Coherence and congruency mediate medial temporal and medial prefrontal activity during event construction☆

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A B S T R A C T

The precise roles of the hippocampus (HPC) and medial prefrontal cortex (mPFC) in initially constructing imagined events remains unclear. HPC activity during imagination may be modulated by mnemonic load, given its role in working memory for complex materials, and/or by the semantic relatedness (i.e. congruency) between items and their context. MPFC activation may track with congruency or mnemonic load, given the role of ventral mPFC in schema processing and the dorsal mPFC in working memory for social information. Sixteen healthy adults (*M* age = 22.3) underwent an event construction task, wherein participants were provided with a context and item words and imagined an event, forming as many inter-item associations as possible among the items. The stimuli varied by set size and by normatively-defined congruence (normative congruency) to explore their effects on HPC and mPFC activity and functional connectivity. We observed HPC connectivity during event construction in general, whereas dorsal mPFC connectivity occurred during imagining only at higher set sizes. Moreover, anterior hippocampal activity correlated positively with increasing coherence between items during imagining, suggesting that the anterior HPC is sensitive to the relational demands of constructing a novel event. Para-hippocampal, hippocampal, temporal pole, and mPFC activity tracked only with individual differences in subjective ratings of congruency of imagined events, which may contribute to construction by retrieving existing schema-related information. Collectively, these findings provide new insights into the factors that modulate HPC and mPFC activity when constructing mental simulations.

1. Introduction

The uniqueness of imagination as a cognitive task lies in the element of novelty: given that imagined events are not a replay of existing memories, some aspect of construction or reconfiguration of details is required to construct a novel mental representation. In addition, to be coherent or meaningful, the imagined event must adhere to schemas appropriate for the event. The hippocampus (HPC) and medial prefrontal cortex (mPFC), two structures implicated in episodic memory and schema representation, along with their functional connections, have been most implicated in event or scene construction that underlies imagination. Here we examine the effects of semantic congruency, memory load, and inter-item relations or coherence, to elucidate the nature of the contributions of mPFC, HPC and other structures to event construction.

Recent evidence suggests that in addition to its roles in retrieval of

autobiographical information, and subsequent encoding of imagined events, the hippocampus (HPC) is also implicated in the constructive aspects of imagination (i.e. *event or scene construction*) (see Addis and Schacter, 2012; Moscovitch, 2008; Schacter et al., 2012; Zeidman and Maguire, 2016). As construction requires (re)-combining information in novel ways, there are several related HPC-dependent processes that may contribute to construction, including the ability to make inferences across sets of related stimuli during reasoning (i.e. transitive inference) and during encoding (Zeithamova and Preston, 2010), and forming a coherent spatial representation for navigation (Johnson and Redish, 2007; Spiers and Maguire, 2007). Taken together, it seems that the HPC is implicated when subjects process a sufficiently complex mental representation that involves explicit, unique relational associations amongst the items (Moscovitch et al., 2016).

Yet, the precise nature of hippocampal involvement during the construction aspects of imagination remains unclear. In addition, given

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recent hippocampal models that draw functional distinctions between anterior and posterior HPC (Poppenk et al., 2013; Robin and Moscovitch, 2017), it is also unclear to what extent subregions of the HPC have unique and dissociable contributions to event and scene construction. HPC activation during construction shows inconsistent modulation by increasing mnemonic load (Summerfield et al., 2010), whereas imagining specific vs. general future events elicits activity in the right anterior HPC (Addis et al., 2011). Similarly, studies of hippocampal lesion patients have shown mixed evidence of construction deficits during future simulation, with some studies showing that amnesic patients demonstrate impaired construction of coherent scenes (Hassabis et al., 2007), complex narratives (Rosenbaum et al., 2009), and picture descriptions ((Race et al., 2011), whereas other studies do not find such deficits (Squire et al., 2010).

In a related vein, the medial prefrontal cortex (mPFC) is also frequently elicited during event construction. Much of this work has indicated the mPFC is sensitive to various parameters during imagination, including whether the event is self-referential (Craik et al., 1998; D'Argembeau et al., 2010), the amount of detail (Addis et al., 2011), and temporal distance (Abraham et al., 2008). Patient studies indicate that ventral mPFC atrophy correlates with impoverished imagined events in people with Alzheimer's disease and fronto-temporal dementia, leading to the suggestion that the mPFC acts in concert with neural regions involved in semantic memory to provide a semantic "scaffold" on which other details are built (Irish and Piguet, 2013). It remains unclear, however, what contribution the mPFC makes during the initial event construction.

1.1. Semantic congruency as a modulator of event construction

Clues as to the HPC and mPFC contributions to event construction may come from the nature of imagining itself. Given that imagining a novel event is an open-ended task, the possible outcomes one may construct inevitably vary along several dimensions. One important dimension is the congruency between items of a mental representation to pre-existing knowledge (i.e. congruency): To the extent that an imagined event is coherent and not a mix of unrelated thoughts, it must relate in varying degrees to pre-existing knowledge. Congruency is also interesting because it can be measured both by averaged normative ratings of semantic association strength between items (i.e. normative congruency) and by individual ratings (i.e. subjective congruency), which may be partially distinct: a set of highly semantically-related items may be judged to be congruent on average, but can nonetheless vary across individuals. Regarding the mPFC, there is consistent evidence that both ventral and dorsal mPFC contribute to event construction and may also be sensitive to aspects of congruency (Abraham et al., 2008; Van Kesteren, Ruiter, Fernández and Henson, 2012).

Whether the HPC is sensitive to the congruency of an imagined event is not clear. Discrepancies in the literature as to whether the hippocampus is implicated in constructing imagined events have been interpreted as resulting, in part, from to the extent to which various tasks draw on congruent, semantic or novel information (Cooper et al., 2011; D'Angelo et al., 2016; Kwan et al., 2010; Moses et al., 2008; Race et al., 2013; Ryan et al., 2013). No studies to date, however, have tested these ideas directly.

1.2. Memory load and coherence as modulators of event construction

Another factor that may modulate HPC and mPFC involvement in event construction is the amount of information initially present. Recent evidence suggests that the HPC is important for working memory for novel and/or complex stimuli (Hannula et al., 2006; Olson et al., 2006; Ranganath and Blumenfeld, 2005; Rose et al., 2012) and for scene construction (Summerfield et al., 2010). Specific to event construction, Romero and Moscovitch (2012) found that amnesic patients' ability to construct novel events was impaired relative to that of controls, with the

degree of impairment increasing with set size: subjects were given 3–6 item words along with a context word, and had to imagine an event, making as many explicit inter-item relations as possible. Whereas healthy controls could construct increasingly complex representations when given more items, patients' performance reached asymptote after only a few items. Moreover, recent work suggests that the amount of perceptual detail retrieved during episodic recall primarily involves the posterior HPC (Moscovitch et al., 2016; St-Laurent et al., 2016). Based on these findings, one would predict hippocampal activity during event construction would increase as a function of mnemonic load: that is, greater hippocampal involvement when constructing events with more items.

There are few studies directly examining the effect of mnemonic load on mPFC activity during autobiographical memory or event construction. Dorsal mPFC shows mnemonic load-dependent increases in activity during a working memory task for social stimuli (Meyer et al., 2012), and there is also strong functional connectivity between dorsal mPFC and the most anterior lateral PFC (i.e. frontal poles), which show consistent load-dependent activity on working memory and reasoning tasks (Prabhakaran et al., 1997; Wendelken and Bunge, 2009). This raises the possibility of similar load-dependent effects in the dorsal mPFC during event construction tasks.

In addition to memory load, relatedness among the items to form an interconnected representation, what Hassabis et al. (2007) termed spatial coherence, also plays a crucial role in scene construction. Coherence was also found to modulate memory in the event construction task used by Romero and Moscovitch (2012), with greater coherence leading to better memory of the imagined event in controls. Patients, by contrast, showed low coherence and poor memory. Indeed, coherence may be enhanced by congruency, a prediction we are testing in the current study.

