques and colleagues (2008), who reported increased precuneus activity as a function of decreasing time lag, our data likewise speak against the precuneus having any role in a chronological organisation process of episodic recollection involving serial scanning through memory traces.

At least two accounts are possible for the selective modulation of activity in the precuneus by the elapsed time between events. The first relates to the *encoding perturbation theory*, a theory originally proposed by Estes (1972, 1985) to explain findings on short-term memory, while the second refers to the *reconstructive theory* proposed by Friedman (1993, 1996, 2001, 2004).

According to the *encoding perturbation theory*, when an event occurs this becomes associated with control elements at different levels within a hierarchically organised structure. The notion has later been elaborated and extended to explain everyday memory phenomena in long-term memory (e.g., Anderson & Conway, 1993; Zacks, Tversky, & Iyer, 2001). On this approach the system encodes continuous streams of observed behaviour by segmenting activities into events and then organising them in memory in a basically hierarchical manner (Zacks et al., 2001), with groups of fine-grained events clustering into larger units (Kurby & Zacks, 2008). In the present study, the observed effects of temporal distance during retrieval may relate to the search for the two test scenes through a hierarchical structure which holds the encoded TV episode. When the two scenes are far apart in time (long Delta *T*), the Temporal task can be solved by searching high/intermediate levels of the knowledge structure. By contrast, when the two scenes are close in time (short Delta *T*), they will be associated with the same node at intermediate levels of the structure and the search has to be continued to lower levels of the structure. Activation of the precuneus could reflect some aspect(s) of this search process, with increased activation when the search involves exploring down to lower levels of the structure. One more specific possibility is that searching the lower levels of the hierarchy requires more of a particular sort of process, such as creating imagery of specific scenes not presented at retrieval (Fletcher et al., 1995; Fletcher, Shallice, Frith, Frackowiak, & Dolan, 1996; Grasby et al., 1993; but see Lundstrom, Ingvar, & Petersson, 2005; Roland & Seitz, 1989). Alternatively, the precuneus may be required for the organisation of levels per se as such an account would also be compatible with a role of the precuneus in structuring knowledge hierarchies of the outside world during perception and memory encoding (Speer, Zacks, & Reynolds, 2007; Zacks et al., 2001; Zacks, Speer, Swallow, & Maley, 2010).

A second possible account for the observed effects of temporal distance concerns *reconstructive theories of memory* (Friedman, 1993; 1996; 2001; 2004). When applied to memory for personal events (Brown, Rips & Shevell, 1985; Friedman & Wilkins, 1985), such theories postulate the existence of a process of reconstruction that draws on a rich knowledge of social, natural, and personal time patterns (e.g., the time of a day). In contrast to the encoding perturbation model discussed above, there is an explicit emphasis on the use of general time knowledge and inferential processes at the time of recall. Reconstruction processes are effortful operations that include retrieving contextual details and using them to infer the order of past events (Curran & Friedman, 2003; Skowronski, Walker, & Betz, 2003). These processes can provide relatively high precision in the resolution of temporal details, and are particularly likely to be employed when past events are close in time and difficult to discern (Burt, Kemp, Grady, & Conway, 2000; Friedman, 1993), such as those involved in the short Delta T trials in our study. The additional amount of time required in short Delta T trials in our study is to be expected if such reconstructive-based processes are operative (Curran & Friedman, 2003; Friedman, 1993; St. Jacques et al., 2008).

Our findings on the engagement of the precuneus in temporal memory judgements have implications with respect to the putative functions of other areas implicated in retrieving temporal information from memory. The greater difficulty associated with distinguishing items closer in time has been reliably reflected in prefrontal activations in fMRI studies (e.g., Konishi et al., 2002; St. Jacques et al., 2008; Suzuki et al., 2002; Zorrilla et al., 1996). However, we have shown that an area, other than the well-documented prefrontal regions, is involved in discriminating the order of events that are closer in time. St Jacques et al. (2008) has provided initial evidence of the role of precuneus in this process. However, as noted in the Introduction, there is a potential task difficulty confound in the study of St Jacques et al. (2008), so our demonstration provides more solid evidence of the effect of temporal distance in retrieval on the operation of the precuneus.

4.2. Retrieval of detailed spatial content in dorsal fronto-parietal cortex

The Spatial task elicited a widespread pattern of activation, including parietal regions (PPC and IPS) and several premotor and prefrontal regions (Fig. 1 panel 3). However, the activation of some of these areas is likely not to be specifically due to a memory process. Spatial trials are more difficult than the other trial types, as manifested by slower reaction time and a higher error rate (Fig. 2 panel 1). We thus ran a set of control analyses to partial out the general effect of task difficulty (RTs) and oculo-motor behaviour; these confirmed the role of the superior parietal cortex and dorsal premotor areas for the spatial memory judgment (Table 3, Figure 2.3 middle and far right), but the lateral premotor and prefrontal activation could also be explained by differences in reaction times and/or oculo-motor behaviour.

A variety of spatial (“where”) tasks have previously been conducted in virtual reality settings. For example, Ekstrom et al. had subjects navigate virtual environments in a taxi-driver game and then had them recall whether they had taken a certain passenger to a certain place (Ekstrom & Bookheimer, 2007) or determine the spatial proximity between two stores

(Ekstrom et al., 2011). The spatial association retrieval task in Ekstrom and Bookheimer (2007) had to be solved on the basis of associating two “object” elements (i.e., the passenger and the store) and this could have evoked both spatial and non-spatial strategies concurrently. Furthermore, navigation and spatial judgement tasks in virtual environments involve several types of spatial representations (e.g., egocentric and allocentric frames of reference) (Neggers, Van der Lubbe, Ramsey, & Postma, 2006; Neil, 2006). These types of spatial representations/maps are unlikely to play a role in the current Spatial task, which requires neither a judgment of relative positions in external space nor the integration of information between different viewpoints.

Instead, we propose that the activation of the dorsal frontoparietal system that was found selectively for the Spatial task relates to post-retrieval processes: i.e., when the subject evaluates the two scenes presented in the test phase with retrieved information about the relevant movie event. Post-retrieval operations are traditionally associated with the lateral prefrontal cortex (Rugg, Henson, & Robb, 2003), which was also activated in the current study, and posterior/superior parietal regions (Hayama & Rugg, 2009; Henson, Rugg, Shallice, Josephs, & Dolan, 1999; Kahn, Davachi, & Wagner, 2004; Rugg et al., 2003), together with selective activation in the most posterior part of IPS and the superior parietal gyrus for source/episodic retrieval compared to semantic retrieval. In the context of the current task, the dorsal fronto-parietal system may be holding a short-term visuo-spatial storage system on which attentional processes can be used to focus/orient to aspects of the available visual input (i.e., the two test images) and on information retrieved from memory (e.g., Ishai, Haxby, & Ungerleider, 2002; Lepsien & Nobre, 2007; Summerfield, Lepsien, Gitelman, Mesulam, & Nobre, 2006). This explanation fits with findings from several imaging studies that have demonstrated the role of the dorsal attention network in working memory tasks which require maintenance and manipulation of spatial information (Harrison, Jolicoeur, & Marois, 2010; Magen, Emmanouil, McMains, Kastner, & Treisman, 2009; Pollmann & Yves von Cramon, 2000).

