

Gradual acquisition of visuo-spatial associative memory representations via the dorsal precuneus

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Supporting Online Information

Supplementary Methods

Analysis of the session-specific and run-specific head motion

We assessed the head motion characteristics over different experimental sessions by means of the six parameter estimates for within scan translation and rotation. In addition, we computed between-scan Euclidean distances (only for translation). Separate 3 x 3 ANOVAs for repeated measures were performed for the individual means of these parameters (Figure S1, Table S1). We report F-values and effect sizes for these analyses. Degrees of freedom were corrected for non-sphericity, using the Greenhouse-Geisser correction when appropriate.

Selection of coordinates and generation of regions of interest

Specific regions of interest (ROIs) for the mPFC (Table S2) and for dorsal and ventral precuneus (Figure S2; Table S3, S4) were generated based on previous studies, using a combined anatomical and functional (i.e., literature-based) approach. Coordinates were obtained from previously published fMRI studies. To this end, we conducted a PubMed search with the search term “precuneus AND memory AND (encoding OR retrieval) AND fMRI” plus approximately 10 references familiar to the authors. Of the resulting >600 hits, 156 studies were considered suitable based on the abstracts, and coordinates were ultimately obtained from 101 references. Coordinates of the ventral precuneus (N = 174; see Table S3) were obtained, for example, from recollection-based recognition, negative subsequent memory effects and autobiographical retrieval, whereas coordinates of the dorsal precuneus (N = 175; see Table S4) stemmed from processes like navigation and spatial memory, visual imagery or familiarity-based recognition. Furthermore, we selected 19 coordinates from studies of schema-dependent memory formation to obtain a probabilistic ROI of the mPFC (Table S2). The distributions of thus obtained coordinates was fit as three-dimensional Gaussian ellipsoids, limited to voxels within the 2 SD borders of these Gaussian models (Schubert et al., 2008; Schott et al., 2013). Due to overlapping ellipsoids for ventral and dorsal coordinate sets, the final ROIs (with respect to the border between precuneus

sub-regions) were computed by means of a maximum probability approach. Finally, we inclusively masked the resulting ROIs with anatomical boundaries obtained from the Automated Anatomical Labeling Atlas (Tzourio-Mazoyer et al., 2002). Anatomical masks were generated separately for the left and right hemisphere and consisted of medial parietal cortices (precuneus, SPL, posterior cingulate).

Supplementary Results

Session-specific and run-specific head motion

Mean rigid-body movement parameters across the group are displayed in Figure S1. Of all movement parameters, only pitch showed a significant main effect of run after correction for multiple comparisons. ($F_{1,7,53.0} = 10.60$; $p < .001$; $\eta^2 = .255$), reflecting stronger movement in the first compared to the second and third run. A trend-wise interaction between run and day (i.e. session) for pitch ($p = .076$, uncorrected) mostly driven by between-session differences in the first run. Importantly, no main effect of session –or day– was observed. For a detailed overview of all results see Supplementary Table S1.

Region of interest analyses in the medial prefrontal cortex

Given the previously described role of the medial prefrontal cortex (mPFC) in memory formation based on prior knowledge (van Kesteren et al., 2012), we performed ROI analyses in this region using the main contrasts of interest (congruency contrast, i.e. constant vs. shuffled on Day 2+5; subsequent memory contrast, i.e. pictures with subsequently remembered vs. forgotten icon positions). Neither the comparison of constant to shuffled configurations nor the reverse contrast showed activations in the mPFC with family-wise error correction for the ROI volume at either voxel or cluster level, even when applying the most liberal a priori significance level of $p < .05$, uncorrected. In the subsequent memory contrast, the ROI-based analysis in the mPFC revealed no activations during successful encoding within the mPFC that remained significant after correction for the ROI volume, even with an a priori significance level of $p < .05$, uncorrected.

Correct, incorrect, and omitted responses across conditions and days

Mean response profiles, separated by condition and day are reported in Supplementary Table S5 (see also Figure 1, main manuscript). In addition to the increasing proportion of correctly recognized icon positions in the constant condition (see Results section, main manuscript), proportions of incorrect and omitted responses also varied as a function of both condition and study day. While the proportion of omitted responses was slightly higher for

shuffled compared to constant configurations (main effect of condition: $F_{1,31} = 13.85$, $p = .001$, partial $\eta^2 = .309$; 2-way ANOVA for repeated measures with condition and day as within-subjects factors), omission rates decreased from day 1 to day 5 at a similar rate in both conditions (main effect of day: $F_{2,1,65.6} = 27.78$, $p < .001$, partial $\eta^2 = .463$; no condition by day interaction, $p > .583$). The proportion of incorrect responses, however, showed a significant decrease from day 1 to day 5 in the constant condition ($t_{31} = 2.93$, $p = .006$, Cohen's $d = .517$), but a trend-wise increase in the shuffled condition ($t_{31} = -1.79$, $p = .083$, Cohen's $d = .317$). Uncertainty-adjusted recognition rates (correct / [1-omissions]) followed the same pattern as raw recognition rates, with a pronounced increase from day 1 to day 2 in the constant condition and a subsequently slower increase in performance from day 2 to day 5 (Table S5). As for raw recognition rates, a two-way ANOVA for repeated measures revealed main effects of condition ($F_{1,31} = 157.94$, $p < .001$, partial $\eta^2 = .836$) and day ($F_{2,8,87.4} = 14.85$, $p < .001$, partial $\eta^2 = .324$), as well as a significant interaction ($F_{3,6,112.4} = 4.98$, $p = .001$, partial $\eta^2 = .138$).

Background position during familiarization and memory performance on day 1

Figure S3 depicts the average memory performance (correctly recognized icon position) for each background picture as a function of its temporal position during the familiarization phase, using a sliding window of +/-5. While there were no clear primacy or recency effects (i.e. memory advantages for the pictures presented first and last), a performance peak could be observed for the background pictures presented around positions 23 to 26, whereas a dip in performance was found for the background pictures presented around positions 44 to 52.

No difference in precuneus activation on day 1

To exclude the possibility that the precuneus activation observed in the comparison of brain responses to constant versus shuffled configurations on Day 2 and 5 might be attributable to item-related effects of the background pictures as observed on Day 1, we computed a t contrast comparing the constant and shuffled conditions on Day 1 only, based on the same ANOVA model as the main contrast of interest (see Methods section of the main manuscript). At $p < .001$, uncorrected, minimum cluster size = 10 voxels, no significant activation differences were observed. When using a more liberal threshold of $p < .005$, uncorrected, minimum cluster size = 10 voxels, two activation clusters were observed in secondary visual areas (Figure S4), but none survived FWE correction at either voxel or cluster level. We further performed a ROI-based analysis in the precuneus, using *a priori* defined literature-based ROIs (Table S3, S4). Even when using an uncorrected $p < .05$ and a minimum cluster size of 5 voxels, we observed no supra-threshold voxels within the precuneus ROIs.