1.3. The current study: coherence, congruency and memory load as modulators HPC and mPFC activity during event construction

A shortcoming of most studies of scene/event construction is the use of open-ended cue-based paradigms, with participants being given a cue and imagining events as fully as possible, after which their responses are scored in terms of the number of details. Consequently, the relative construction performance depends largely on how much information is generated or recovered from long-term memory, making it difficult to tease apart the contribution of the HPC and surrounding medial temporal lobe structures to different aspects of future imagination independent of their role in memory retrieval. In addition, most studies attempting to identify processes that are special to constructing imaginative events, do not control for processes involved in maintaining and manipulating information in working memory which cut across other cognitive tasks. To date, the only study to directly address these issues using fMRI is Gaesser et al. (2013), who used a recombination paradigm whereby subjects either imagined items from a previous memory, or recalled a previously imagined event, and found different hippocampal regions that were implicated in retrieval, recombination, and subsequent memory of imagined events.

Thus, using univariate and functional connectivity analyses of fMRI data, we sought to determine how the HPC and mPFC are involved in constructing novel, non-personal events when limiting retrieval from long-term memory and controlling the effects of working memory. Doing so allowed us to ask how coherence, congruency, and memory load influence event construction, as well as to identify their neural correlates. In order to systematically examine the constructive component of imagining, we conducted an fMRI study using an existing event construction paradigm in which subjects were given a context and various item words, thereby minimizing the effects of retrieval from long term memory of the items that form the crux of the imagined event. Participants were asked to generate an event containing the target items, and to relate them explicitly to the context and to each other, to form a coherent representation (Romero and Moscovitch, 2012) (Fig. 1). Such a paradigm allows for the measurement of constructive ability and coherence, while
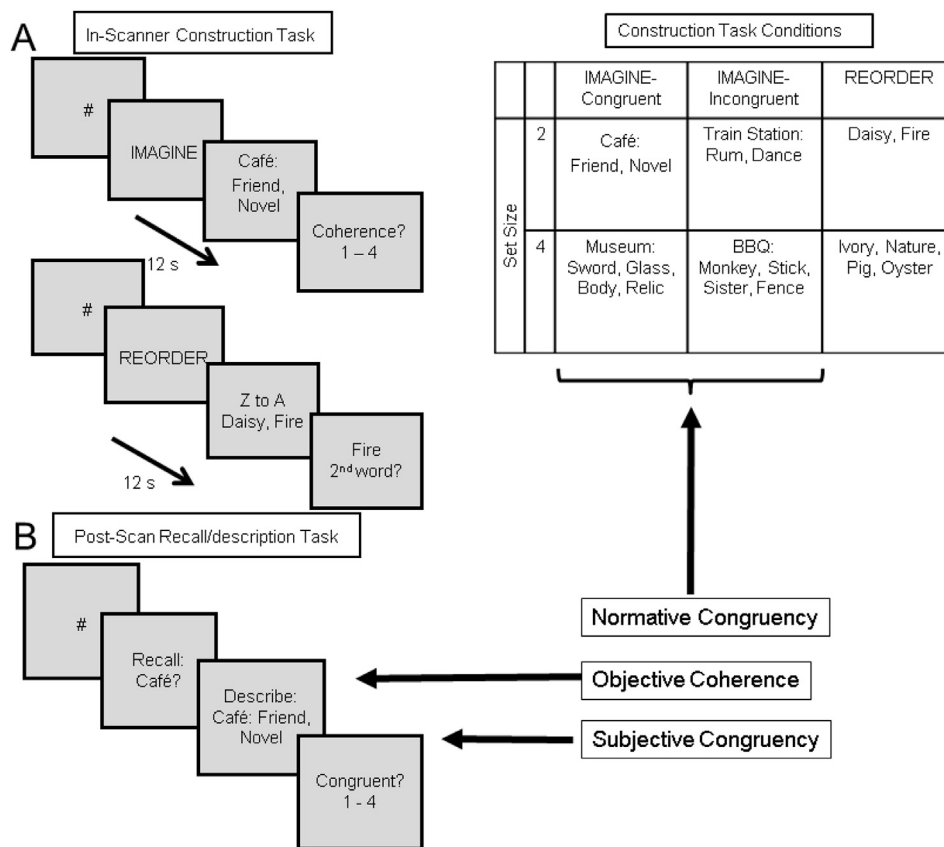
Fig. 1. A: Event construction task. In the scanner, subjects imagined events using the provided words, forming as many inter-relations as possible. Participants were given 2 or 4 words to manipulate set size, with those words being relatively congruent or incongruent based on previous normative ratings (Normative Congruency). They subsequently gave a subjective rating of the coherence of their imagined event. The control condition involved reordering words into reverse alphabetical order and being probed on the position of one of the words. **B:** Recall/description task. Outside the scanner, participants were shown the context word and were asked to recall the items. They were then shown the items and asked to describe what they had imagined. Responses were transcribed, and scored by multiple raters for the number of explicit inter-item relations (Objective Coherence). Subjects also rated how congruent their imagined event was (Subjective Congruency). These two scores were used for the behavioural PLS analyses.

decreasing retrieval demands from long-term memory. To measure coherence, we tallied the number of inter-item relations generated by subjects during event construction, which we refer to as *objective coherence*.

We explored the association between congruency and event construction-related brain activity in two ways: First, we experimentally-manipulated the congruency of the items with the context (i.e. congruent or incongruent) during the in-scanner event construction task, by using stimuli with previously-collected normative data (i.e. *normative congruency*). Second, outside the scanner, we collected subjects' ratings of how typical their imagined events were, which we use as a measure of *subjective congruency*.

To investigate the effect of memory load, we manipulated the number of items provided during the in-scanner task (set size: 2 or 4), in order to determine whether these factors mediate HPC and/or mPFC involvement in event construction. To control for the effects of maintaining and manipulating information in working memory, we added a condition in which participants completed a working memory task, in which 2 or 4 words had to be put in reverse alphabetical order and rehearsed until the end of the trial.

2. Methods and materials

2.1. Participants

Nineteen right-handed volunteers participated in the study. Three subjects had to be removed from analysis: two for excessive head movement, and one for extremely low performance, who could not recall any information pertaining to the task. The remaining 16 subjects (7 males, M age $= 22.3$, $SD = 4.16$) were analyzed in the study. All were native-English speakers, with no history of neurological or psychological illness. Prior to participating, all subjects gave informed consent in accordance with the Research Ethics Board at the University of Toronto

and were paid $45 for their participation.

2.2. Design and procedure

Subjects completed an imagining task (IMAGINE) similar to that of Romero and Moscovitch (2012). Subjects were shown a context word with 2 or 4 item words and instructed to imagine an event with those items in that context, relating the items explicitly in their mind as much as possible (Fig. 1a). In addition, the context-item pairing could be relatively congruent (e.g. 'tide' and 'sandal' paired with 'beach') or incongruent ('salad' and 'clown' paired with 'cruise ship'): these stimuli were chosen based on pilot testing where we obtained normative ratings of various context-item word pairings, which reflect how these stimuli sets are viewed on average [i.e. *normative congruency*; Incongruent-2 $= 3.27$ (0.71), Incongruent-4 $= 2.65$ (0.72). congruent-2 $= 4.3$ (0.62), congruent-4 $= 3.72$ (0.63) on a 1–5 Likert scale]. In the control condition, participants completed a working memory task (REORDER) in which they were only shown 2 or 4 words without a context word and had to reorder them in their mind in reverse alphabetical sequence (i.e. Z to A). As the task involved manipulation in working memory according to the word characteristics, there was no context word provided on each trial, and so it was not possible to manipulate the congruency of the items in the control condition. Thus, the experiment was comprised of a 3×2 design, with condition (IMAGINE-incongruent, IMAGINE-congruent, REORDER) and set size (2, 4) as within-subjects variables.

Prior to the fMRI scanning session, subjects completed a practice session, in which the task instructions were specified, and two examples given. Subjects completed one block of 20 trials, 10 IMAGINE and 10 REORDER trials. The experimenter was present during the practice session to answer any questions about the task.

During the scanning session, on each trial, a task cue appeared for 1.25 s indicating the task that was to follow (Fig. 1a). On IMAGINE trials, subjects saw a context word and 2 or 4 item words simultaneously for

12 s and had to imagine an event with all the items related. The duration of 12 s was chosen based on pilot testing. Once they had constructed the event, they pressed a button, and were told to rehearse the event mentally until the 12 s had elapsed. Then, they had 3.5s to rate the subjective coherence of the imagined event on a 4-point scale (1 = not coherent at all, 4 = very coherent; Table 1). On REORDER trials, subjects were shown 2 or 4 words, and had 12 s to put the words in reverse alphabetical order, pressing a key once the order was determined. Subjects had to rehearse that new order mentally until the 12s elapsed. Then, subjects were shown a probe word, and had 3.5 s to answer whether it appeared in the 2nd or 4th position in reverse alphabetical sequence (Table 1). The probe word was in the correct position on 50% of the trials. Following each trial, a fixation cross appeared for 1.5–7.5 s, to create an inter-trial jitter.