4.3. Retrieval of object content in the anterior hippocampus

The third domain-specific effect involved the anterior section of the hippocampus. Activation of the hippocampus during retrieval of autobiographical memories is well known (Addis, Moscovitch, Crawley, & McAndrews, 2004; Maguire, Vargha-Khadem, & Mishkin, 2001; Milton et al., 2011; Ryan et al., 2001) and is observed during spatial retrieval (Burgess et al., 2001), navigation tasks (Iglói, Doeller, Berthoz, Rondi-Reig, & Burgess, 2010), disambiguation of non-spatial temporal sequences (Kumaran & Maguire, 2006), temporal sequence recall (Lehn et al., 2009; Ross, Brown, & Stern, 2009) and source retrieval (Ekstrom et al., 2011). However the current study is the first to find hippocampal activity preferentially for an object retrieval task. The anterior activations obtained contrast with those involving more posterior regions (including posterior hippocampi and parahippocampal gyri), which were activated in all three retrieval conditions in the current study (Fig. 1 panel 4).

One may argue that the increased activity in the Object task reflects the detection of associative novelty, or the new arrangements of familiar stimuli (i.e., the old scene now presented within a pair), requiring the hippocampus (Düzel et al., 2003; Schott et al., 2004). Yet, this is unlikely as no similar hippocampal activation was found in the Temporal and Spatial retrieval conditions, which also entailed – previously unencountered – pairs of familiar scenes. The lack of activations in either perirhinal or prefrontal cortices also count against an explanation based on novelty detection and encoding of a new, unseen picture during the retrieval test (Bakker, Kirwan, Miller, & Stark, 2008; Davachi, Mitchell, & Wagner, 2003; Gold et al., 2006; Strange, Hurlemann, Duggins, Heinze, & Dolan, 2005).

Instead we suggest that the hippocampus is engaged in the mental reconstruction of complex scenes (Hassabis, Kumaran, & Maguire, 2007). Compared to the Spatial task in which only spatial (“where”) information contributed to the selection of the target scene, in the Object task subjects could use both what and where signals (i.e., objects/people and location) to make the decision. The joint contribution of both what and where signals during retrieval operations is consistent with the role of the hippocampus for the integration of multiple elements of episodes during processing of complex scenes (Eichenbaum, 2004; Montaldi, Spencer, Roberts, & Mayes, 2006; Shimamura, 2010). A related possibility is that the hippocampus supports the formation and recovery of relationships between the separate components, such as people, actions, or objects, within an episode (e.g., Aggleton & Brown, 1999; Eichenbaum, Otto, & Cohen, 1994), in keeping with findings on hippocampal amnesic patients (Konkel, Warren, Duff, Tranel, & Cohen, 2008) and neuroimaging studies showing hippocampal involvement in relational processes (Giovanello, Schnyer, & Verfaellie, 2004; Preston, Shrager, Dudukovic, & Gabrieli, 2004; Prince, Daselaar, & Cabeza, 2005).

4.4. Process- vs. content-specific retrieval

Additional analyses assessing task/domain-specificity as a function of retrieval success (task×accuracy interactions) revealed that the functional dissociations obtained were not selective for successful retrieval, but rather can be observed irrespective of performance. Assessing different hypotheses on retrieval-associated activation was beyond the scope of the current study, but our finding of a task-dependent, but success-independent dissociation for different tasks may have implications for the debate on retrieval success for regions other than prefrontal areas (e.g., Rugg, Fletcher, Frith, Frackowiak, & Dolan, 1996; and also Rugg & Wilding, 2000; Wilding, 1999). Previous fMRI studies of recognition memory have shown that several prefrontal regions, notably bilateral anterior, right dorsolateral, and ventrolateral cortex, have a degree of activity at retrieval which increases with successful performance in certain episodic memory paradigms (e.g., Cansino, Maquet, Dolan, & Rugg, 2002; Henson et al., 1999; Kahn et al., 2004; Rugg et al., 2003; for a review, cf. Rugg, Otten, & Henson, 2002). Our findings here favour the hypotheses emphasising the centrality of “retrieval attempts” and demonstrate that these can engage separate networks outside the prefrontal cortex, depending on the type of information that subjects are asked to retrieve. Our interpretation is that attempts to retrieve Spatial and Temporal order information initiate specific processes of search and evaluation of the retrieval products that do not merely reflect general, task-independent effort or post-retrieval decision making (cf. also control analyses of task difficulty). For instance, on all Temporal trials, we suggest that subjects initiated some “search” or “reconstructive” processes even on those trials wherein they eventually failed to produce the correct response.

5. Conclusion

The current study suggests that memory traces of complex naturalistic temporal events are stored in a structured, rather than serial, manner. It also provides fMRI evidence to support a tripartite process-specific retrieval model of episodic memory. Activity in the precuneus is associated with temporal retrieval, a dorsal fronto-parietal network is engaged during spatial retrieval, while antero-medial temporal regions activate selectively during object-related retrieval. We link this selectivity with the engagement of specific retrieval processes, rather than memory content. We propose that systems in the precuneus retrieve temporal information by being involved in either searching within a hierarchical knowledge structure or in reconstructing moments/events of contextual details when considerable temporal precision is required. By contrast, decisions about spatial details utilise operations on a visuo-spatial short-term storage system that can maintain and compare online sensory information and signals retrieved from episodic long-term memory; these processes involve dorsal fronto-parietal cortex. Finally, the anterior hippocampus is held to be involved in object-retrieval when the process needs to combine spatial ("where") and non-spatial ("what") information. By isolating the contribution of these regions, the present fMRI findings contribute to a theory of dissociations between retrieval-related processes and highlights a role of the precuneus in searching information within a "structured" long-term temporal memory store.