Supplementary Discussion

Analysis of the session-specific and run-specific head motion

In our analyses, the only motion parameter estimates that significantly differ between experimental runs, is the rotation around the x-axis (pitch). This parameter is known to be associated with MR signal fluctuations and image distortions in ventral frontal and temporal brain regions. Although we addressed this so called susceptibility x motion interaction by involving the motion parameter estimates in our 1st level models, a complete correction of the influence of this motion (specifically in connectivity analyses, e.g. Satterthwaite et al. 2012) is virtually impossible and might thus affect also the goodness of parameter estimation in 1st level models (due to differences in signal-to-noise ratio). However, for the runs 2 and 3 we found no differences between mean pitch estimates for Day 1, 3 and 5. Thus only in the first run, the estimation of model parameters may be affected. Because our contrast images were computed using all three runs of a session, the influence of this effect is – in our view – tolerable. Regarding possible image distortions, the position of our main effect in the dorsal precuneus is, given the absence of air-tissue borders in that region, not considered to be vulnerable for the image distortions and can be therefore neglected.

Response profiles to constant and shuffled configurations

Analysis of the response types (correct, incorrect, omissions) revealed a pattern of responses that separated constant from shuffled configurations from day 2 onwards (Figure 2, Table 1, Supplementary Table 5). In the constant condition, the most pronounced increase in correct response rates was observed from day 1 to day 2, whereas subsequent improvement was only moderate —a phenomenon that we had already observed during a behavioral piloting phase in ten healthy volunteers who did not participate in the main experiment (E.L. and B.S., unpublished observations). Such negatively accelerated learning curves are a well-known phenomenon in conditioning as described by Rescorla and Wagner (1972), and they have been observed in spatial learning experiments at different time scales (Fatima et al., 2016), and are commonly interpreted as reflecting ceiling effects. The fact that the learning rate was markedly lower on days 3-5 compared to days 1-2 probably reflects the high difficulty of the task, although it is, in our view, rather likely that participants' performance would have further improved if additional training sessions had been performed over a more extended time window (Sommer, 2017).

While the performance increase in the constant condition was highly expected, shuffled configurations were also associated with a distinctive development of participants' response patterns from day 1 to day 5. While only a marginal increase of correct response rates could be observed, participants did show a continuous decrease in response omission

and a corresponding increase in incorrect response rates (Supplementary Table S5). One possible explanation for this response pattern may be associative interference from repeatedly presented icons. As described in the methods section, icons were presented in three to seven different configurations, and different positions of the same icon in other trials. As the same icon could be presented in both conditions, we suspect that, while interference might have arisen particularly from the stronger representations of the constant condition, as, for example, commonly observed with the retrieval-practice paradigm and the phenomenon of retrieval-induced forgetting and strength-dependent interference (Anderson, Bjork, & Bjork, 1994; Bäuml, 1997; Wimber et al., 2011; Verde, 2013).

A non-linear relationship between icon position during familiarization and memory performance on Day 1

An unexpected result of our analyses was a significant difference in memory performance between the constant and the shuffled conditions already on day 1 (see Table 1 of the main manuscript). Detailed control analyses showed that the only difference between (subsequently) constant and (subsequently) shuffled items on day 1 was the serial position of the background pictures during the familiarization phase. While we acknowledge that the performance difference constitutes a limitation, particularly with respect to extrastriate activations (Supplementary Figure S4), this incidental observation also highlights the importance of the background pictures in the learning process. As icons were not unique to a specific configuration, merely studying the icon configurations, ignoring the background pictures, would have been highly unlikely to result in a performance difference on day 1.

Effects of temporal –or serial– position on memory performance are a well-known phenomenon and occur most prominently as primacy and recency effects that have been observed in several different species (Wright et al., 1985). In the present study, no classic primacy or recency effects of the serial position of background pictures during familiarization could be observed on recognition performance on day 1. As depicted in Figure S3, the relationship between the temporal position of the background pictures during familiarization and recognition of the configurations on Day 1 was nevertheless not random. The pattern shown in Figure S3 is suggestive for the relationship being best characterized by a slow drift with a negative slope and superimposed oscillatory fluctuations. Brain states during (Otten et al., 2002) or even before (Guderian et al., 2009) the occurrence of an item have been associated with successful explicit memory formation, and it is tempting to conclude that a fluctuation of such states may underlie the observed relationship between serial position and memory performance. However, given the lack of an *a priori* hypothesis regarding this incidental observation and the thus far descriptive nature of the observed relationship, future studies need to be conducted to systematically investigate this intriguing possibility.

Brain-behavior correlations and statistical power

We observed a positive correlation between the BOLD response of the precuneus during presentation of constant versus shuffled configurations and the recognition rate of the (altered) configurations in the delayed memory test (Figure 5, main manuscript). While this observation further supports the notion that the precuneus actually supports long-term memory for visuo-spatial information, it must be noted that brain-behavior correlations have been criticized in the recent years for various reasons. Most prominently, Vul and colleagues (2009) have demonstrated that, particularly in social neuroscience, brain-behavior correlations have been commonly based on non-independently selected sets of voxels (“double-dipping”), resulting in inflated correlation coefficients and significance levels. In the present study, we had selected the peak voxel from a one-sample *t*-test at group level testing the contrasts between the two conditions (constant and shuffled) on Day 2 and 5 at the single-subject level against zero. It was thus selected independently from the behavioral measure of interest (recognition in the delayed memory test). Another issue that has been raised with respect to brain-behavior correlations is the common occurrence of outliers, which have been shown to increase the risk for false-positive correlations (Rousselet and Pernet, 2012). Several methods have been proposed to detect and exclude outliers (Rousselet and Pernet, 2012; Schwarzkopf et al., 2012). In our study, outlier exclusion using Shepherd’s *Pi* correlation (Schwarzkopf et al., 2012) did not affect the sign or significance of the correlation between precuneus activation during study of constant configurations and delayed recognition rate.