Subjects completed 24 trials per condition, resulting in 144 trials overall. Each word was only used once for a specific trial and was not repeated. Trials were divided into 6 runs with 4 trials per condition in each run, with conditions presented in random order. Each run lasted approximately 8.5 min, with 30–60 s in between runs to reiterate instructions. The entire scanning session lasted approximately 90 min.

Following the scanning session, subjects completed a 2-step recall/description task for words presented in the IMAGINE condition in a separate testing room with the experimenter present (Fig. 1b). Subjects were shown a context word, and had to recall all the words that were presented with the context word in the scanner. Then, subjects pressed a key and all associated item words were shown, at which point the subject was to describe what he/she imagined with those items, noting the relations between them. Subjects then provided ratings from 1 to 4 (1 = low, 4 = high) for the congruency of the event they imagined (i.e. *subjective congruency;* Table 1). These ratings allowed us to measure individual differences in the subjective congruency of each event, which may not be captured in the experimental manipulation of the normative congruency between item and context words.

Performance for both recall and description phases was self-paced. For the description phase, the experimenter provided no probes, other than to remind the subjects to describe the event they had imagined in the scanner. The descriptions were recorded, and later transcribed and scored according to Romero and Moscovitch (2012). Briefly, for each trial, the number of explicitly mentioned relations between item words was tallied, to provide a measure of how related the constituent items were, as an objective index of event or scene construction ability (i.e. *objective coherence*). In order to be given a score, a relation between two items had to be explicitly stated: inferred or implied relations were not counted in order to minimize any subjective judgment. Relations between item words and pronouns were not counted unless a relation between item words was absolutely clearly based on the sentence. Previous studies have shown excellent inter-rater reliability using this objective coherence scoring method (Romero and Moscovitch, 2012). Transcriptions were scored by 3 raters who were naïve to the experimental hypotheses. Any discrepancies between scorers (5.1% of scores) were resolved by discussion.

2.3. fMRI acquisition

Data were acquired using a Siemens Tim Trio 3.0 T MRI scanner using a 12-channel head coil, at the Rotman Research Institute, Baycrest Centre, Toronto, Ontario. T1-weighted images were acquired in the axial oblique plane using a gradient echo-planar imaging (EPI) sequence (repetition time [TR] = 2000 ms, echo time [TE] = 30 ms, field of view = 200 mm, voxel size = $3 \times 3 \times 3.5$ mm^3). Each volume contained 30 slices acquired in an interleaved fashion, covering the entire cerebral cortex. High resolution T1-wieghted images were acquired prior to the functional scans using an MPRAGE sequence (TR = 2000 ms TE = 2.63 ms, field of view = 256 mm, voxel size = 1 mm^3, 160 slices).

2.4. fMRI preprocessing

For each run, the first 4 scans were discarded for scanner equilibration. Data were preprocessed using SPM12. The functional volumes were corrected for slice acquisition times, realigned to the mean image, and coregistered with each subject's structural image. The resulting parameters were then used to spatially normalize the images to the MNI template brain provided in SPM, resampling to 2 mm^3 isotropic voxels. Finally, the images were smoothed with an 8 mm full width half-maximum Gaussian kernel.

2.5. fMRI data analysis

2.5.1. Whole-brain GLM analysis

The fMRI data were analyzed with SPM12. BOLD signal was decomposed using the general linear model (Friston et al., 1995) separately for each run. Activity from stimulus onset until the button press indicating the subject had finished the trial was modeled using the canonical hemodynamic response function. Six separate regressors were modeled for each task condition, as well as 6 regressors corresponding to the realignment parameters for each subject, to correct for motion artifacts. A 1/128 Hz high-pass filter was applied to the data and model. Parameters for each regressor were estimated using a least-mean-squares fit of the model to the functional data. Parameter estimates for all 6 task conditions were entered into a flexible factorial ANOVA at the 2nd level using a random-effects analysis and a non-sphericity correction.

We conducted whole-brain analyses comparing functional activation across the different task conditions. To test the main effect of construction, we contrasted activity across all IMAGINE task conditions (collapsing across normative congruency and set size) with activity across all REORDER conditions (collapsing across set size) (IMAGINE > REORDER). Peak activity in the HPC and mPFC was used as seed coordinates for the primary analysis (seed PLS) described below. To test the effect of set size during construction, we ran IMAGINE-4 > IMAGINE-

Table 1

: Event construction task performance, cued recall, and subjective ratings for imagined events at set sizes 2 and 4 and incongruent and congruent conditions.

Measure		IMAGINE-Incongruent		IMAGINE-Congruent		REORDER	
		2	4	2	4	2	4
		M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)
In-scanner							
Reaction time	(Seconds)	5.18 (.54)	7.26 (.61)	4.31 (.53)	6.38 (.59)	2.94 (.52)	5.70 (.48)
REORDER task	(Accuracy)	–	–	–	–	.88 (.08)	.87 (.11)
Subjective Coherence	(Rating 1–4)	2.89 (.14)	2.62 (.16)	3.66 (.06)	3.41 (.07)	–	–
Post-scan							
Cued Recall	(# of items recalled)	13.81 (2.81)	18.31 (4.61)	19.19 (2.92)	29.19 (4.96)	–	–
Objective Coherence	(# inter-item relations)	1.05 (.38)	1.64 (.52)	1.18 (.35)	1.69 (.54)	–	–
Subjective Congruency	(Rating 1–4)	2.06 (.13)	1.79 (.08)	3.28 (.14)	3.04 (.16)	–	–

2 and IMAGINE-2>IMAGINE-4 contrasts, and also compared the IMA-GINE conditions after subtracting out their respective control conditions (IMAGINE-4>REORDER-4) > (IMAGINE-2>REORDER-2). Finally, to test the effect of normative congruency, within the IMAGINE conditions, we also calculated IMAGINE-Congruent > IMAGINE-Incongruent and IMAGINE-Incongruent > IMAGINE-congruent contrasts, collapsing across set sizes. All whole-brain analysis contrasts were corrected for multiple comparisons using a family-wise error (FWE) correction ($p < .05$).

2.5.2. Seed partial least squares (PLS) analysis

To test our main hypotheses, we conducted a seed PLS analysis on brain activity for the entire trial duration, within all IMAGINE conditions (see Krishnan et al., 2011; McIntosh and Lobaugh, 2004; for a review). Because the seeds were defined based on increased mean-level activity in the IMAGINE vs. REORDER conditions, the seed PLS would allow us to explore the connectivity between HPC and mPFC seeds within the different IMAGINE condition manipulations (i.e. congruency and set size). In general, PLS is a multivariate, data-driven technique, designed to investigate individual differences in brain-behaviour associations. PLS identifies a set of latent variables (LVs), which maximally explain the association between brain activity and any other variable of interest (i.e. behavioural performance, mean BOLD activity within a defined seed), across conditions and across subjects. The results reveal whole-brain patterns of activity that correlate positively or negatively with the variable of interest, and also reveal how the nature of those correlations change across task conditions. PLS first calculates correlations between brain activity and the variable(s) of interest per condition, creating a vector for each subject. These vectors are stacked into a single matrix and decomposed using single value decomposition, yielding orthogonal LVs that express the commonalities and differences in networks of brain regions across all task conditions. The result is an extraction of patterns of activation that are positively or negatively associated with the variable(s) of interest. Moreover, there is no assumption of the shape of the hemodynamic response and no explicit contrast of activity across task conditions: Instead, the algorithms calculate the hemodynamic response that best explains the association between brain activity and behaviour across all conditions.

The statistical significance of each LV is assessed by permutation testing, in which behavioural observations are shuffled within subject, to calculate the probability of each LV occurring by chance alone. The reliability of each voxel's contribution to the LVs is determined through bootstrap resampling, whereby subjects are randomly resampled and replaced, and the standard errors computed, in order to obtain an estimate of the standard error for each voxel. The result is a bootstrap ratio (BSR) for each voxel that is proportional to a z-score. By convention, voxels with BSR exceeding a certain threshold (i.e. >|3.0|) reliably contribute to the pattern of brain activation. Because calculation of the LVs is done simultaneously, there is no need to correct for multiple statistical comparisons.