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References

Addis DR, Moscovitch M, Crawley AP, McAndrews MP. Recollective qualities modulate hippocampal activation during autobiographical memory retrieval. Hippocampus. 2004; 14:752–762. [PubMed: 15318333]

Aggleton JP, Brown MW. Episodic memory, amnesia, and the hippocampal-anterior thalamic axis. Behavioral and Brain Sciences. 1999; 22:425–444. [PubMed: 11301518]

Amunts K, Kedo O, Kindler M, Pieperhoff P, Mohlberg H, Shah NJ, Habel U, Schneider F, Zilles K. Cytoarchitectonic mapping of the human amygdala, hippocampal region and entorhinal cortex: intersubject variability and probability maps. Anatomy and Embryology. 2005; 210:343–352. [PubMed: 16208455]

Anderson SJ, Conway MA. Investigating the structure of autobiographical memories. Journal of Experimental Psychology: Learning, Memory, and Cognition. 1993; 19:1178–1196.

Bakker A, Kirwan CB, Miller M, Stark CEL. Pattern separation in the human hippocampal CA3 and dentate gyrus. Science. 2008; 319:1640–1642. [PubMed: 18356518]

Barsalou, LW. Remembering reconsidered: ecological and traditional approaches to the study of memory. Neisser, U.; Winograd, E., editors. Cambridge University Press; Cambridge: 1988. p. 193-243.

Brown, GDA.; Chater, N. Time and memory: issues in philosophy and psychology. Hoerl, CM.; T., editors. Oxford University Press; Oxford: England: 2001. p. 77-110.

Brown NR, Rips LJ, Shevell SK. The subjective dates of natural events in very-long-term memory. Cognitive Psychology. 1985; 17:139–177.

Bruce D, Van Pelt M. Memories of a bicycle tour. Applied Cognitive Psychology. 1989; 3:137–156.

Burgess N, Maguire EA, Spiers HJ, O'Keefe J. A temporoparietal and prefrontal network for retrieving the spatial context of lifelike events. NeuroImage. 2001; 14:439–453. [PubMed: 11467917]

Burgess PW, Shallice T. Confabulation and the control of recollection. Memory. 1996; 4:359–411. [PubMed: 8817460]

Burt CDB, Kemp S, Grady JM, Conway M. Ordering autobiographical experiences. Memory. 2000; 8:323–332. [PubMed: 11045240]

Butters MA, Kaszniak AW, Glisky EL, Eslinger PJ, Schacter DL. Recency discrimination deficits in frontal lobe patients. Neuropsychology. 1994; 8:343–354.

Cabeza R, Nyberg L. Imaging cognition II: An empirical review of 275 PET and fMRI studies. Journal of Cognitive Neuroscience. 2000; 12:1–47. [PubMed: 10769304]

Cansino S, Maquet P, Dolan RJ, Rugg MD. Brain activity underlying encoding and retrieval of source memory. Cerebral Cortex. 2002; 12:1048–1056. [PubMed: 12217968]

Christoff K, Prabhakaran V, Dorfman J, Zhao Z, Kroger JK, Holyoak KJ, Gabrieli JDE. Rostrolateral prefrontal cortex involvement in relational integration during reasoning. NeuroImage. 2001; 14:1136–1149. [PubMed: 11697945]

Ciaramelli E, Grady CL, Moscovitch M. Top-down and bottom-up attention to memory: a hypothesis (AtoM) on the role of the posterior parietal cortex in memory retrieval. Neuropsychologia. 2008; 46:1828–1851. [PubMed: 18471837]

Clayton NS, Dickinson A. Episodic-like memory during cache recovery by scrub jays. Nature. 1998; 395:272–274. [PubMed: 9751053]

Curran T, Friedman WJ. Differentiating location- and distance-based processes in memory for time: an ERP study. Psychonomic Bulletin and Review. 2003; 10:711–717. [PubMed: 14620368]

Davachi L, Mitchell JP, Wagner AD. Multiple routes to memory: distinct medial temporal lobe processes build item and source memories. Proceedings of the National Academy of Sciences of the United States of America. 2003; 100:2157–2162. [PubMed: 12578977]

Diana RA, Yonelinas AP, Ranganath C. Imaging recollection and familiarity in the medial temporal lobe: a three-component model. Trends in Cognitive Sciences. 2007; 11:379–386. [PubMed: 17707683]

Düzel E, Habib R, Rotte M, Guderian S, Tulving E, Heinze H-J. Human hippocampal and parahippocampal activity during visual associative recognition memory for spatial and nonspatial stimulus configurations. Journal of Neuroscience. 2003; 23:9439–9444. [PubMed: 14561873]

Eichenbaum H. Hippocampus: cognitive processes and neural representations that underlie declarative memory. Neuron. 2004; 44:109–120. [PubMed: 15450164]

Eichenbaum H, Otto T, Cohen NJ. Two functional components of the hippocampal memory system. Behavioral and Brain Sciences. 1994; 17:449–518.

Ekstrom AD, Bookheimer SY. Spatial and temporal episodic memory retrieval recruit dissociable functional networks in the human brain. Learning & Memory. 2007; 14:645–654. [PubMed: 17893237]

Ekstrom AD, Copara MS, Isham EA, Wang W.-c. Yonelinas AP. Dissociable networks involved in spatial and temporal order source retrieval. NeuroImage. 2011; 56:1803–1813. [PubMed: 21334445]

Estes, WK. An associative basis for coding and organization in memory. In: Melton, AW.; Martin, E., editors. Coding processes in human memory. V. H. Winston; Washington, D.C: 1972. p. 161-190.

Estes, WK. Memory for temporal information. In: Michon, JA.; Jackson, J., editors. Time, mind and behavior. Springer-Verlag; Berlin: 1985. p. 151-168.

Fletcher PC, Frith CD, Baker SC, Shallice T, Frackowiak RSJ, Dolan RJ. The mind’s eye—precuneus activation in memory-related imagery. NeuroImage. 1995; 2:195–200. [PubMed: 9343602]

Fletcher PC, Shallice T, Frith CD, Frackowiak RS, Dolan RJ. Brain activity during memory retrieval. The influence of imagery and semantic cueing. Brain. 1996; 119:1587–1596. [PubMed: 8931582]

Friedman WJ. A follow-up to “scale effects in memory for the time of events”: the earthquake study. Memory & Cognition. 1987; 15:518–520. [PubMed: 3695946]

Friedman WJ. Memory for the time of past events. Psychological Bulletin. 1993; 113:44–66.

Friedman, WJ. The psychology of learning and motivation. Medin, DL., editor. Vol. Vol. 35. Academic Press; San Diego: 1996. p. 1-41.

Friedman, WJ. Time and memory: issues in philosophy and psychology. Hoerl, C.; McCormack, T., editors. Oxford University Press; Oxford: England: 2001. p. 139-167.

Friedman WJ. Time in autobiographical memory. Social Cognition. 2004; 22:591–605.