Nevertheless, the sample size may constitute a limitation. In a commentary to the widely cited work by Vul and colleagues (2009), Yarkoni (2009) argued that correlational analyses inherently bear a more fundamental problem, namely their substantially lower statistical power in comparison to *t* statistics. According to the simulations performed by Yarkoni (2009), the power to detect a correlation of $r = .4$ with a significance level of $p < .05$, as in the present study, would be approximately .6 in a population of 30 participants, but the power would drop to about .2 when assuming that the true r was closer to .2 (see Yarkoni, 2009, Figure 1). Yarkoni pointed to the risk of low power leading not only to under-reporting of small, but significant effects, but also to inflated r values and to effects appearing more circumscribed than they truly are. Button and colleagues (2013) have further pointed out that low power increases the risk of reporting false positive results, as it decreases the positive predictive value. Therefore, given the moderate sample size in our study ($N = 31$), we consider the positive correlation of precuneus activation and delayed memory performance as additional evidence for a critical role of the precuneus in spatial associative memory, but we acknowledge that the result must be interpreted with some caution.

Supplementary Figures

Figure S1: Plots of session- and run-specific, mean motion parameter estimates. *Abbreviations: transX, transY, transZ – translation parallel to the x, y and z-axis respectively, transED – translation associated Euclidean distances.*

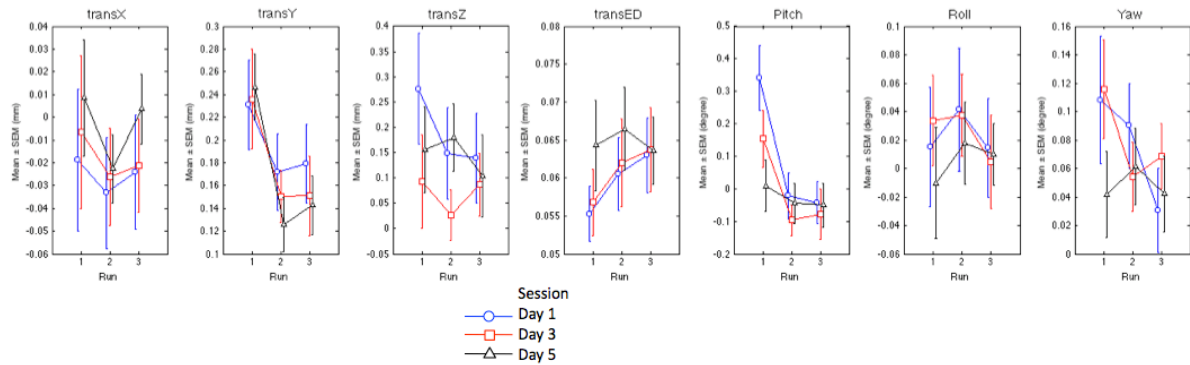


Figure S2: Literature-based anatomical parcellation of the precuneus. Panel (A): Fitted 3D-gaussians for the dorsal and ventral coordinate set. (B) Final binarized regions of interest (ROIs), additionally masked with anatomical boundaries defined by ROIs from the Automated Anatomical Labeling (AAL) atlas. Binarization was done by means of maximum probability voxel assignment.

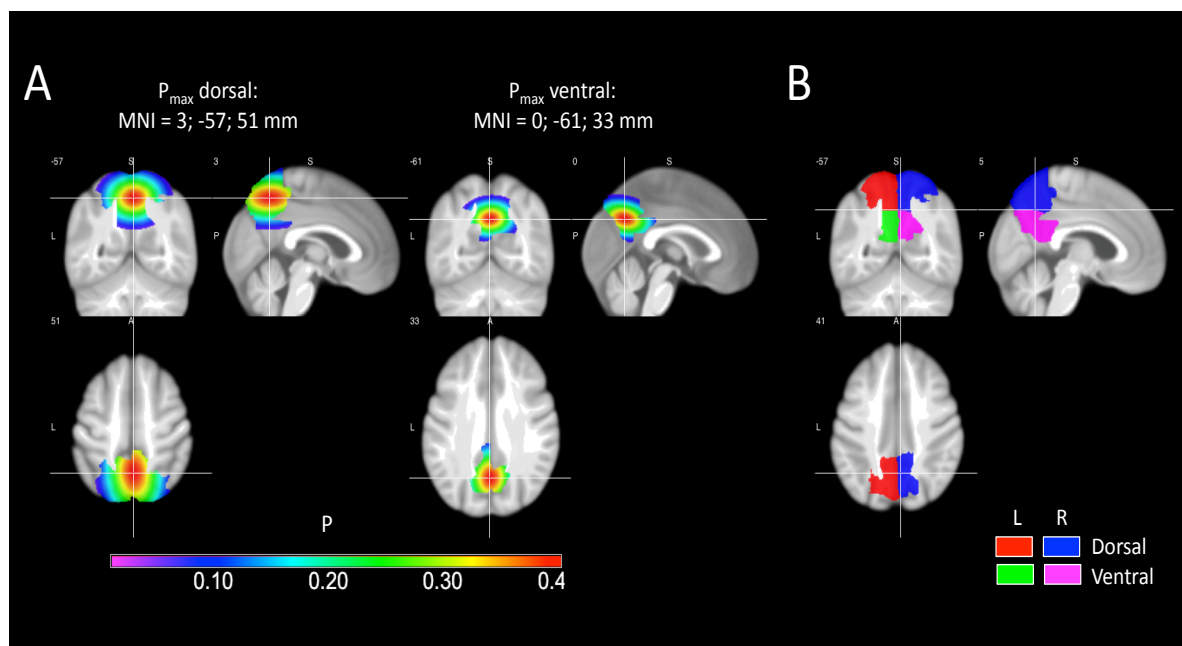


Figure S3: The estimated relationship between the temporal positions of the background pictures during familiarization and performance on Day 1. Plots depict the average rates of correct (A) and incorrect (B) responses as a function of position (sliding window ± 5 background pictures) across all subjects. Error bars show standard errors of the mean.

