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Childhood Poverty is Associated with Altered Hippocampal Function and Visuospatial Memory in Adulthood

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Abstract

Childhood poverty is a risk factor for poorer cognitive performance during childhood and adulthood. While evidence linking childhood poverty and memory deficits in adulthood has been accumulating, underlying neural mechanisms are unknown. To investigate neurobiological links between childhood poverty and adult memory performance, we used functional magnetic resonance imaging (fMRI) during a visuospatial memory task in healthy young adults with varying income levels during childhood. Participants were assessed at age 9 and followed through young adulthood to assess income and related factors. During adulthood, participants completed a visuospatial memory task while undergoing MRI scanning. Patterns of neural activation, as well as memory recognition for items, were assessed to examine links between brain function and memory performance as it relates to childhood income. Our findings revealed associations between item recognition, childhood income level, and hippocampal activation. Specifically, the association between hippocampal activation and recognition accuracy varied as a function of childhood poverty, with positive associations at higher income levels, and negative associations at lower income levels. These prospective findings confirm previous retrospective results detailing deleterious effects of childhood poverty on adult memory performance. In addition, for the first time, we identify novel neurophysiological correlates of these deficits localized to hippocampus activation.

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Keywords

visuospatial memory; hippocampus; fMRI; childhood poverty

1. Introduction

Childhood poverty is a risk factor for problems in cognition (Adler et al. 2012; Bradley & Corwyn 2002; Hackman et al. 2010; Hackman & Farah 2009), which likely contribute to robust income achievement gaps, deficits in math and reading, increased school drop-out, and decreased graduation rates among the poor (Brooks-Gunn & Duncan 1997; Duncan 2012). The impact of poverty is complex and linked to various environmental risk factors, including parenting, school, and neighborhood quality (Brooks-Gunn & Duncan 1997), that often co-occur. Living in poverty is more stressful, which can have detrimental effects on cognitive development (Evans 2003) and working memory (Evans & Schamberg 2009). Thus, poverty-related factors may impact brain function and cognitive development. Since these factors both co-occur and interact, it is very difficult to isolate single factors that lead to developmental differences from the overall effects of the complex construct of poverty as a whole, both experimentally and conceptually.

Deficits in memory encoding and recognition are hallmarks of poverty effects in children (Farah et al. 2006; Noble et al. 2007) and adults (Herrmann & Guadagno 1997). The association between family income and memory performance is mediated, in part, by chronic stress exposure (Evans & Schamberg 2009; Evans 2003). Findings linking poverty and its associated risk factors to cognitive impairment, including poorer memory (Lipina & Posner 2012; Raizada & Kishiyama 2010), highlight the potentially key role of the hippocampus. The hippocampus plays both a central role in memory (Scoviille & Milner 1957; Jarrard 1993; Vann & Albasser 2011; Lavenex & Lavenex 2009) and is sensitive to chronic stress during early development (McEwen & Magarinos 2001; Meaney et al. 1991; Lupien et al. 2009). Previous studies demonstrate that hippocampus might be especially vulnerable to early poverty, as adverse life events occurring in childhood (~age 8–9) are associated with altered hippocampal development, potentially influencing mental health symptoms in adulthood (Schalinski et al. 2016). Some (Hanson et al. 2011; Hanson et al. 2014; Luby et al. 2012; Luby et al. 2013),, but not all studies (Hanson et al. 2013), link specific poverty-associated factors (e.g. maternal support, environmental stress) to altered hippocampus, amygdala, and cortical brain volume. Much remains to be learned about complex interactions between poverty, hippocampal function and memory performance.

There is strong evidence linking stronger recruitment of hippocampus with better memory recall (Wong et al. 2013; Bergmann et al. 2016), and visuospatial memory tasks are most commonly used in this context (De Rover et al. 2011; Wong et al. 2013; Longoni et al. 2013). Thus, we had hypothesized that childhood income might affect both hippocampal recruitment and visuospatial memory performance, in subjects that experienced low income as children. One possibility is that the effect of childhood income on memory recognition is directly mediated by hippocampal function, but it is also possible that childhood poverty moderates the relationship between hippocampal function and memory performance, altering the “normal” relationship between the two. We therefore set out to further assess how childhood poverty-related variability impacts hippocampal function during visuospatial memory performance in adults. This is one of the first prospective longitudinal studies examining links between brain function and cognitive abilities associated with income. We used an existing, prospective longitudinal cohort to test the following hypotheses: (1) Childhood income will positively relate to visuospatial memory performance; (2) Visuospatial memory performance will be reflected in hippocampal activation; and (3) The association between memory recognition and hippocampal activation will differ across income levels.

2. Materials and Methods

2.1 Subjects

Fifty-four adults from age 20 to 27 ($M = 23.72$, $SD = 1.31$) participated in this study within the context of an ongoing, larger longitudinal study examining associations between income and child development (Kim et al. 2015; Javanbakht et al. 2015; Evans 2003; Kim et al. 2013; Sripada et al. 2014; Evans et al. 2016; Liberzon et al. 2015). Eleven of the 54 participants did not have data on at least one of our measurements of interest (e.g. income to need ratio in adulthood), and thus were not included in the analyses. This resulted in a total of 43 participants with data on all measures. For the sample reported here, 54% were male and 91% were Caucasian. Poverty was defined according to US census calculations using income to need ratios at age 9. An income to need ratio below 1.0 is typically considered below the poverty line, with the average American household reporting an income to need ratio around 2.0. In our sample, income to need ratios at age 9 ranged from 0.16 to 4.30 ($M = 1.75$, $SD = 1.11$), with an equal number of subjects raised below ($N = 26$) and above ($N = 28$) the poverty line. Income to needs ratios in adulthood were reported from 0.29 to 9.11 ($M = 2.82$, $SD = 2.21$). For the analyses reported here, we used the earliest available data point in this cohort (income to needs at age 9), to examine links between childhood poverty specifically and adult cognitive abilities. All participants were right handed, had no prior or current treatment for psychiatric disorders, neurological conditions, or MRI contraindications.