Friedman WJ, Wilkins A. Scale effects in memory for the time of events. Memory & Cognition. 1985; 13:168–175. [PubMed: 4033419]

Friston KJ, Penny W, Phillips C, Kiebel S, Hinton G, Ashburner J. Classical and Bayesian inference in neuroimaging: theory. NeuroImage. 2002; 16:465–483. [PubMed: 12030832]

Fujii T, Suzuki M, Okuda J, Ohtake H, Tanji K, Yamaguchi K, Itoh M, Yamadori A. Neural correlates of context memory with real-world events. NeuroImage. 2004; 21:1596–1603. [PubMed: 15050583]

Giovanello KS, Schnyer DM, Verfaellie M. A critical role for the anterior hippocampus in relational memory: evidence from an fMRI study comparing associative and item recognition. Hippocampus. 2004; 14:5–8. [PubMed: 15058477]

Gold JJ, Smith CN, Bayley PJ, Shrager Y, Brewer JB, Stark CEL, Hopkins RO, Squire LR. Item memory, source memory, and the medial temporal lobe: concordant findings from fMRI and memory-impaired patients. Proceedings of the National Academy of Sciences. 2006; 103:9351–9356.

Grasby PM, Frith CD, Friston KJ, Bench C, Frackowiak RS, Dolan RJ. Functional mapping of brain areas implicated in auditory-verbal memory function. Brain. 1993; 116:1–20. [PubMed: 8453452]

Harrison A, Jolicoeur P, Marois R. "What" and "where" in the intraparietal sulcus: an fMRI study of object identity and location in visual short-term memory. Cerebral Cortex. 2010; 20:2478–2485. [PubMed: 20100899]

Hassabis D, Kumaran D, Maguire EA. Using imagination to understand the neural basis of episodic memory. Journal of Neuroscience. 2007; 27:14365–14374. [PubMed: 18160644]

Hassabis D, Kumaran D, Vann SD, Maguire EA. Patients with hippocampal amnesia cannot imagine new experiences. Proceedings of the National Academy of Sciences. 2007; 104:1726–1731.

Hasson U, Furman O, Clark D, Dudai Y, Davahi L. Enhanced inter-subject correlations during movie viewing correlate with successful episodic encoding. Neuron. 2008; 57:452–462. [PubMed: 18255037]

Hayama HR, Rugg MD. Right dorsolateral prefrontal cortex is engaged during post-retrieval processing of both episodic and semantic information. Neuropsychologia. 2009; 47:2409–2416. [PubMed: 19383503]

Hayes SM, Ryan L, Schnyer DM, Nadel L. An fMRI study of episodic memory: retrieval of object, spatial, and temporal information. Behavioral Neuroscience. 2004; 118:885–896. [PubMed: 15506871]

Henson RN, Rugg MD, Shallice T, Josephs O, Dolan RJ. Recollection and familiarity in recognition memory: an event-related functional magnetic resonance imaging study. Journal of Neuroscience. 1999; 19:3962–3972. [PubMed: 10234026]

Hutchinson JB, Uncapher MR, Wagner AD. Posterior parietal cortex and episodic retrieval: convergent and divergent effects of attention and memory. Learning & Memory. 2009; 16:343–356. [PubMed: 19470649]

Huttenlocher J, Hedges L, Prohaska V. Hierarchical organization in ordered domains: estimating the dates of events. Psychological Review. 1988; 95:471–484.

Iglói K, Doeller CF, Berthoz A, Rondi-Reig L, Burgess N. Lateralized human hippocampal activity predicts navigation based on sequence or place memory. Proceedings of the National Academy of Sciences. 2010; 107:14466–14471.

Ishai A, Haxby JV, Ungerleider LG. Visual imagery of famous faces: effects of memory and attention revealed by fMRI. NeuroImage. 2002; 17:1729–1741. [PubMed: 12498747]

Kahn I, Davachi L, Wagner AD. Functional-neuroanatomic correlates of recollection: implications for models of recognition memory. The Journal of Neuroscience. 2004; 24:4172–4180. [PubMed: 15115812]

King JA, Hartley T, Spiers HJ, Maguire EA, Burgess N. Anterior prefrontal involvement in episodic retrieval reflects contextual interference. NeuroImage. 2005; 28:256–267. [PubMed: 16027012]

Konishi S, Uchida I, Okuaki T, Machida T, Shirouzu I, Miyashita Y. Neural correlates of recency judgment. The Journal of Neuroscience. 2002; 22:9549–9555. [PubMed: 12417679]

Konkel A, Warren DE, Duff MC, Tranel D, Cohen NJ. Hippocampal amnesia impairs all manner of relational memory. Frontiers in Human Neuroscience. 2008:2.

Kumaran D, Maguire EA. The dynamics of hippocampal activation during encoding of overlapping sequences. Neuron. 2006; 49:617–629. [PubMed: 16476669]

Kurby CA, Zacks JM. Segmentation in the perception and memory of events. Trends in Cognitive Sciences. 2008; 12:72–79. [PubMed: 18178125]

Laming D. Testing the idea of distinct storage mechanisms in memory. International Journal of Psychology. 1999; 34:419–426.

Lehn H, Steffenach H-A, van Strien NM, Veltman DJ, Witter MP, Håberg AK. Specific role of the human hippocampus in recall of temporal sequences. Journal of Neuroscience. 2009; 29:3475–3484. [PubMed: 19295153]

Lepsien J, Nobre AC. Attentional modulation of object representations in working memory. Cerebral Cortex. 2007; 17:2072–2083. [PubMed: 17099066]

Linton, M. Ways of searching and the contents of memory. In: Rubin, DC., editor. Autobiographical memory. Cambridge University Press; New York: 1986. p. 51-67.

Lundstrom BN, Ingvar M, Petersson KM. The role of precuneus and left inferior frontal cortex during source memory episodic retrieval. NeuroImage. 2005; 27:824–834. [PubMed: 15982902]

Magen H, Emmanouil T-A, McMains SA, Kastner S, Treisman A. Attentional demands predict short-term memory load response in posterior parietal cortex. Neuropsychologia. 2009; 47:1790–1798. [PubMed: 19428411]

Maguire EA, Vargha-Khadem F, Mishkin M. The effects of bilateral hippocampal damage on fMRI regional activations and interactions during memory retrieval. Brain. 2001; 124:1156–1170. [PubMed: 11353732]

McAndrews MP, Milner B. The frontal cortex and memory for temporal order. Neuropsychologia. 1991; 29:849–859. [PubMed: 1944882]

Mendelsohn A, Chalamish Y, Solomonovich A, Dudai Y. Mesmerizing memories: brain substrates of episodic memory suppression in posthypnotic amnesia. Neuron. 2008; 57:159–170. [PubMed: 18184572]

Mendelsohn A, Furman O, Dudai Y. Signatures of memory: brain coactivations during retrieval distinguish correct from incorrect recollection. Frontiers in behavioral neuroscience. 2010; 4:1–12. [PubMed: 20126432]

Milner B, Corsi P, Leonard G. Frontal-lobe contribution to recency judgements. Neuropsychologia. 1991; 29:601–618. [PubMed: 1944864]

Milton F, Muhlert N, Butler CR, Smith A, Benattayallah A, Zeman AZ. An fMRI study of long-term everyday memory using SenseCam. Memory. 2011; 19:733–744. [PubMed: 21409716]

Montaldi D, Spencer TJ, Roberts N, Mayes AR. The neural system that mediates familiarity memory. Hippocampus. 2006; 16:504–520. [PubMed: 16634088]

Nairne JS. The loss of positional certainty in long-term memory. Psychological Science. 1992; 3:199–202.