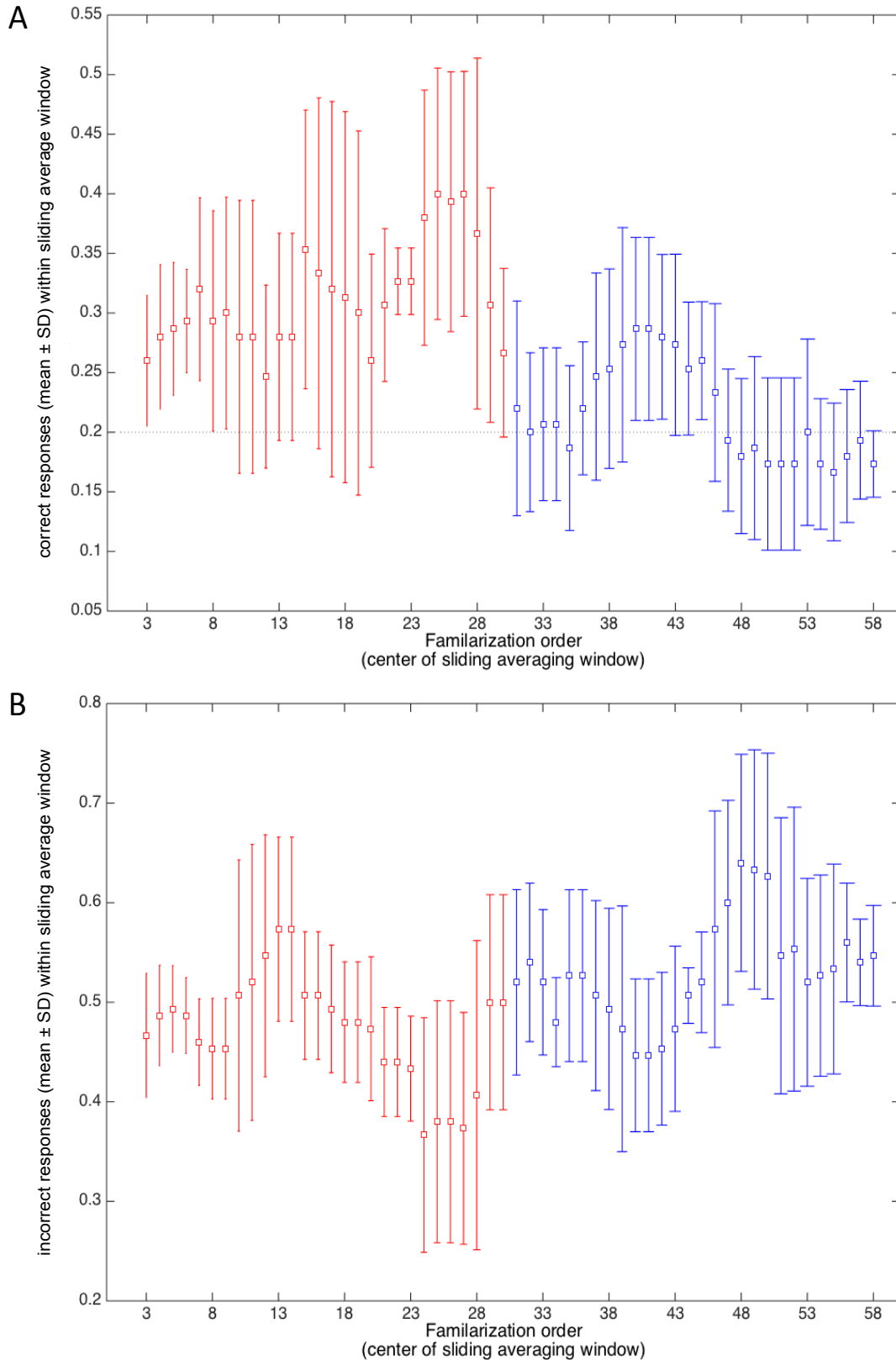
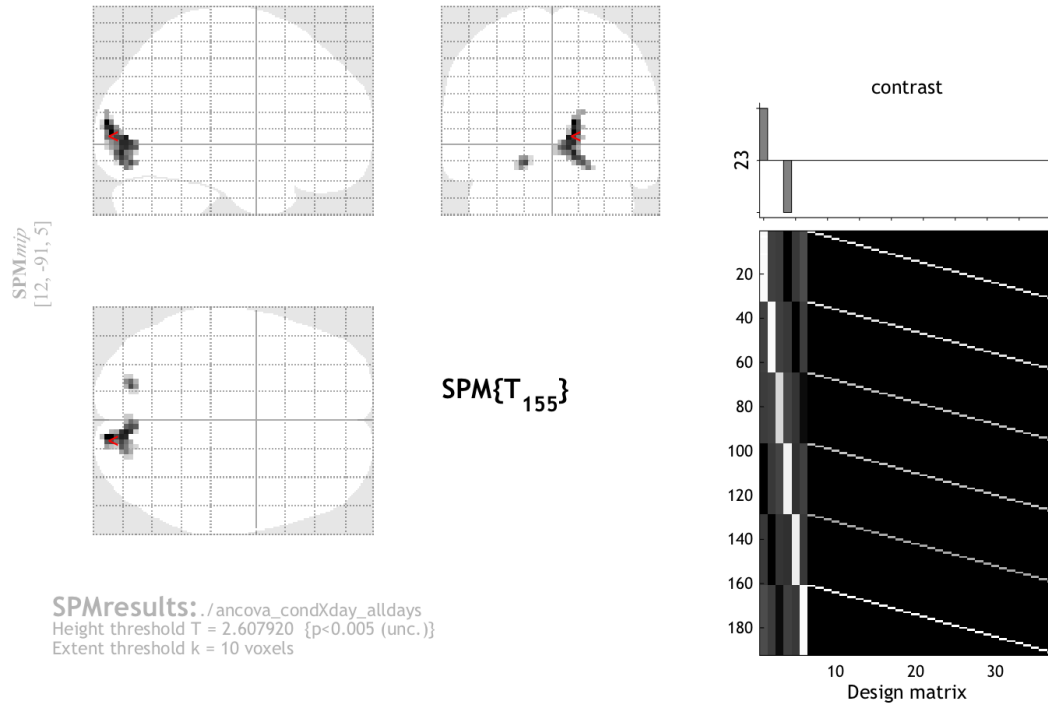


Figure S4: SPM contrast testing the BOLD responses to (subsequently) constant versus (subsequently) shuffled configurations on Day 1. For illustrative purposes, contrasts of parameter estimates are shown at $p < .005$, uncorrected, with a minimum cluster size of 10 adjacent voxels. At $p < .001$, uncorrected, no significant activation differences were observed with the same minimum cluster size.



Supplementary Tables

Table S1: Results of repeated measures 3 x 3 ANOVA for the six rigid-body motion parameter estimates and translation-associated Euclidean distances of head displacement.