In seed PLS, the variable(s) of interest are mean level activity within predefined seeds of interest (i.e. HPC and mPFC), calculated within each task condition, for each subject. Thus, seed PLS allows us to extract LVs that reflect which brain areas are reliably functionally connected with the HPC and mPFC, across all subjects. Crucially, we can explore how the strength of the correlations changes across experimental task conditions, thus allowing us to determine how HPC and mPFC connectivity varies according to congruency and set size.

To perform the seed PLS analysis, we extracted mean activity from a 50-voxel cluster around the peak coordinates in the HPC and mPFC (as defined using the AAL atlas) from the IMAGINE vs. REORDER contrast, using a $5 \times 5 \times 5$ voxel cube with the seed at the centre. Mean-level activity was extracted for each condition across all participants. We used seed activity from the second TR (4–6 s post-stimulus) for the analysis as it showed the strongest correlations over the trial time series. These data were then entered into a two-seed PLS, which determines the covariance

between each seed and the patterns of whole-brain activity. For this analysis, 1000 permutations were run, and the data were resampled 500 times. Brain regions were considered reliably active if they had a cluster size of 10 contiguous voxels with a BSR of ± 3.5, corresponding to a probability of $p < .0005$.

2.5.3. Behavioural PLS

Furthermore, to test whether behavioural measures of task performance correlated with brain activity, we conducted a behavioural PLS analysis on brain activity for the entire trial duration, across all IMAGINE conditions. Similar to seed PLS, behavioural PLS identifies a set of latent variables (LVs), which maximally explain the association between brain activity and task performance, across conditions and across subjects. The results reveal whole-brain patterns of activity that correlate positively or negatively with task performance. We performed two behavioural PLS analyses: The first analysis was conducted using the objectively scored measures of task performance (objective coherence; Fig. 1b), which revealed the association between patterns of brain activity and objective measures of event construction ability. The second analysis was conducted on subjective congruency ratings provided during the recall/description task (Fig. 1b), which revealed the association between brain activity during event construction, and individual differences in how congruent the imagined events were perceived. Clusters of 10 or more voxels with a BSR ± 3.5 (i.e. $p < .0005$) were considered significant.

All behavioural data were analyzed using IBM SPSS 20. Subjective coherence ratings for 4 subjects, and congruency ratings for 2 subjects were not recorded due to computer malfunction. Data for 1 run from one participant had to be excluded due to an unforeseen task interruption. Nineteen recall trials from another subject were not recorded due to computer malfunction, and these trials were not included in the fMRI analyses.

3. Results

3.1. Behavioural results

3.1.1. Objective coherence

The number of relations formed during the IMAGINE conditions was entered into a 2×2 repeated-measures ANOVA with congruency and set size as within-subjects variables. There was a main effect of set size, with trials having 4 items containing more relations than trials with 2 items ($F(1,15) = 33.19$, $p = .001$, $\eta^2 = 0.69$). The main effect of congruency approached significance, with congruent items having more relations ($F(1,15) = 3.30$, $p = .09$, $\eta^2 = 0.18$). The interaction was not significant ($F < 1$) (Table 1).

3.1.2. Completion time

Latency to constructing an event in the IMAGINE conditions or manipulating the stimuli in the REORDER condition was entered into a 3×2 repeated-measures ANOVA, with task (IMAGINE-Incongruent, IMAGINE-Congruent, REORDER-control) and set size (2,4) as factors. There was a main effect of task ($F(2,30) = 28.27$, $p < .001$, $\eta^2 = 0.65$): tests of simple effects showed that reaction time in the IMAGINE-incongruent condition was significantly slower than in the IMAGINE-congruent condition ($t = 7.83$, $p < .001$, $d = 1.38$), and the REORDER-control condition ($t = 7.65$, $p < .005$, $d = 1.35$). There was also a main effect of set size ($F(1,30) = 88.14$, $p < .001$, $\eta^2 = 0.86$), with 4 items taking longer than 2 items. The interaction was also significant ($F(2,30) = 7.94$, $p < .005$). Post hoc tests determined that at a set size of 2, the incongruent condition was slower than the congruent condition ($t = 6.10$, $p < .001$, $d = 1.53$), and the congruent and incongruent conditions were each slower than the control condition ($t = 5.76$ $p < .001$, $d = 1.44$; $t = 6.48$, $p < .001$, $d = 1.62$). At a set size of 4, the incongruent condition was slower than the congruent condition ($t = 4.99$, $p < .001$, $d = 1.25$) and control condition ($t = 4.50$ $p < .005$, $d = 1.13$), but the congruent condition was not different from the control condition ($t = $

2.21, $p = .13$) (Table 1).

3.1.3. Cued recall

The number of trials in which at least a single word was recalled (i.e. recall success) was entered into a 2×2 repeated-measures ANOVA with normed congruency (congruent, incongruent) and set size (2, 4) as factors. There was a main effect of condition, with congruent trials being more frequently recalled than incongruent trials ($F(1,15) = 44.18$, $p < .001$, $\eta^2 = 0.75$). Neither the main effect of set size, nor the interaction, was significant (all $Fs < 1$) (Table 1).

3.1.4. Subjective ratings of coherence and congruency

Subjective coherence ratings (in-scanner) were entered into 2×2 repeated-measures ANOVA with normative congruence (congruent, incongruent) and set size (2, 4) as factors. For subjective coherence ratings, there was a main effect of congruence ($F(1,11) = 37.47$, $p < .001$), with congruent items being rated as more coherent, and a main effect of set size ($F(1,11) = 14.06$, $p < .005$), with set size 2 trials being rated as more coherent than that of 4-item trials. The interaction was not significant ($F < 1$).

For subjective congruency ratings, both the main effects of normative congruency ($F(1,13) = 100.38$, $p < .001$) and the effect of set size ($F(1,13) = 30.86$, $p < .001$) were significant. As expected, congruent trials were given higher congruency ratings. Also, set size 2 trials were rated as more congruent than set size 4 trials. The interaction was not significant ($F < 1$) (Table 1).

3.2. fMRI results

3.2.1. Whole-brain GLM analyses

We contrasted activity in all IMAGINE conditions to all REORDER conditions with an independent samples t-test, modeling activity for the duration of the trial. Imagining a novel event in general (IMAGINE > REORDER) activated regions of the default mode network that have been previously implicated in future imagining tasks (Andrews-Hanna, 2012), including the bilateral mPFC, left precuneus, and right anterior HPC ($p < .05$, FWE corrected) (Fig. 2, Supplementary Table 1). The reverse contrast of REORDER > IMAGINE showed peak activation in lateral frontal and parietal regions bilaterally, which are commonly activated in working memory tasks (Champod and Petrides, 2010; Nee
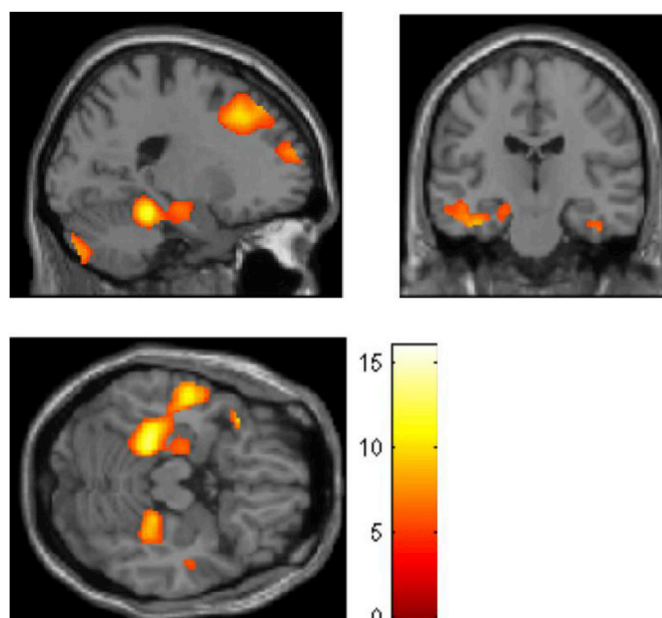
Fig. 2. Whole-brain activation for the IMAGINE > REORDER contrast, collapsing across congruency and set size, p < .05, FWE correction.

et al., 2013; Rottschy et al., 2012) (Supplementary Table 1).