Neath I, Crowder RG. Schedules of presentation and temporal distinctiveness in human memory. Journal of Experimental Psychology: Learning, Memory, and Cognition. 1990; 16:316–327.

Neath I, Crowder RG. Distinctiveness and very short-term serial position. Memory. 1996; 4:225–242. [PubMed: 8735609]

Neggers SFW, Van der Lubbe RHJ, Ramsey NF, Postma A. Interactions between ego- and allocentric neuronal representations of space. NeuroImage. 2006; 31:320–331. [PubMed: 16473025]

Neil B. Spatial memory: how egocentric and allocentric combine. Trends in Cognitive Sciences. 2006; 10:551–557. [PubMed: 17071127]

Nichols T, Brett M, Andersson J, Wager T, Poline J-B. Valid conjunction inference with the minimum statistic. NeuroImage. 2005; 25:653–660. [PubMed: 15808966]

Nyberg L, McIntosh A, Cabeza R, Habib R, Houle S, Tulving E. General and specific brain regions involved in encoding and retrieval of events: what, where, and when. Proceedings of the National Academy of Sciences of the United States of America. 1996; 93:11280–11285. [PubMed: 8855347]

Nyberg L, Persson J, Habib R, Tulving E, McIntosh AR, Cabeza R, Houle S. Large scale neurocognitive networks underlying episodic memory. Journal of Cognitive Neuroscience. 2000; 12:163–173. [PubMed: 10769313]

Penny, W.; Holmes, A. Random effects analysis. In: Frackowiak, RS.; Friston, KJ.; Frith, CD.; Dolan, RJ.; Price, CJ.; Zeki, S.; Ashburner, J.; Penny, W., editors. Human brain function. 2nd ed. Elsevier; San Diego, CA: 2004.

Pollmann S, Yves von Cramon D. Object working memory and visuospatial processing: functional neuroanatomy analyzed by event-related fMRI. Experimental Brain Research. 2000; 133:12–22.

Preston AR, Shrager Y, Dudukovic NM, Gabrieli JDE. Hippocampal contribution to the novel use of relational information in declarative memory. Hippocampus. 2004; 14:148–152. [PubMed: 15098720]

Price CJ, Friston KJ. Cognitive conjunction: a new approach to brain activation experiments. NeuroImage. 1997; 5:261–270. [PubMed: 9345555]

Prince SE, Daselaar SM, Cabeza R. Neural correlates of relational memory: successful encoding and retrieval of semantic and perceptual associations. The Journal of Neuroscience. 2005; 25:1203–1210. [PubMed: 15689557]

Roland, PE.; Seitz, RJ. Mapping of learning and memory functions in the human brain. In: Ottoson, D.; Rostene, W., editors. Visualization of brain functions. Macmillan Press; Basingstoke: 1989. p. 141-151.

Ross RS, Brown TI, Stern CE. The retrieval of learned sequences engages the hippocampus: evidence from fMRI. Hippocampus. 2009; 19:790–799. [PubMed: 19219919]

Rugg MD, Fletcher PC, Frith CD, Frackowiak RSJ, Dolan RJ. Differential activation of the prefrontal cortex in successful and unsuccessful memory retrieval. Brain. 1996; 119:2073–2083. [PubMed: 9010011]

Rugg MD, Henson RNA, Robb WGK. Neural correlates of retrieval processing in the prefrontal cortex during recognition and exclusion tasks. Neuropsychologia. 2003; 41:40–52. [PubMed: 12427564]

Rugg MD, Otten LJ, Henson RN. The neural basis of episodic memory: evidence from functional neuroimaging. Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences. 2002; 357:1097–1110.

Rugg MD, Wilding EL. Retrieval processing and episodic memory. Trends in Cognitive Sciences. 2000; 4:108–115. [PubMed: 10689345]

Ryan L, Nadel L, Keil K, Putnam K, Schnyer D, Trouard T, Moscovitch M. Hippocampal complex and retrieval of recent and very remote autobiographical memories: evidence from functional magnetic resonance imaging in neurologically intact people. Hippocampus. 2001; 11:707–714. [PubMed: 11811665]

Schott BH, Sellner DB, Lauer C-J, Habib R, Frey JU, Guderian S, Heinze H-J, Düzel E. Activation of midbrain structures by associative novelty and the formation of explicit memory in humans. Learning & Memory. 2004; 11:383–387. [PubMed: 15254215]

Sestieri C, Shulman GL, Corbetta M. Attention to memory and the environment: functional specialization and dynamic competition in human posterior parietal cortex. Journal of Neuroscience. 2010; 30:8445–8456. [PubMed: 20573892]

Shimamura AP. Hierarchical relational binding in the medial temporal lobe: the strong get stronger. Hippocampus. 2010; 20:1206–1216. [PubMed: 20824723]

Shimamura AP, Janowsky JS, Squire LR. Memory for the temporal order of events in patients with frontal lobe lesions and amnesic patients. Neuropsychologia. 1990; 28:803–813. [PubMed: 2247207]

Skowronski J, Walker WR, Betz A. Ordering our world: an examination of time in autobiographical memory. Memory. 2003; 11:247–260. [PubMed: 12908674]

Speer NK, Zacks JM, Reynolds JR. Human brain activity time-locked to narrative event boundaries. Psychological Science. 2007; 18:449–455. [PubMed: 17576286]

St. Jacques P, Rubin DC, LaBar KS, Cabeza R. The short and long of it: neural correlates of temporal-order memory for autobiographical events. Journal of Cognitive Neuroscience. 2008; 20:1327–1341. [PubMed: 18284345]

Staresina BP, Davachi L. Mind the gap: binding experiences across space and time in the human hippocampus. Neuron. 2009; 63:267–276. [PubMed: 19640484]