	ME sess	ME run	Interaction
transX	$F(1.6,49.8) = 0.65$ ($p = .495$); $\eta^2 = .020$	$F(1.7,53.0) = 0.57$ ($p = .541$); $\eta^2 = .018$	$F(3.3,102.7) = 0.09$ ($p = .972$); $h^2 = .003$
transY	$F(1.7,52.2) = 0.31$ ($p = .700$); $\eta^2 = .010$	$F(1.2,37.5) = 5.64$ ($p = .018$); $\eta^2 = .154$	$F(2.7,82.4) = 0.37$ ($p = .750$); $\eta^2 = .012$
transZ	$F(1.8,56.6) = 1.59$ ($p = .215$); $\eta^2 = .049$	$F(1.6,49.8) = 0.55$ ($p = .542$); $\eta^2 = .017$	$F(3.2,100.2) = 0.75$ ($p = .534$); $\eta^2 = .024$
transED	$F(1.9,59.0) = 1.37$ ($p = .261$); $\eta^2 = .042$	$F(1.5,47.6) = 3.35$ ($p = .056$); $\eta^2 = .097$	$F(2.6,81.7) = 1.09$ ($p = .354$); $\eta^2 = .034$
Pitch	$F(1.6,50.2) = 2.06$ ($p = .146$); $\eta^2 = .062$	$F(1.7,53.0) = 10.60$ ($p < .001^*$); $\eta^2 = .255$	$F(3.0,91.9) = 2.38$ ($p = .076$); $\eta^2 = .071$
Roll	$F(1.9,60.2) = 0.35$ ($p = .699$); $\eta^2 = .011$	$F(1.5,48.0) = 0.51$ ($p = .558$); $\eta^2 = .016$	$F(3.0,94.5) = 0.215$ ($p = .889$); $\eta^2 = .007$
Yaw	$F(1.9,58.3) = 1.14$ ($p = .326$); $\eta^2 = .035$	$F(1.7,51.2) = 1.20$ ($p = .304$); $\eta^2 = .037$	$F(3.4,105.0) = 1.42$ ($p = .237$); $\eta^2 = .044$

Reported are F-values and effect sizes. The only Bonferroni-corrected significant finding is shaded in gray. For a graphical depiction see Supplementary Figure 4. *Abbreviations:* ME – main effect; sess – experimental session or Day 1, 3 and 5 respectively; transX, transY, transZ – translation parallel to the x, y and z-axis respectively, transED – translation associated Euclidean distances; * - significant at $p < .05$ (Bonferroni corrected for multiple comparisons). Degrees of freedom are Greenhouse-Geisser corrected for sphericity violation.

Table S2: Coordinates employed for generation of the probabilistic mPFC ROI.

Author, year	Contrast	[x y z]	Ref. space
Sommer, 2017	related > control paired associates	-6 48 -10	mni
	retrieval of related paired associates	0 56 -8	mni
van Buuren et al., 2014	memory representation > no representation	0 14 10	mni
		4 38 4	mni
		4 56 4	mni
	interaction representation X set	0 14 42	mni
		4 38 4	mni
		4 63 14	mni
van Kesteren et al., 2013	congruent > incongruent representation	-2 40 2	mni
	interaction congruency X memory	2 46 0	mni
van Kesteren et al., 2014	interaction congruency X memory	2 46 0	mni
van Kesteren et al., 2010	representation-related synchronization	-4 24 -21	mni
Schlichting et al., 2015	separation (main effect)	1 58 -20	mni
	integration (main effect)	-8 44 -17	mni
	interaction intgration X learning	3 15 -17	mni
		-7 18 -24	mni
Kizilirmak et al., 2016	insight > control	-14 43 26	mni
Brod et al., 2015	schema-congruent successful retrieval	-10 44 -6	mni
	interaction congruency X retrieval success	-4 32 -16	mni
Mack et al., 2016	learning-related hippocampal connectivity	10 43 -6	mni

Coordinates are shown as in the respective original references in either Montreal Neurological Institute (mni) or Talairach (tal) reference space.

Table S3: Coordinates employed for generation of the probabilistic ventral precuneus ROI.

Reference	contrast	x	y	z	MNI/Tal	overlap
Addis et al., 2012	autobiographic retrieval > imagery	4	-60	12	mni	
	generative > direct retrieval	-12	-72	20	mni	
Basso et al., 2013	picture naming high > low frequency	-25	-61	39	tal	
	picture naming trained > untrained	-4,4	-71	31	tal	
Blondin & Lepage, 2008	recognition high > low discriminability	-12	-60	16	mni	
Bradley et al., 2015	repetition enhancement	-14	-63	26	tal	
Brodts et al., 2016	intecation condition X day	15	-63	33	mni	
		-12	-67	30	mni	
Burianova et al., 2012	overlapp bottom-up & top-down AtoM	20	-68	36	mni	+
		24	-68	52	mni	+
		-12	-76	40	mni	+
Chow et al., 2018	memory self vs. other	-3	-60	27	mni	
		39	-54	45	mni	
Compere et al., 2016	autobiographic memory > control	-6	-54	30	mni	
Daselaar et al., 2009	encoding-retrieval flip (faces)	-12	-43	34	tal	
	encoding-retrieval flip (scenes)	11	-49	28	tal	
	encoding-retrieval flip (word pairs)	4	-50	30	tal	
	encoding-retrieval flip (words, Exp. 4)	8	-42	37	tal	
	encoding-retrieval flip (words, Exp. 5)	-8	-42	33	tal	
Daselaar et al., 2008	memory access > elaboration	4	-54	20	tal	
de Zubicaray et al., 2005	retrieval hits > correct rejections	-33	-60	45	mni	
Dhindsa et al., 2014	judgment of relative direction	29	-56	21	tal	
		2	-53	24	tal	
Donaldson et al., 2001	recognition old > new	10	-66	30	tal	
		-7	-69	30	tal	
		-4	-45	30	tal	
		37	-69	36	tal	
Dörfel et al., 2009	remember vs. miss	-3	-60	30	mni	
	know vs. miss	-6	-60	27	mni	
Duarte et al., 2011	source > no source (retrieval)	12	-45	15	mni	
		-6	-51	27	mni	
Elman et al., 2013a	personally familiar > studied	-6	-62	12	mni	
		-12	-60	14	mni	
		14	-58	16	mni	
Elman et al., 2013b	negative subsequent memory effect	10	-68	32	mni	
Elman & Shimamura, 2011	high confidence recognition > new	-6	-66	24	mni	
		-10	-58	20	mni	
Frithsen & Miller, 2014	remember > know	-9	-43	34	mni	
	source > no source (retrieval)	-6	-58	28	mni	
Gardini et al., 2006	retrieval (autobiographic > specific)	-8	-63	20	tal	
		8	-54	12	tal	
		-10	-54	12	tal	
Gomes et al., 2016	intact > recombined (recognition)	12	-50	24	mni	
	conjunction priming & recognition	-26	-72	28	mni	
		32	-68	32	mni	
Gomez et al., 2013	egocentric > allocentric recognition	-6	-63	19	tal	
	recognition hits > correct rejections	-6	-68	39	tal	
Gvozdanovic et al., 2017	experimental trauma, explicit retrieval	14	-72	34	mni	
		24	-64	16	mni	
		-6	-72	32	mni	
		-14	-64	22	mni	
		-14	-72	38	mni	
Habeck et al., 2005	DMS, stimulus phase, deactivations	-10	-49	30	tal	
	DMS, maintenance phase, deactivations	10	-63	31	tal	
		-8	-59	29	tal	
	DMS, probe phase, deactivations	-6	-52	45	tal	
Habib & Nyberg, 2008	recall + recognition > forgotten	-2	-74	40	tal	
Herron et al., 2003	main effect old > new	-12	-66	39	mni	
		-33	-72	30	mni	
		9	-63	33	mni	
		36	-66	36	mni	
		9	-39	18	mni	
Hirose et al., 2013	retrieval no recency > recency	-18	-64	30	mni	
		-28	-76	40	mni	
		-32	-76	28	mni	
		-12	-64	18	mni	
Hirshhorn et al., 2012	retrieval > baseline	-4	-58	14	tal	
		38	-74	36	tal	