3.2.2. Set size

Contrasting the IMAGINE conditions after subtracting out their respective control conditions (i.e. [IMAGINE-4 > REORDER-4] > [IMAGINE-2 > REORDER-2]) yielded no significant clusters. The opposite contrast yielded significant clusters in left posterior medial frontal regions and lateral parietal cortices bilaterally ($p < .05$, FWE corrected) (Supplementary Table 2).

3.2.3. Normative congruency

At a threshold of $p < .05$, FWE-corrected, whole-brain analyses yielded no clusters significantly more active when imagining incongruent as compared to congruent events (IMAGINE-Incongruent > IMAGINE-congruent). Similarly, the IMAGINE-congruent > IMAGINE-Incongruent contrast yielded no significant effects at a threshold of $p < .05$ FWE-corrected.

3.2.4. Subsequent memory

To examine increased activation for successfully-recalled items, collapsing across all IMAGINE conditions we modeled two regressors representing trials where at least one item word was recalled, and trials where no words were recalled (Successful recall > Unsuccessful recall). There were no significant clusters at a threshold of $p < .05$, FWE corrected. The reverse contrast (Unsuccessful recall > Successful recall) similarly yielded no significant clusters at a threshold of $p < .05$, FWE corrected.

3.2.5. Seed PLS

For the seed PLS, we used left anterior hippocampal [-20 -14 -16] and dorsal medial prefrontal [-6 58 24] seeds from our GLM contrast of IMAGINE > REORDER conditions (see Whole-brain GLM analyses), as these regions were significantly active during the imagining task, and our primary interest was to examine variations in functional connectivity between the seeds and the rest of the brain, and how such connectivity can vary within the imagining task conditions. Although the seeds were derived from the IMAGINE > REORDER contrast, seed PLS examines patterns of covarying activity between the seeds and the rest of the brain: as activity in the rest of the brain is not defined based on the GLM contrast, the results from the seed PLS are not dependent on the results from the GLM contrast. Similar studies have also used this approach to examine HPC-mPFC connectivity across task conditions (Robin et al., 2015) (see also Grigg and Grady, 2010). Seeds were chosen in the left hemisphere based on the use of verbal stimuli during the task, and are similar to those used in previous studies to identify sub-networks of the default-mode network (Andrews-Hanna, 2012).

The seed PLS analysis resulted in one significant LV, accounting for 46% of the variance ($p < .001$). Fig. 3 displays the pattern of functionally connected brain regions across subjects, and the correlation between HPC and mPFC seeds with that network: correlations where the bootstrapped 95% confidence interval does not cross 0 indicates a significant correlation between that seed and the pattern of brain activity, for that particular task condition. Notably, the extent to which both the HPC and mPFC seeds are significantly correlated with the network also indicates functional connectivity with each other. The seed PLS revealed a functional network corresponding to the default-mode network, and included the right HPC, right dorsal mPFC, left precuneus and inferior parietal regions, and lateral temporal cortices (Table 2; Fig. 3a). The left HPC seed was reliably correlated with this network across all imagining conditions except during the Congruent-set size 2 condition (Incongruent-2 $r = 0.41$, [0.03, 0.79] 95% CI; Incongruent-4 $r = 0.44$ [0.08, 0.81] 95% CI; Congruent-2 $r = .25$, [-0.02, 0.67] 95% CI; Congruent-4 $r = 0.76$, [0.67, 0.91] 95% CI), bolstering the notion that the HPC generally contributes to event construction (Fig. 3b). In contrast, dorsal mPFC seed connectivity with other regions was only reliably observed at a set size 4, irrespective of congruency (Incongruent-2 $r = .32$, [-0.12, 0.68] 95% CI;
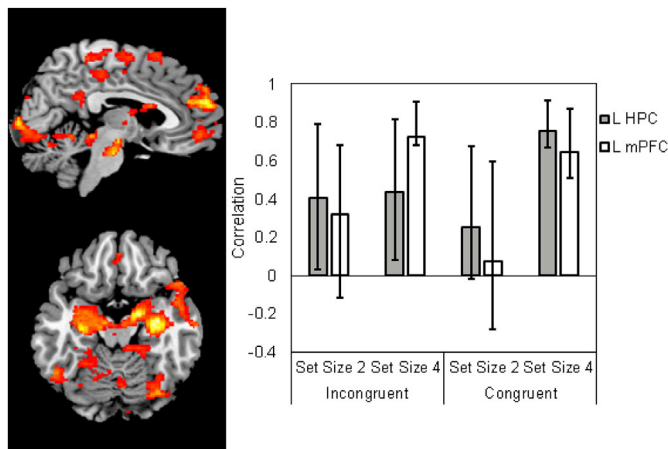
Fig. 3. A: Patterns of significant functional connectivity with mean left hippocampal and left medial prefrontal seed activity during the IMAGINE conditions of the event construction task at TR 2 (4–8 s post-stimulus onset). Images are thresholded at a bootstrap ratio > |3.5|, corresponding approximately to a p < .0005, minimum cluster size = 10 voxels. **B**: Correlations between left hippocampal and left medial prefrontal seeds and pattern of brain activity, across all IMAGINE conditions in the event construction task. Error bars represent bootstrapped 95% confidence intervals. Conditions where the correlation error bars do not cross the x-axis indicate significant functional connectivity between that seed and the pattern of brain activity shown.

Incongruent-4 $r = .72$ [0.68, 0.91] 95% CI; Congruent-2 $r = .07$, [-0.28, 0.59] 95% CI; Congruent-4 $r = .65$, [0.51, 0.87] 95% CI): this result suggests that the dorsal mPFC seed is only reliably recruited when mnemonic load becomes sufficiently high. Thus, the emerging picture reflects a core network of regions which are functionally connected during event construction, including the bilateral HPC and ventral mPFC; dorsal mPFC shows increased connectivity with the related functional network only when there is a sufficient amount of information to be constructed.

3.2.6. Behavioural PLS

To obtain a more complete view of the association between brain activity and different aspects of task performance, two separate Behavioural PLS analyses were conducted on a) the mean objective coherence scores calculated by objective scoring of subject's responses, and b) the subjective ratings of how congruent an imagined event was. There was no significant correlation across subjects between mean objective coherence scores and subjective congruence scores, $r = 0.04$. These analyses extracted latent variables that maximized the covariance between behavioural measures and brain activity, thus revealing a pattern of brain regions that were associated with different aspects of task performance. Similar to the seed PLS analysis, correlations where the bootstrapped 95% confidence interval does not cross 0 indicates a significant correlation between the pattern of brain activity and the particular measure of task performance, across subjects.

The first behavioural PLS analysis examined brain regions that covaried with objective measures of the coherence of imagined events. One significant LV emerged that accounted for 48% of the variation in brain activity and objective coherence, with activity at the second TR (4–6 s post-stimulus) showing the most prominent association with higher scores (Incongruent-2 $r = .71$, [0.63, 0.92] 95% CI; Incongruent-4 $r = .66$ [0.56, 0.92] 95% CI; Congruent-2 $r = .88$, [0.78, 0.97] 95% CI; Congruent-4 $r = .47$, [0.29, 0.88] 95% CI). Notably, bilateral anterior HPC activity was associated with increased objective coherence across subjects, suggesting that subjects who made more inter-item relations activated the anterior HPC to a larger extent than subjects whose performance generated fewer relations (Fig. 4a). Other regions positively correlated with the number of relations include the bilateral inferior

Table 2

Regions demonstrating significant positive functional connectivity with left anterior hippocampal and left medial prefrontal seeds within IMAGINE task conditions (Incongruent-2, Incongruent-4, Congruent-2, Congruent-4), as assessed by seed-based partial least squares.