Strange BA, Hurlemann R, Duggins A, Heinze H-J, Dolan RJ. Dissociating intentional learning from relative novelty responses in the medial temporal lobe. NeuroImage. 2005; 25:51–62. [PubMed: 15734343]

Summerfield JJ, Lepsien J, Gitelman DR, Mesulam MM, Nobre AC. Orienting attention based on long-term memory experience. Neuron. 2006; 49:905–916. [PubMed: 16543137]

Suzuki M, Fujii T, Tsukiura T, Okuda J, Umetsu A, Nagasaka T, Mugikura S, Yanagawa I, Takahashi S, Yamadori A. Neural basis of temporal context memory: a functional MRI study. NeuroImage. 2002; 17:1790–1796. [PubMed: 12498752]

Swallow KM, Barch DM, Head D, Maley CJ, Holder D, Zacks JM. Changes in events alter how people remember recent information. Journal of Cognitive Neuroscience. 2011; 23:1052–1064. [PubMed: 20521850]

Swallow KM, Zacks JM, Abrams RA. Event boundaries in perception affect memory encoding and updating. Journal of Experimental Psychology: General. 2009; 138:236–257. [PubMed: 19397382]

Tulving, E. Organization of memory. Tulving, E.; Donaldson, W., editors. Academic Press; New York: 1972. p. 381-403.

Tulving E. Memory and consciousness. Canadian Psychology. 1985; 26:1–12.

Vilberg KL, Rugg MD. Memory retrieval and the parietal cortex: a review of evidence from a dual-process perspective. Neuropsychologia. 2008; 46:1787–1799. [PubMed: 18343462]

Wagner AR, Shannon B, Kahn I, Buckner R. Parietal lobe contributions to episodic memory retrieval. Trends in Cognitive Sciences. 2005; 9:445–453. [PubMed: 16054861]

Wilding EL. Separating retrieval strategies from retrieval success: an event-related potential study of source memory. Neuropsychologia. 1999; 37:441–454. [PubMed: 10215091]

Worsley KJ, Marrett S, Neelin P, Vandal AC, Friston KJ, Evans AC. A unified statistical approach for determining significant signals in images of cerebral activation. Human Brain Mapping. 1996; 4:58–73. [PubMed: 20408186]

Yntema DB, Trask FP. Recall as a search process. Journal of Verbal Learning and Verbal Behavior. 1963; 2:65–74.

Zacks JM, Braver TS, Sheridan MA, Donaldson DI, Snyder AZ, Ollinger JM, Buckner RL, Raichle ME. Human brain activity time-locked to perceptual event boundaries. Nature Neuroscience. 2001; 4:651–655.

Zacks JM, Speer NK, Swallow KM, Maley CJ. The brain's cutting-room floor: segmentation of narrative cinema. Frontiers in Human Neuroscience. 2010:4. [PubMed: 20198130]

Zacks JM, Tversky B, Iyer G. Perceiving, remembering, and communicating structure in events. Journal of Experimental Psychology: General. 2001; 130:29–58. [PubMed: 11293458]

Zorrilla LT, Aguirre GK, Zarahn E, Cannon TD, D'Esposito M. Activation of the prefrontal cortex during judgments of recency: a functional MRI study. NeuroReport. 1996; 7:2803–2806. [PubMed: 8981471]

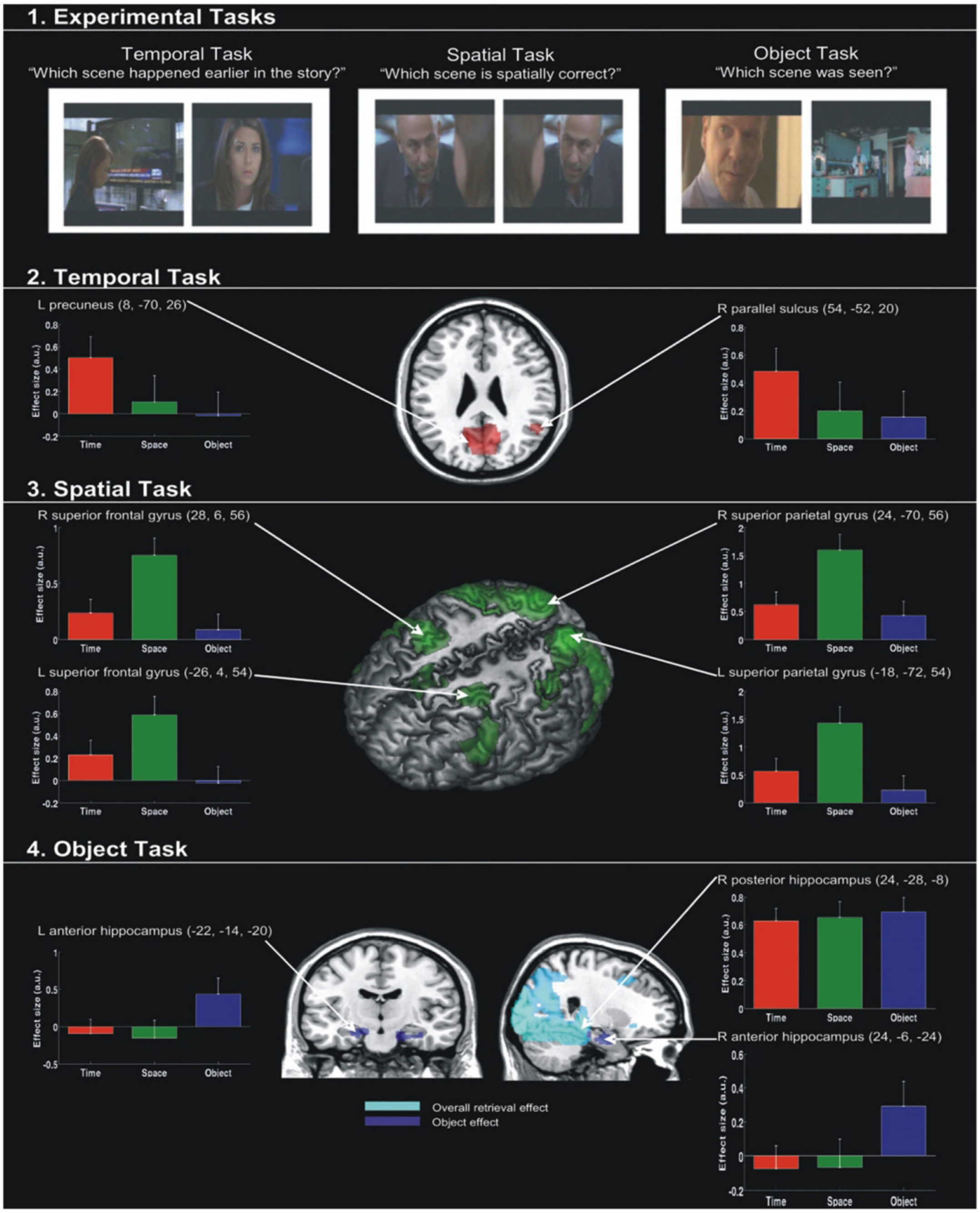

Fig. 1. Depictions of experimental tasks, clusters of activations and signal plots for the Temporal, Spatial and Object retrieval tasks.