Hornberger et al., 2006	hits > correct rejections, across conditions	-38	-78	32	tal	
Hutchinson et al., 2015	memory strength	6	-75	42	mni	+
Hutchinson et al., 2014	any source > item only	-12	-66	36	mni	
		-3	-57	27	mni	
		-3	-69	36	mni	
		-3	-39	6	mni	
		-15	-69	27	mni	
Iidaka et al., 2006	hits > repetitions	-4	-42	10	mni	
Jessen et al., 2001	first repetition > novel	-6	-72	27	tal	
	second repetition > novel	-6	-69	27	tal	
Kim & Cabeza 2009	recognition (high & low confidence)	28	-72	46	tal	+
		-34	-64	46	tal	+
	high confidence recognition	-11	-50	34	tal	
Klostermann et al., 2008	high confidence recognition abstract	-28	-72	40	tal	
		22	-74	44	tal	
Kompus et al., 2010	incidental > intentional retrieval	-10	-72	32	mni	
Kondo et al., 2005	recall (uninstructed)	12	-74	28	tal	
	recall (method of loci)	-4	-76	46	tal	+
		4	-74	30	tal	+
Kwok & Macaluso, 2015	scene recognition	3	-42	35	mni	
Kwok et al., 2012	retrieval temporal > spatial	14	-60	28	mni	
		-8	-70	26	mni	
Liu Q et al., 2014	negative subsequent memory effect	2	-54	34	mni	
		10	-50	28	mni	
Lundström et al., 2005	correct sources > misses	-4	-40	32	mni	
		-6	-78	42	mni	
Lundström et al., 2003	source memory imagined > new	-6	-64	30	mni	
		-6	-70	36	mni	
	source memory viewed > new	-10	-68	26	mni	
Maillet & Rajah, 2016	pleasantness rating > semantic encoding	-4	-50	26	mni	
Manelis et al., 2016	old > partially new > new	12	-64	24	mni	
	old > partially new & old > new	12	-50	32	mni	
McDermott et al., 2017	hits > corr. rej.; false alarms > corr. rej.	-4	-67	30	tal	
		-4	-47	27	tal	
		9	-55	31	tal	
Morcom & Rugg, 2012	old > new (targets)	10	-72	44	mni	+
Nadel et al., 2007	autobiographic memory > rest	-6	53	31	tal	
		8	-53	29	tal	
Nelson et al., 2013	tested > restudied > no practice	-8	-73	36	mni	+
Otten et al., 2002	subsequent memory effect (state)	-3	-60	30	mni	
Philips et al., 2009	retrieval preparation	-28	-73	24	tal	
		29	-74	25	tal	
	retrieval phase	-14	-68	25	tal	
		-15	-72	47	tal	
Raposo et al., 2016	semantic > perceptual encoding	-4	-54	16	mni	
Reas & Brewer, 2013	memory strength (high > low)	34,9	-70,6	23,1	tal	
Rekkas & Constable, 2005	recent memory retrieval	-7	-48	30	tal	
		7	-48	30	tal	
	remote memory retrieval	-9	-48	20	tal	
		9	-48	20	tal	
Rosen et al., 2018	retrieval > stimulus-guided attention	-4,8	-80,4	23,8	mni	
		6,9	-78,8	20,1	mni	
	memory-guided > stimulus-guided attention	-13,6	-67,4	39,6	mni	+
		6,9	-65,2	40,9	mni	+
Schott et al., 2005	retrieval > priming	-9	-60	31	tal	
		-6	-54	33	tal	
Schott et al., 2013	hippocampal connectivity (deep study)	3	-57	45	tal	+
		6	-45	50	tal	+
	hippocampal connectivity (shallow study)	0	-72	35	tal	+
		6	-65	51	tal	+
Sestieri et al., 2011	memory search > baseline	-2	64	24	tal	
Sheldon & Levine, 2018	hippocampal conn. (autobiograph. retrieval)	8	-52	16	mni	
		4	-56	34	mni	
Smith & Squire, 2009	age of memory	26,2	-83,7	36,1	tal	
Sommer et al., 2006	primacy effect	18	-75	30	mni	
		-12	-84	30	mni	
	subsequent memory effect	12	-75	21	mni	
		-3	-78	24	mni	
St Jacques et al., 2018	episodic counterfactual simulation	-4	-68	38	mni	
Sagiura et al., 2009	face recognition (personally familiar)	-10	-62	42	mni	+
	face recognition (famous)	-4	-56	44	mni	+