	Brain Region	X	Y	Z	BSR[a]	Cluster size (voxels)
Frontal						
R	Superior frontal gyrus	16	52	18	−11.66	4505
L	Superior frontal gyrus	−12	42	44	−6.61	571
L	Superior orbital gyrus	−26	56	−4	−5.4	73
R	Middle frontal gyrus	36	24	46	−5.4	298
L	Middle frontal gyrus	−36	8	60	−3.83	11
R	Middle orbital gyrus	32	50	−2	−5.33	70
R	Inferior frontal gyrus	32	22	20	−5.29	81
		32	10	32	−4.68	23
		40	38	−14	−4.17	11
L	Inferior frontal gyrus	−34	22	−12	−4.21	34
R	Precentral gyrus	60	−8	46	−9.37	5876
L	Precentral gyrus	−46	−4	52	−5.16	31
Temporal						
L	Hippocampus	−28	−14	−12	−12.51	26424[b]
L	Temporal pole	−40	20	−32	−6.72	57
L	Superior temporal gyrus	−58	−44	14	−7.09	275
L	Middle temporal gyrus	−68	−32	−4	−5.6	36
L	Inferior temporal gyrus	−60	−20	−24	−5.46	36
Parietal						
L	Precuneus	−12	−74	46	−4.03	35
L	Inferior parietal lobule	−56	−28	44	−5.13	62
L	Middle cingulate cortex	−16	−50	28	−7.76	589
R	Middle cingulate cortex	12	24	40	−4.59	12
Occipital						
R	Cuneus	18	−74	30	−8.2	168
R	Calcarine gyrus	22	−82	8	−4.38	16
L	Calcarine gyrus	−14	−70	18	−5.33	51
R	Middle occipital gyrus	34	−84	34	−4.68	29
L	Superior occipital gyrus	−22	−90	24	−4.12	14
Other						
L	Cerebellum	−2	−54	−40	−6.43	372
R	Cerebellum	22	−36	−50	−5.95	172
		44	−52	−32	−4.98	89
		12	−42	−44	−4.15	12

[a] BSR = Bootstrap ratio, which is roughly equivalent to a z-score. Negative BSR values denote a positive correlation between these regions and both left hippocampal and medial prefrontal seeds.

[b] Large cluster continuous with left hippocampal seed.

frontal gyri, bilateral superior frontal gyri, and bilateral precuneus (Table 3). Given that the strength of the correlations did not consistently vary as a function of task condition, brain activity was associated with objective coherence scores, regardless of whether subjects imagined incongruent or congruent events, using 2 or 4 item words.

Next, the second analysis behavioural PLS was conducted using subjective congruency scores generated during the description task in order to identify the regions that correlated with subjective ratings of congruency. One LV was significant, accounting for 48% of the variance across subjects, with similar brain-behaviour correlations occurring across task conditions: thus, it represented a pattern of brain activity that was significantly positively correlated with subjects' ratings of congruency, irrespective of normative congruency or set size. Activity associated with higher subjective congruency scores was most prominent at the first TR (2–4 s post-stimulus) in the bilateral parahippocampal cortex with activity extending into the anterior HPC, as well as bilateral lateral temporal cortex, bilateral temporal poles, and right frontal pole (Fig. 4b) (Table 4).

4. Discussion

The goal of our study was to understand, at a neural systems level, the process of constructing imagined events from discrete elements in relation to a schema to form a coherent and meaningful representation. To do
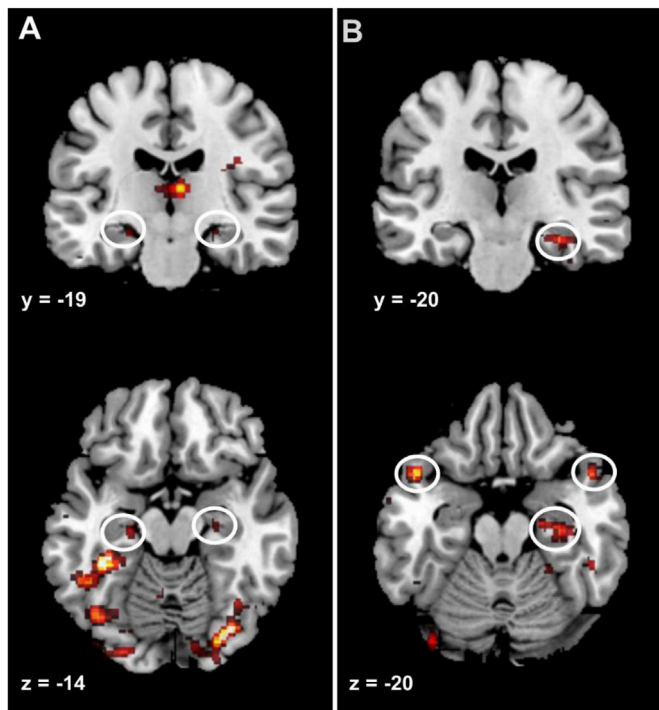
Fig. 4. Patterns of activation significantly correlated with objective coherence scores and subjective congruency ratings. Images are thresholded at a bootstrap ratio > |3.5|, corresponding approximately to a p < .0005, minimum cluster size = 10 voxels. **A:** Increased bilateral hippocampal activity at TR 2 (4–6 s post-stimulus onset) is positively correlated with a larger number of relations formed/trial across all conditions. **B:** Increased bilateral parahippocampal and temporal pole activity at TR 1 (2–4 s post-stimulus onset) is positively correlated with higher congruency scores across all conditions.

so, we focused on two structures, the HPC and mPFC, which are implicated in relational binding and schema instantiation. We sought to clarify how mean-level activity and connectivity of the HPC and mPFC during event construction would be modulated by congruency, set size, and coherence when minimal demands were placed on retrieval from remote memory.

We found that engaging in event construction for non-personal events activated regions commonly associated with simulation of future events and scene construction. As expected, these regions included the anterior HPC and mPFC and also parahippocampal gyrus, posterior cingulate cortex, lateral parietal regions, and medial parietal cortex. Importantly, connectivity analyses revealed significant HPC seed connectivity with DMN regions across most of the task conditions, and was not reliably affected by congruency or set size, suggesting the HPC is implicated in all construction conditions (Moscovitch, 2008). In contrast, dorsal mPFC connectivity was only reliably observed at higher set sizes, when integration into a schema is needed to cope with a higher mnemonic load. Moreover, brain-behaviour correlations revealed that anterior HPC activity tracked with objective coherence scores and subjective congruency ratings, consistent with the hypothesis that the anterior HPC is implicated processing gist, which relates thematic elements associated with congruency to individual items, yielding a coherent representation.

4.1. The role of the hippocampus in constructing coherent events

The results from the whole-brain GLM analysis indicated the anterior HPC showed significantly greater activation during event construction, but that mean-level activation was not modulated by mnemonic load or the congruency of the items, suggesting a general role of the anterior HPC for event construction (McCormick et al., 2015; Moscovitch et al., 2016; Zeidman and Maguire, 2016). Moreover, the seed PLS analysis showed

Table 3
Local maxima of regions showing a significant positive correlation with objective coherence scores across all IMAGINE task conditions (Incongruent-2, Incongruent-4, Congruent-2, Congruent-4), as assessed by behavioural partial least squares.

TR = 2 (4–6 s post-stimulus onset)		X	Y	Z	BSR[a]	Cluster Size (# voxels)
Frontal						
L	Middle frontal gyrus	−38	14	38	−6.49	101
L	Inferior frontal gyrus	−44	20	−6	−6.33	344
R	Medial frontal gyrus	10	18	52	−6.23	357
		2	6	48	−4.58	18
R	Inferior frontal gyrus	56	24	6	−5.40	54
R	Superior frontal gyrus	28	20	32	−5.28	105
R	Superior medial gyrus	4	46	40	−4.36	32
Temporal						
R	Hippocampus	26	−16	−14	−3.90	14
L	Hippocampus	−20	−24	−16	−5.25	45
L	Inferior temporal gyrus	−36	−40	−14	−9.08	487
R	Inferior temporal gyrus	50	−68	−4	−4.57	38
		48	−8	−30	−4.36	34
L	Middle temporal gyrus	−60	−46	10	−6.92	139
R	Fusiform gyrus	34	−78	−16	−8.75	837
Parietal						
L	Superior parietal lobe	−20	−50	72	4.13	17
L	Superior parietal lobe	−30	−72	54	−8.70	1919
R	Superior parietal lobe	36	−52	62	−5.57	204
		18	−58	48	−4.91	31
R	Angular gyrus	28	−50	44	−6.74	129
R	Precuneus	12	−54	24	−4.82	94
L	Precuneus	−6	−56	12	−4.18	25
R	Paracentral lobule	8	−28	72	−5.54	83
Occipital						
R	Middle occipital gyrus	40	−78	32	−10.21	833
		32	−94	18	−5.27	18
L	Middle occipital gyrus	−18	−86	−6	−6.20	270
L	Lingual gyrus	−24	−52	0	−5.97	93
		−12	−34	−4	−5.34	70
R	Lingual gyrus	4	−82	−6	−4.08	14
Other						
L	Thalamus	−20	−28	12	−5.14	72
R	Thalamus	6	−20	8	−7.01	250
R	Caudate	20	4	14	−8.01	293
R	Brainstem	12	−26	−46	−5.94	175
L	Cerebellum	−38	−50	−50	−4.41	38
		−4	−56	−30	−4.38	21
		−14	−42	−18	−4.15	19
		−12	−38	−50	−6.34	290
		−30	−84	−46	6.52	14
R	Cerebellum	4	−88	−32	6.15	11

[a] BSR = Bootstrap ratio, which is roughly equivalent to a z-score. Negative BSR values denote a positive correlation between activation and objective coherence scores.

significant functional connectivity between the left HPC seed and regions comprising the default mode network (i.e. bilateral medial mPFC, medial and lateral parietal cortices), except in the congruent-set size 2 condition, which had the least associative processing demands. The fact that a similar correlation was found between the HPC seed and the functional network for all but the easiest task condition (congruent-set size 2) suggests that working memory demands do not modulate anterior HPC connectivity: rather, the results indicate a general recruitment of the anterior HPC in event construction, reflecting its role in binding items together and forming a gist-like representation along thematic lines. The behavioural PLS analyses provided complementary evidence to support the role of the anterior HPC in event construction: anterior HPC activity was positively associated with objective coherence scores in all conditions, implying they were directly associated with how well events were constructed.