Panel 1: Exemplary trials of three retrieval tasks and corresponding instructions for subjects. *Panel* 2: Clusters of activation (in red) and signal plots for the precuneus and the right angular gyrus that activated selectively in the Temporal task. *Panel* 3: Clusters of activation (in green) and signal plots for the dorsal fronto-parietal network observed in the Spatial task. *Panel* 4: Clusters of activation observed in the Object task (in blue) and for the overall effect of retrieval across the 3 tasks (in cyan), with corresponding signal plots for anterior and posterior hippocampi. Statistical thresholds were set to *p*-FWE=0.05, whole brain corrected at cluster level (cluster size estimated at p-unc.=0.001). Effect sizes correspond to “activation vs. rest”, in arbitrary units (a.u.). Error bars: Standard error of the mean.

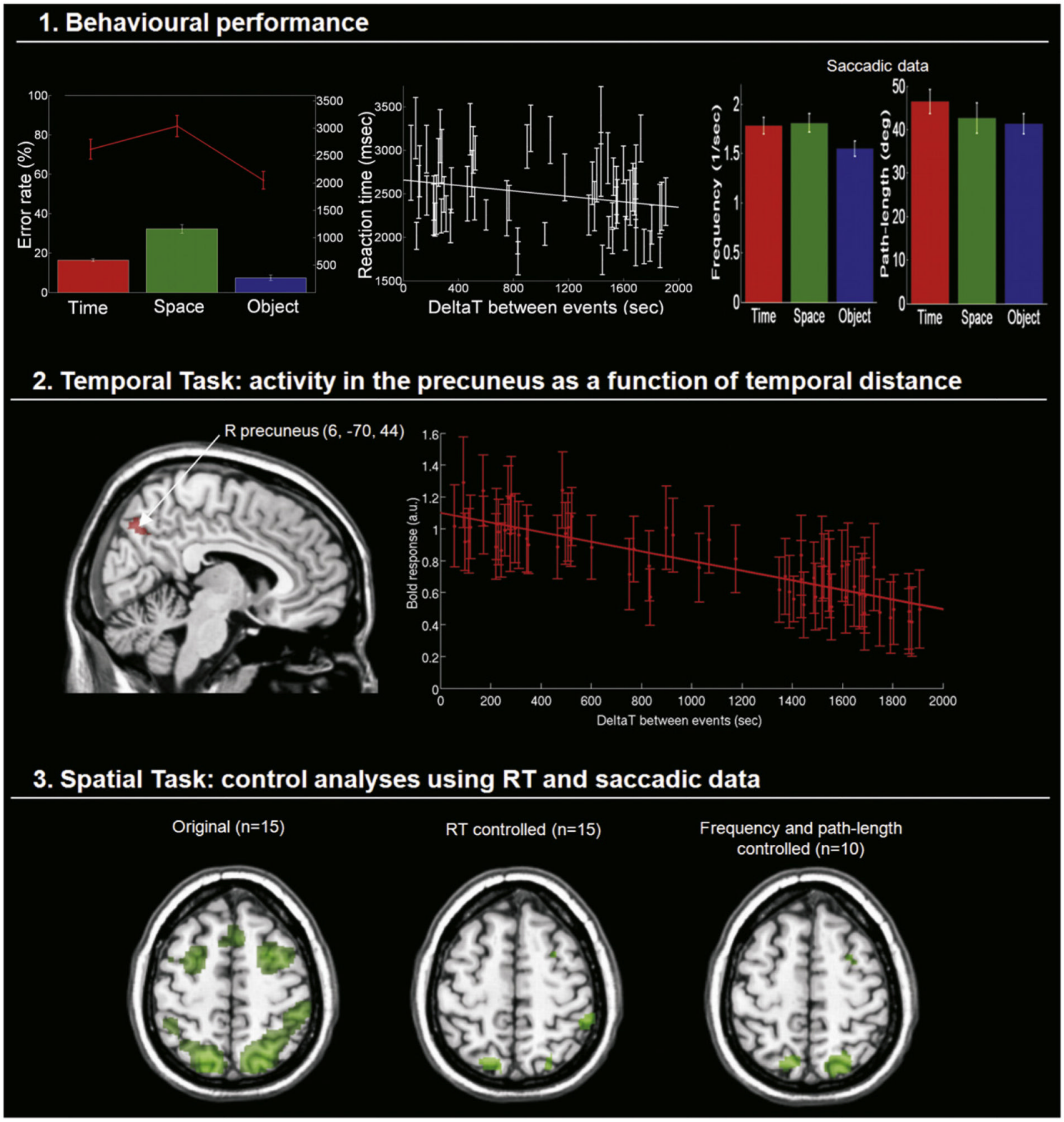

Fig. 2. Behavioural data, temporally modulated activity in the precuneus, and control analyses in the Spatial task

Panel 1: (a) Mean error rates (%) and reaction times (ms) across the three retrieval tasks; (b) reaction times plotted against temporal distance (Delta *T*) for high consistency trials of the Temporal task, showing a significant negative correlation (p=0.045); (c) Saccadic data obtained in 10 subjects, histograms depicting the median saccadic frequencies (1/s; on the left) and mean saccadic path-lengths (deg; on the right) executed during the 5-s trials across tasks. *Panel* 2: Cluster of activation (in red) in the right precuneus modulated as a function of temporal distance (x, y, z=6, −70, 44; p-FWE<0.007), with the corresponding BOLD response (a.u.) plotted against Delta *T*. The activation data for this plot were extracted from subject-specific fitted-responses (first level analyses), 5 scans after the onset of the

Temporal trials. *Panel* 3: Clusters of activation in the dorsal fronto-parietal network that activated selectively in the Spatial task in: (a) the main analysis; (b) control analysis accounting for differences in task difficulty between conditions (reaction times as a covariate of no interest); and (c) control analysis accounting for differential patterns of eye movements between conditions (saccadic frequency and path-lengths, in a sub-group of 10 subjects). Activations are displayed at *p*-unc.=0.001. Error bars: Standard error of the mean.

Table 1
Common activation across the three retrieval tasks.