	face recognition (unfamiliar)	-2	-56	38	mni	+
Saguira et al., 2005	familiar > unfamiliar	-4	-72	36	tal	
Takahashi et al., 2009	hits > correct rejections	24	-62	22	tal	
Takashima et al., 2007	stable > labile memory	-4	-54	36	mni	
		2	-50	34	mni	
Trinkler et al., 2009	main effect of recollection	-6	-87	12	mni	
		-30	-84	30	mni	
Uncapher et al., 2006	subsequent memory effect (features)	24	-72	27	mni	
van der Linden et al., 2017	parametric schema effect	15	-46	40	tal	+
van Mulukom et al., 2013	repeated future imagery	14	-66	36	mni	
Vilberg and Rugg, 2009	hits > correct rejections	18	-57	18	mni	
von Zerssen et al., 2001	hits > correct rejections	-5	-69	35	tal	
	old & related > new	-8	-69	30	tal	
	related > new	-8	-64	36	tal	
		1	-67	31	tal	
	related false alarms > new	-8	-68	40	tal	
		1	-70	32	tal	
Weymar et al., 2018	repetition enhancement	-6	-70	25	mni	
		13	-68	25	mni	
Wimber et al., 2008	retrieval practice > no practice	2	-54	36	mni	+
		8	-62	36	mni	+
		-10	-56	36	mni	+
		-10	-64	48	mni	+
		10	-74	32	mni	+
		16	-66	56	mni	+
		10	-70	52	mni	+
Wimber et al., 2010	subsequent priming effect	-12	-60	21	mni	
		12	-57	24	mni	
		9	-54	33	mni	
	subsequent memory effect	-15	-81	42	mni	
Yamawaki et al., 2017	self-referential face encoding (hipp. conn.)	-2	-74	37	mni	
		17	-51	37	mni	
Yonelinas et al., 2005	increase with familiarity	9	-72	36	mni	
Zeithamova et al., 2008	prototype learning	-20	-60	36	mni	+
		22	-64	48	mni	+

Coordinates are shown as in the respective original references in either Montreal Neurological Institute (mni) or Talairach (tal) reference space. "Overlap" denotes coordinates used in both ROIs.

Table S4: Coordinates employed for generation of the probabilistic dorsal precuneus ROI.

Reference	contrast	x	y	z	MNI/Tal	overlap
Addis et al., 2012	imagery > autobiographic retrieval	12	-64	48	mni	
	direct > generative retrieval	-4	-56	40	mni	
		36	-52	40	mni	
Aso et al., 2007	object orientation (rotation) > baseline	-32	-60	49	tal	
	object orientation (translation) > baseline	26	-67	49	tal	
Blondin & Lepage, 2008	recognition low > high discriminability	-16	-54	54	mni	
		-12	-70	62	mni	
		34	-42	38	mni	
Bradley et al., 2015	processing of novel scenes	-26	-62	45	tal	
		26	-63	47	tal	
Brod et al., 2015	successful > unsuccessful retrieval	18	-42	70	mni	
	schema-incongruent successful retrieval	-6	-76	52	mni	
		-4	-36	48	mni	
Brodt et al., 2016	decision > no decision	15	-73	52	mni	
		9	-63	60	mni	
		-9	-85	46	mni	
Burianova et al., 2012	overlapp bottom-up & top-down AtoM	20	-68	36	mni	+
		24	-68	52	mni	+
		-12	-76	40	mni	+
Cabeza et al., 2011	orienting-related activity	-26	-67	45	tal	
		30	-52	45	tal	
		11	-71	39	tal	
Chow et al., 2018	previewed vs. not previewed	-33	-75	39	mni	
Daselaar et al., 2008	memory elaboration > access	-26	-52	58	tal	
de Zubicaray et al., 2005	retrieval correct rejections > hits	6	-63	60	mni	
		21	-63	21	mni	
Dhindsa et al., 2014	pointing from imagery	23	-56	48	tal	
		8	-44	45	tal	
		-28	-47	51	tal	
Duarte et al., 2011	no source > source (encoding)	-9	-69	42	mni	
		15	-66	39	mni	
Elman et al., 2013a	studied > personally familiar	-36	-52	52	mni	
		-32	-58	56	mni	
		38	-44	54	mni	
		34	-52	54	mni	
Elman et al., 2013b	positive subsequent memory effect	-21,9	-59	51,8	mni	
		23,8	-61	50,6	mni	
Frings et al., 2006	encoding vs. viewing	36	-72	33	mni	
		-24	-53	57	mni	
	recognition vs. viewing	-15	-66	30	mni	
		0	-63	57	mni	
	(encoding + recognition) > viewing	3	-63	57	mni	
	encoding > control (encoding)	-24	-69	57	mni	
		15	-66	54	mni	
	recognition > control (recognition)	18	-75	45	mni	
		-9	-75	48	mni	
	(encoding + recognition) > control	-24	-69	57	mni	
	15	-66	54	mni		
Frithsen & Miller, 2014	know > new	-9	-70	43	mni	
	no source hits > correct rejections	36	-73	40	mni	
Gardini et al., 2006	retrieval (specific > autobiographic)	-30	-67	49	mni	
		24	-78	30	tal	
		16	-74	39	tal	
		26	-59	64	tal	
		34	62	45	tal	
Gomes et al., 2016	recombined > new (priming)	34	-54	49	tal	
		2	-64	36	mni	
	recombined > new (recognition)	-32	-46	38	mni	
		36	-62	46	mni	
Gomez et al., 2013	egocentric-updated specific processing	-36	-77	43	mni	
Habeck et al., 2005	DMS, stimulus phase, activations	-2	-72	46	tal	
Hales & Brewer, 2011	associative > item only	14	-45	72	tal	
Hales & Brewer, 2013	location > no location	26	-65	24	tal	
		-14	-57	48	tal	
Handy et al., 2004	imagery pictures > nouns	15	-72	36	tal	
		36	-57	45	tal	
Herron et al., 2003	encoding pictures > baseline	-30	-63	51	tal	
	interaction old-new X probability	-39	-30	54	mni	