Although all the precise functions of the anterior HPC have not been fully characterized, anterior hippocampal activity is also found when

Table 4
Local maxima of regions showing a significant positive correlation with subjective congruency ratings across all IMAGINE task conditions (Incongruent-2, Incongruent-4, Congruent-2, Congruent-4), as assessed by behavioural partial least squares.

TR = 1 (2–4 s post-stimulus onset)						
	Brain regions	X	Y	Z	BSR[a]	Cluster Size (# voxels)
Frontal						
R	Superior frontal gyrus	22	60	14	−5.2258	46
		30	12	62	−5.022	62
		20	46	42	−4.2291	29
		16	30	60	−4.2873	84
L	Superior medial gyrus	−4	30	62	−4.4066	16
		−4	54	42	−4.0253	10
L	Supplementary motor area	−8	−12	60	5.5607	89
Parietal						
R	Postcentral gyrus	46	−36	60	−5.2429	28
R	Precentral gyrus	56	0	48	−4.7397	13
R	Superior parietal lobule	34	−58	62	−4.2644	18
Temporal						
L	Parahippocamal gyrus	−18	−28	−14	−4.9411	10
R	Parahippocamal gyrus[b]	32	−22	−18	−6.2926	163
L	Temporal Pole	−48	14	−20	−7.3244	86
R	Temporal Pole	50	12	−18	−5.9854	68
L	Inferior temporal gyrus	−48	−50	−12	−5.8805	88
R	Inferior temporal gyrus	56	−52	−14	−4.782	24
		52	−14	−32	−4.7055	16
L	Middle temporal gyrus	−64	−2	−26	−3.8704	13
L	Superior temporal gyrus	−58	0	−8	−5.5105	51
R	Superior temporal gyrus	68	−8	10	−4.2438	26
R	Fusiform gyrus	28	−44	−18	−4.6048	24
Occipital						
L	Lingual gyrus	−38	−86	−16	−8.3547	280
Other						
R	Caudate	14	14	14	−5.3487	40
L	Cerebellum	−46	−62	−36	−5.7595	89
		18	−86	−36	−4.6184	22
R	Cerebellum	46	−48	−34	4.6366	11
		4	−74	−38	−5.5594	129
		6	−52	6	−4.8485	21

[a] BSR = Bootstrap ratio, which is roughly equivalent to a z-score. Negative BSR values denote a positive correlation between activation and congruency ratings.
[b] Activity extends into the hippocampus.

encountering novel information (Köhler et al., 2005; Poppenk et al., 2010) encoding overlapping associative information (Shohamy and Wagner, 2008; Wimmer and Shohamy, 2012; Zeithamova et al., 2012) initial construction processes during recollection (Conway, 2009; McCormick et al., 2015), during scene construction (Zeidman and Maguire, 2016) and processing the general gist of new information (Moscovitch et al., 2016; Poppenk et al., 2013; Robin and Moscovitch, 2017). As the nature of the task in our study focused only on the initial construction of general, non-personal events, without the requirement for elaboration, and as the resulting imagined event typically lacked perceptual details, the most parsimonious explanation is that the anterior HPC is implicated in forming the inter-item associations between items currently present in conscious awareness creating a gist of the event. That is, imagining a novel event is a task with high associative memory demands (Irish et al., 2012), thus likely implicating the anterior HPC regardless of the nature of the stimuli. Indeed, Gaesser et al. (2013) also found right anterior HPC activity in response to the initial construction of binding disparate details into an event.

These findings are consistent with Zeidman & Maguire's (2016) proposal that the anterior HPC is implicated in constructing spatially coherent representations, and Poppenk et al.'s (2013) proposal that the anterior HPC is more implicated in processing general schematics of a new memory (i.e. the gist), whereas the posterior regions are more implicated in retrieval (and possibly encoding) of specific details of a

memory. Such an account would also be consistent with recent evidence demonstrating that patients with hippocampal lesions also produce impoverished descriptions of future semantic events (Race et al., 2013). Consequently, this distinction between gist-like and more detailed imagined events may result in a preferential involvement of anterior HPC in event construction, particularly for generic, non-personal events such as those used in the present study. These results, however, do not preclude the possibility that hippocampal activity during event construction depends on the nature of the events to be imagined: if the imagined events are more perceptually detailed, one may find posterior hippocampal activity if elaboration is also required (Gaesser et al., 2013; McCormick et al., 2015).

4.2. Normative vs. subjective congruency in event construction

Behavioural evidence suggested the manipulation of item congruency by using normatively-derived ratings was effective: Responses in the congruent condition showed a performance advantage as evidenced by faster completion times, and better subsequent memory, compared to the incongruent condition. In addition, subjective ratings provided by participants in the present study confirmed that events in the congruent condition were indeed judged as more congruent than the events in the incongruent condition. The whole-brain GLM analyses, however, did not reveal any significant activation between the experimental manipulations of normative congruency during event construction. Instead, robust congruency effects emerged when examining individual differences in subjective congruency ratings, and not experimenter-defined conditions: Specifically, higher ratings of congruency were positively correlated with increased early activity (i.e. within the first 2–4 s) in bilateral parahippocampal cortex, right HPC, bilateral lateral temporal cortices including the temporal poles, and right frontal pole.

One plausible explanation is that the above regions were implicated in the retrieval of prior semantic contexts (Liu et al., 2018) early in the event construction process. That is, those subjects who perceived the stimuli as fairly congruent were more likely to retrieve a pre-existing contextual schema or associative semantic information to aid in the construction task, compared to subjects who perceived the stimuli as incongruent. Such an account is consistent with the role of the parahippocampal cortex in future simulation of familiar events (Szpunar et al., 2009), and with the role of the lateral temporal cortex and semantic memory in future imagining (Irish et al., 2012). Regarding the mPFC, the peak activation fell within the frontal pole, which has recently been thought to have strong functional associations with the dorsal mPFC (Liu et al., 2013). In addition, more recent evidence suggests that connectivity between the dorsal and ventral mPFC is positively modulated by familiarity (Benoit et al., 2014), which mirrors our finding that increasing congruency scores were correlated with right frontal pole activity. Thus, these regions may contribute to the initial construction of imagined events by retrieving contextual and semantic information, providing the mental representation upon which a novel event may be constructed (Irish and Piguet, 2013; La Corte and Piolino, 2016). Taken together, our results suggest that event construction proceeds in a serial or cascading fashion, wherein a stimulus elicits rapid retrieval of previously stored contextual and semantic information, which may then be associated and bound with additional information by the anterior HPC.

These results highlight the importance of individual differences in brain activation within the same task. Similar effects of variation in brain activation are observed when using individual differences in personality traits (Hassabis et al., 2014), autobiographical memory ability (Sheldon et al., 2016), or individual variations in strategy use (Barnes et al., 2014; Sanfratello et al., 2014). It is germane to note that although the HPC is traditionally associated with episodic memory/future imagination, practically, autobiographical memory is necessarily imbued with semantic and schematic knowledge (i.e. Renoult et al. (2012)), and in fact personal semantics may be a special class of semantic memory. In a similar vein, whether participants judged imagined events to be

relatively congruent or not may also have varied as a function of personal life experience: items judged to be relatively incongruous on average may have been quite typical or congruent for some participants (or vice versa). As personal semantics necessarily differs across individuals, future studies should examine further such individual differences and their impact on future imagining and other related tasks such creative idea generation (Benedek et al., 2014; Madore et al., 2015; Sheldon et al., 2013).