Brain region	**Cluster**		**Voxel**	
	k	***p*-FWE**	***Z***	***x y z***
Occipital pole, L	37,502	<0.001	>8	−16, −100, 4
Occipital pole, R			>8	18, −102, 10
Dorsal occipital cortex, L			>8	−22, −96, 12
Dorsal occipital cortex, R			>8	30, −92, 24
Lateral occipital cortex, L			>8	−38, −88, 10
Lateral occipital cortex, R			>8	48, −74, −8
Ventral occipital cortex, L			>8	−40, −76, −18
Ventral occipital cortex, R			>8	38, −58, −16
Posterior hippocampus, L			>8	−22, −28, −6
Posterior hippocampus, R			>8	24, −28, −8
Intraparietal sulcus, L			5.01	−24, −64, 46
Intraparietal sulcus, R			6.15	32, −56, 52
Precuneus, R			5.06	8, −58, 50
Medial superior frontal gyrus, R	811	<0.001	7.38	8, 16, 56
Precentral gyrus, L	2,403	<0.001	7.31	−40, −20, 60
Superior frontal gyrus, R	5,632	<0.001	7.12	40, 0, 54
Middle frontal gyrus, R			7.16	46, 24, 22
Inferior frontal gyrus, R			6.34	48, 26, 6
Anterior insula, R			6.38	36, 24, −6
Middle frontal gyrus, L	996	<0.001	6.18	−46, 20, 24
Anterior insula, L	322	0.009	5.44	−34, 22, −4

Areas activated during all three retrieval conditions vs. rest (null-conjunction: [T>0] and [S>0] and [O>0]; p-FWE<0.05, whole-brain corrected at cluster level, cluster size estimated at p-unc.=0.001; k=number of voxels).

Table 2
Direct comparisons between retrieval conditions.

Contrast	Brain region	Cluster		Voxel	
		k	*p*-FEW	*Z*	*x y z*
T>(***S***+***O***)/2	Precuneus, R	2635	<0.001	5.45	14, −60, 28
	Precuneus, L			5.14	−8, −70, 26
	Angular gyrus, R	343	0.0067	4.42	54, −52, 20
S>(***O***+***T***)/2	Superior parietal gyrus, L	4427	<0.001	7.10	−18, −72, 54
	Intraparietal sulcus, L			5.88	−38, −42, 40
	Dorsal occipital cortex, L			5.28	−30, −86, 32
	Lateral occipital cortex, L			4.80	−54, −66, −2
	Superior parietal gyrus, R	6292	<0.001	6.46	24, −70, 56
	Intraparietal sulcus, R			6.03	44, −40, 46
	Dorsal occipital cortex, R			6.20	42, −80, 26
	Lateral occipital cortex, R			5.61	58, −58, −8
	Superior frontal gyrus, R	2117	<0.001	6.39	28, 6, 56
	Middle frontal gyrus, R			5.60	52, 10, 24
	Middle frontal gyrus, L	1619	<0.001	5.48	−46, 2, 32
	Superior frontal gyrus, L			5.29	−26, 4, 54
	Medial sup. frontal gyrus, R	401	0.003	5.02	4, 18, 54
	Inferior lingual gyrus, R	290	0.014	4.66	32, −42, −14
	Inferior lingual gyrus, L	203	0.056	4.28	−30, −46, −16
	Anterior insula, L	209	0.051	4.28	−36, 20, −4
O>(***S***+***T***)/2	Hippocampus, L	212	0.048	4.34	−22, −14, −20
	Hippocampus, R	469	0.001	4.59	24, −6, −24

T-contrasts compared each condition vs. the mean of the other two conditions (e.g., [*T*>(*S*+*O*)/2]), each was inclusively masked with 3 additional contrasts, namely activation for the critical condition vs. rest (e.g., [*T*>0]) and activation for the critical condition vs. each of the two other conditions (e.g., [*T*>*S*] and [*T*>*O*]). The threshold of the contrasts was set to *p*-FWE=0.05, whole-brain corrected at cluster level, cluster size estimated at *p*-unc.=0.001; the threshold of additional masking contrasts was set to *p*-unc.=0.05; *k*=number of voxels.

Table 3
Additional control analyses for the Spatial task.

Brain region	**RTs controlled**		**Saccadic data controlled**	
	Z	***x y z***	***Z***	***x y z***
Superior parietal gyrus, L	4.46	−18, −72, 54	4.10	−12, −68, 58
Superior parietal gyrus, R	3.81	28, −66, 62	4.51	22, −72, 60
Intraparietal sulcus, L	3.81	−44, −44, 46	3.69	−38, −42, 38
Intraparietal sulcus, R	4.25	52, −42, 58	–	–
Middle frontal gyrus, L	3.44	−46, 0, 28		
Middle frontal gyrus, R	3.34	52, 10, 28		
Superior frontal gyrus, L	–	–	3.23	−26, 0, 52
Superior frontal gyrus, R	3.64	28, 6, 54	3.85	30, 4, 58
Lateral occipital cortex, R	3.26	58, −58, −10	3.75	62, −56, −2

Comparisons between the Spatial condition vs. the mean of the other two conditions ($[S>(T+O)/2]$, inclusively masked with $[S>0]$, $[S>T]$ and $[S>O]$) controlled for differential RTs and eye movements between conditions (cf. also Figure 2.1). The first control analysis included subject- and condition- specific RTs as a covariate to account for differences in task difficulty ($n=15$). The second control analysis included subject- and condition-specific saccadic frequency and path-length as additional covariates to exclude any contribution of differential patterns of eye-movements ($n=10$). For these additional analyses, we report voxels at p-unc.=0.001 that are located within the clusters showing space-specific activation in the main analysis (cf. Table 2).

Table 4

Probabilistic localisation of the voxels belonging to the left and right hippocampal activation clusters (Object task).

Cytoarchitectonic area	Current study	
	Hippocampus, L	Hippocampus, R
Hippocampus, CA	42.8 (12.2)	17.8 (10.4)
Hippocampus, SUB	4.7 (2.0)	14.4 (12.8)
Hippocampus, EC	Nil	16.7 (11.8)
Amygdala, LB	27.8 (18.9)	20.3 (28.2)
Amygdala, SF	9.1 (10.0)	Nil

For the two clusters (cf. Figure 1.4, in blue), the table reports the percentage of voxels located within specific cytoarchitectonic areas of the medial temporal cortex: Cornu ammonis (CA), the subicular complex, the entorhinal cortices (EC), the laterobasal (LB) and superficial (SF) nuclear groups of the amygdala (Amunts et al., 2005). For each of the cytoarchitectonic areas, the table also reports the proportion of the area that was activated during the current Object retrieval task (in parenthesis).