Hirose et al., 2013	retrieval recency > no recency	-33	57	60	mni	
Hirshhorn et al., 2012	difficult allocentric retrieval	6	-48	42	mni	
		22	-62	20	tal	
		10	-78	52	tal	
Hornberger et al., 2006	hits > correct rejections, across conditions	6	-75	42	mni	+
Hutchinson et al., 2015	decision uncertainty	15	-69	57	mni	
		-9	-72	57	mni	
	decision uncertainty (PPI)	-12	-66	60	mni	
Hutchinson et al., 2014	item only > correct rejections	-12	-66	45	mni	
		-12	-63	60	mni	
	task source > specific source	-15	-66	54	mni	
		18	-66	51	mni	
Iidaka et al., 2006	hits > correct rejections	6	-74	46	mni	
Jessen et al., 2001	second > first repetition	6	-57	42	tal	
Jordan et al., 2004	navigation > control	12	-76	56	mni	
Kim & Cabeza 2009	recognition (high & low confidence)	28	-72	46	tal	+
		-34	-64	46	tal	+
	low confidence recognition	11	-61	52	tal	
Klostermann et al., 2008	high confidence recognition concrete	24	-78	48	tal	
		-8	-62	26	tal	
Klostermann et al., 2009	positive subsequent memory effect	-14	-72	62	mni	
		24	-44	76	mni	
	hits > correct rejections	-10	-60	60	mni	
		-12	-66	-70	mni	
		12	-50	56	mni	
Kompus et al., 2010	intentional > incidental retrieval	24	-50	56	mni	
		-12	-62	70	mni	
Kondo et al., 2005	encoding (method of loci)	-6	-80	48	tal	
	recall (method of loci)	-4	-76	46	tal	+
		4	-74	30	tal	+
Kwok & Macaluso, 2015	scene chronology	6	-54	47	mni	
	scene layout	-21	-66	59	mni	
		21	-63	59	mni	
Kwok et al., 2012	retrieval spatial > temporal	-18	-72	54	mni	
		24	-70	56	mni	
Lambrey et al., 2012	spatial perspective taking (encoding)	12	-66	54	mni	
		-3	-54	54	mni	
		-12	-60	54	mni	
	spatial perspective taking (delay)	27	-72	54	mni	
Lundström et al., 2005	correct sources > false alarms	12	-74	54	mni	
		22	-74	52	mni	
		-6	70	60	mni	
Lundström et al., 2003	source > item memory imagined	-12	-64	46	mni	
	source memory imagined > viewed	-18	-66	40	mni	
	item memory viewed > new	-2	-64	42	mni	
Maillet & Rajah, 2016	item > source memory	6	-78	50	mni	
		-4	76	52	mni	
		4	-66	60	mni	
Minamoto et al., 2012	distracters forgotten > remembered	2	-48	41	tal	
		0	72	42	tal	
		8	-47	63	tal	
Morcom & Rugg, 2012	old > new (targets)	10	-72	44	mni	+
Nadel et al., 2007	multiple > recent retrieval	9	-67	48	tal	
		-15	-47	52	tal	
		15	-65	51	tal	
		-25	53	39	tal	
Nelson et al., 2013	tested > restudied > no practice	-8	-73	36	mni	+
Otten et al., 2002	negative subsequent memory effect (state)	0	-54	60	mni	
Pollmann et al., 2003	visual marking of distractors	7	-65	50	tal	
		-7	-62	52	tal	
		-3	-57	48	mni	
Richter et al., 2016	memory vividness	-3	-57	48	mni	
Rosen et al., 2018	memory-guided > stimulus-guided attention	-13,6	-67	39,6	mni	+
		6,9	-65	40,9	mni	+
	stimulus-guided attention > retrieval	15,9	-58	57,4	mni	
Schinazi & Epstein, 2010	navigation; decision > no decision	3	-61	59	mni	
		17	-61	63	mni	
		-16	-60	63	mni	
Schott et al., 2013	hippocampal connectivity (deep study)	3	-57	45	tal	+
		6	-45	50	tal	+
	hippocampal connectivity (shallow study)	0	-72	35	tal	+
		6	-65	51	tal	+

Sheldon & Levine, 2018	hippocampal conn. (spatial retrieval)	8	-70	54	mni	
		0	-34	70	mni	
Shelton & Gabrieli, 2002	spatial encoding (routes)	6	-45	54	mni	
		-18	-63	60	mni	
		15	-63	57	mni	
	spatial encoding (survey)	-18	-66	60	mni	
		15	-63	57	mni	
Smith & Squire, 2009	encoding of test questions	-3,7	-52	67,4	tal	
Sommer et al., 2005	subsequent memory effect (spatial)	27	-60	54	mni	
		-15	-78	54	mni	
St Jacques et al., 2017	perspective shift during retrieval	0	-60	44	mni	
Stock et al., 2009	visual encoding locations > objects	6	-58	44	tal	
		-5	-59	45	tal	
Sagiura et al., 2009	face recognition (personally familiar)	-10	-62	42	mni	+
	face recognition (famous)	-4	-56	44	mni	+
	face recognition (unfamiliar)	-2	-56	38	mni	+
Saguira et al., 2005	places > objects	2	-46	42	tal	
Takashima et al., 2007	stable & labile > no memory	16	-66	54	mni	
		12	-68	67	mni	
Uncapher & Rugg, 2005	encoding / divided attention (hard > easy)	24	-60	57	mni	
Uncapher & Rugg, 2009	feature-specific encoding of location	9	-54	69	mni	
		-12	45	60	mni	
van Assche et al., 2016	familiar > unfamiliar places	0	-67	52	mni	
van der Linden et al., 2017	parametric schema effect	15	-46	40	tal	+
Wimber et al., 2008	retrieval practice > no practice	2	-54	36	mni	+
		8	-62	36	mni	+
		-10	-56	36	mni	+
		-10	-64	48	mni	+
		10	-74	32	mni	+
		16	-66	56	mni	+
		10	-70	52	mni	+
Yang et al., 2017	object location (source of N1 ERP effect)	-22	-66	45	mni	
Yu & Shin, 2017	visual working memory maintenance	-24,6	-62	47,3	tal	
		18,5	-63	51,4	tal	
Zeithamova et al., 2008	prototype learning	-20	-60	36	mni	+
		22	-64	48	mni	+

Coordinates are shown as in the respective original references in either Montreal Neurological Institute (mni) or Talairach (tal) reference space. "Overlap" denotes coordinates used in both ROIs.

Table S5: Response rates, separated by condition and day.

	Constant		Shuffled	
	Mean	Std. Dev.	Mean	Std. Dev.
Day 1				
correct	.288	.1223	.201	.0819
incorrect	.440	.1506	.499	.1807
omissions	.273	.1970	.300	.2159
adjusted recognition	.398	.1501	.294	.1463
Day 2				
correct	.431	.1347	.252	.1033
incorrect	.388	.1311	.538	.1806
omissions	.181	.1635	.210	.2128
adjusted recognition	.524	.1411	.325	.1321
Day 3				
correct	.484	.1328	.291	.0925
incorrect	.380	.1712	.555	.1652
omissions	.135	.1547	.154	.1454
adjusted recognition	.570	.1517	.354	.1220
Day 4				
correct	.514	.1414	.318	.1016
incorrect	.388	.1853	.528	.1725
omissions	.099	.1118	.154	.1586
adjusted recognition	.580	.1795	.388	.1494
Day 5				
correct	.533	.1597	.294	.1216
incorrect	.365	.1606	.553	.1714
omissions	.102	.1253	.153	.1531
adjusted recognition	.596	.1644	.353	.1539
Delayed memory				
correct	.274	.1300	.217	.0924
incorrect	.521	.2201	.554	.2173
omissions	.205	.2206	.229	.2414
adjusted recognition	.359	.1645	.300	.1306

Adjusted recognition: recognition rates adjusted for uncertainty as indicated by omitted responses (correct / [1-omissions]). Std. Dev. = standard deviation.

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