4.3. Mnemonic load and event construction

With respect to set size effects, interestingly, we found reliable functional connectivity between the dorsal mPFC seed and default mode network regions only at a set size of 4, suggesting recruitment of this region during event construction tends to occur at higher mnemonic loads when schemas may be most useful in integrating items in memory. Several lines of work suggest the dorsal mPFC is heavily implicated in 'mentalizing' or creating simulations of one's self, another person (i.e. theory of mind) (Amodio and Frith, 2006). A handful of studies also indicate that activity in this region tracks with the relative processing demands during mentalizing tasks, such as making comparative judgments between oneself and similar or dissimilar others (Raposo et al., 2011), or completing working memory tasks about close friends (Meyer et al., 2012). Although our finding greater dorsal mPFC involvement with increased mnemonic load is consistent with the latter reports on processing demands, it is not clear why a region associated with mentalizing should be implicated in our study where such processes were not needed to form coherent scenarios. A possible interpretation is that although mentalizing was not a requirement, participants created many scenarios in which they themselves or another person were involved either as observers or participants.

In contrast to our predictions, we did not find set size effects in the HPC. Despite recent work suggesting the posterior HPC is implicated for working memory involving complex or novel stimuli (Hannula et al., 2006; Moscovitch et al., 2016; Olson et al., 2006; Yonelinas, 2013), there were no modulations of HPC connectivity as a function of set size, nor was mean level activation higher in the GLM contrast of set size conditions. One possibility is that because our paradigm focused on the initial construction of imagined events, and did not emphasize perceptual elaboration of those events (McCormick et al., 2015), there may not have been sufficient detail to elicit the significant posterior HPC activity observed in other studies of future imagining (Addis et al., 2011). Another possibility is that the voxel size and smoothing kernel size limited our ability to detect posterior hippocampal activation due to partial voluming effects: interestingly, some recent evidence suggests that fundamental differences in anterior vs. posterior hippocampus may be found even after accounting for differences in temporal or spatial signal-to-noise ratio across these two regions (Brunec et al., 2018). Nevertheless, we are left with anterior hippocampal activity associated with event construction at encoding that is comparable in activation to the initial construction phase when retrieving complex events (McCormick et al., 2015).

4.4. Hippocampal-prefrontal network contributions to construction and behaviour

Our findings collectively suggest that the anterior HPC contributes to construction via its role in general associative processing. However, another interpretation is that the anterior HPC plays a specific role in scene construction: this interpretation would account for the increased mean-level activation during imagining, the general HPC seed connectivity with the DMN across most imagining task conditions, and the positive correlation between HPC activity and objective coherence scores. Indeed, given the task was to construct an event with words as cues, it is likely that participants formed visual mental representations of their event, likely with a spatial component (Robin et al., 2016).

Although we cannot definitively rule out this interpretation, it is germane to note that hippocampal activity also tracks with associative tasks that do not have a strong scene construction component, such as transitive inference (Zeithamova et al., 2012). The simplest interpretation, which we noted earlier, is that the hippocampus is obligatorily implicated in relational binding during encoding no matter how many items are involved (Moscovitch, 2008).

Although not the focus of our study, the parietal cortex (superior and inferior aspects, including the angular and supramarginal gyri, and the precuneus) figured significantly in the results. Specifically, bilateral inferior parietal regions including the angular gyrus were significantly positively correlated with left HPC and mPFC seeds, and also positively correlated with relational coherence performance. Recent evidence suggests that angular gyrus activity tracks with subjective ratings of vividness, confidence, and emotional saliency during both recollection of episodic details (Bonnici et al., 2016; Wagner et al., 2005) and levels of episodic detail during future imagining (Thakral et al., 2017). Although the present experimental design did not emphasize construction of detailed events, the measure of objective coherence emphasized specific inter-item relations, akin to the 'internal' details of the Autobiographical Interview, commonly used in future imagining studies (Levine et al., 2002). Regarding the precuneus, left precuneus activity was correlated with left HPC and mPFC seeds, and bilateral precuneus activity was also correlated with objective coherence scores, consistent with its contribution as part of a core system for mental construction (Andrews-Hanna, 2012).

Collectively, the present results reveal a core network of regions involved in the initial construction of an imagined event when demands on retrieval from long-term (remote) memory are minimized. Despite minimizing these demands, activated regions include the anterior HPC, parahippocampal cortex, lateral temporal regions, inferior parietal cortex, precuneus and dorsal and ventral mPFC which are part of the default mode and recollection network. Activity in the anterior HPC showed significant functional connectivity with default mode regions and the recollection network, and was also correlated with individual differences in objective coherence. Moreover, early activity in bilateral parahippocampal cortex, right HPC, lateral temporal cortex, and right frontal pole were positively associated with subjective congruency ratings, reflecting the rapid formation of a gist-like template or schema to facilitate event construction. Similarly, others have noted the brain may have a tendency to form rapid, schema-like templates of situations to aid in everyday decision-making (i.e. "affective forecasting"; Gilbert and Wilson, 2007) or in trying to predict incoming information from the environment (Bar, 2007). Increased dorsal mPFC connectivity with the HPC and the default mode network was only apparent at higher set sizes, indicating that this region is only recruited as the mental representation becomes more complex, which may be closely tied to its role in mentalizing.

In light of these findings, it is interesting to consider the extent to which constructed events actually impact behaviour. Recent work on empathy and mental simulation also suggest that simulation increases subjective willingness to be empathic (Ciaramelli et al., 2013) and prosocial (Madore et al., 2014). There were no data, however, examining whether simulation changed actual prosocial behaviour (but see Sawczak et al., 2016). Previous models of behaviour change note a distinction between forming more process-vs. outcome-focused plans (see Szpunar, 2010), suggesting one needs to imagine events in detail in order to change behaviour. Indeed, it is well-known clinically that many psychotherapies utilize mental imagery of past/future scenarios or the construction of adaptive narratives (De Jong and Berg, 2007; Moscovitch et al., 2011) in order to adjust maladaptive thoughts or find actionable solutions to problems. Determining when mental simulations do or do not affect actual behaviour is a fruitful avenue of future research. Last, given the significant results of subjective congruency on brain activation, further studies need to consider the interaction between task-related manipulations and individual differences: In particular, further

attention must be paid to effects observed when measuring within-vs. across-subject functional connectivity, as recent results indicate that these approaches produce different results (Braga and Buckner, 2017; Roberts et al., 2016).

These effects must be couched within the limitations of this study. The voxel size and subsequent smoothing kernel were relatively coarse, which leave open the possibility that activity in adjacent medial temporal lobe structures may also have contributed to the pattern of results reported. In addition, we did not obtain field maps during acquisition to correct for B0 inhomogeneities. Regarding the design, the study with 16 participants and some loss of behavioural data is somewhat underpowered for an fMRI investigation. Moreover, the nature of the paradigm required an assumption that the subjects' cued recall of what was imagined was qualitatively similar to their experience when imagining the event itself in-scanner. While we cannot confirm this definitively, the task design was constructed bearing in mind the time constraints of fMRI protocols, and the pragmatic challenges of having verbal responses during scanning. Finally, our behavioural PLS results utilized objective coherence scores and subjective congruence ratings, which may have been conflated to some extent in participants' minds: However, given that we obtained very distinct patterns of connectivity by using these separate measures, it is likely that subjects were able to generally distinguish between the concepts of coherence and congruence.

5. Summary

We demonstrated that anterior HPC is generally elicited in the service of constructing a novel event, particularly with respect to forming inter-item associations, even when retrieval from long-term memory is minimized. Dorsal mPFC, on the other hand, was more sensitive to mnemonic load, and only showed functional connectivity with the HPC and default mode regions at higher set sizes, suggesting that its schema functions are recruited when high mnemonic load makes integration difficult. Regions implicated in semantic memory showed increased early activation with more congruent imagined events, consistent with observations on the early role of schemas and semantics in perception and memory (Gilboa and Moscovitch, 2017). These results reflect a nuanced role for medial temporal and medial prefrontal regions in the construction of novel events, with a core set of regions involved in simulating novel representations, and other functional networks coming online in response to different task demands.

Declarations of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2018.12.047.

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