2.2 Procedures

All of the procedures were approved by the Institutional Review Boards of Cornell University, the University of Michigan, and the Veterans Affairs Ann Arbor Healthcare System. Written consent was obtained from all subjects. MRI scanning was performed with a Philips 3-T Achieva X-series MRI (Philips Medical Systems). T1-weighted anatomical images (FOV = 256 X 256 mm, slice thickness= 1 mm, 0 mm gap) were completed for slice localization, Talairach transformation, and coregistration. Gradient echo blood oxygen level dependent (BOLD) scans (contiguous axial slices; TR/TE = 2000/30 ms, flip angle = 90°, FOV = 220 X 220 mm, slice thickness = $3mm^3$, 0 mm gap, 42 slices) were completed to assess brain function during tasks. E-prime v2.0 was used to present stimuli and record responses (Psychology Software Tools, Pittsburgh, PA). Participants viewed stimuli through MRI-compatible liquid crystal display goggles (NordicNeuroLabs http://www.nordicneurolab.com) and responded to stimuli using an MRI-compatible button box.

During BOLD scanning, participants completed a two-part visuospatial memory task involving an encoding phase and a recognition phase. During encoding, participants viewed 92 line drawings in one of four quadrants of the screen depicting common objects, animals, and plants. They had to indicate whether each image was "alive" or "not alive". Each image was on the screen for 1000 ms plus the response time of the participant (not to exceed an additional 2000 ms). Inter-stimulus intervals (ISIs) were jittered 3000–7000 ms. During recognition testing (starting 10–15 minutes following the end of encoding), participants were presented with 59 images previously viewed and 45 new images in random order. They had to indicate whether the image was "old" or "new". For "old" images, participants would also indicate where it was initially presented (top left, top right, bottom left, bottom right). Images were presented until the participant made their response(s). ISIs were 1000 ms in duration. The sequence of encoding and recall was repeated, resulting in 2 runs for each portion of the task. Reaction time and accuracy were measured on all trials (Figure 1).

2.3 Data Scoring and Analysis

Signal detection, a method that accounts for response bias to provide a more precise measure of accuracy, was used for item recall (Stanislaw & Todorov 1999). Participant responses were identified as hits (image old and responded "old"), misses (image old and responded "new"), false alarms (image new and responded "old") and correct rejections (image new and responded "new"). D-Prime (d′) was calculated for each subject: $d' = NORMSINV(H) - NORMSINV(F)$. Greater values for d′ indicate better accuracy. We also calculated a measure of response bias (C): $C = \frac{-(NORMSINV(H)+NORMSINV(F))}{2}$. Positive values for C indicate a propensity to respond "new", while negative values indicate a propensity to respond "old". For both formulas, H = hit rate and F = false alarm rate. Analyses were conducted using IBM SPSS (v. 21) to examine associations between income, d′, and brain function during encoding and recognition.

MRI data processing and analysis were performed using the statistical parametric mapping extension for MATLAB (SPM8; www.fil.ion.ucl.ac.uk/spm). Images were motion corrected, slice-time corrected, realigned to the first scan in each run, co-registered with the T1 structural image, normalized to the Montreal Neurological Institute (MNI) template brain, resampled to 3 mm^3 voxels and smoothed with a 5 mm^3 kernel. Motion parameters for all six planes (x, y, z, roll, pitch, yaw) were examined, and any run with greater than 3mm of motion in any direction was discarded before analysis. Two runs were excluded from analysis due to excessive motion. All 6 motion parameters were entered as nuisance regressors. Maximum motion per run ranged from 0.16 – 2.98 mm ($M = 0.65$, $SD = 0.59$). Motion was not associated with childhood income ($p = 0.58$). MRI analyses were conducted in three steps, as described below. This method was conducted for encoding and recognition portions of the task separately.

Step 1—First, we ran a whole brain analysis to examine regions of activation associated with visuospatial memory across all our subjects, irrespective of accuracy on the task or income levels. We included all trial types in this contrast (modeled this as all trials minus the implicit baseline) to identify activation associated with visuospatial memory in general. We included all subjects' data, and consistent with prior studies, this contrast yielded hippocampus which was our *a priori* region of interest, based on childhood poverty literature. We also observed activation in additional regions associated with visuospatial memory, task performance and salience processing (Talairach & Tournoux, 1988) (See Table 1). Activation clusters in our ROI – hippocampus, were small volume corrected and clusters that met FWE SVC criteria at $p < .05$ were identified as significant peaks. As expected, we identified significant peaks in hippocampus during both encoding and recognition.

Step 2—Next, to specifically examine the relationships between childhood income, hippocampal activation, and memory performance, we extracted beta weights from a 10mm sphere around the significant peaks in hippocampus for each individual subject, as defined in step 1, and ran a regression in SPSS with extracted hippocampal beta weight, childhood income, and their interaction as predictors of task accuracy (d′). This analysis controlled for other variables that were found to be correlated with childhood income, including verbal IQ (PPVT score) and adult income levels. For a similar approach, see Whittle et al., 2016. All regressors were mean centered and examined for outliers prior to analysis. Univariate outliers were defined as any value exceeding 3 standard deviations of the mean for that measure, and we examined Mahalanobis distance to screen for multivariate outliers. None of our data points met this criteria, thus all points of measurement were included in the analyses.

Step 3—Finally, as an exploratory analysis, we submitted each of the other regions associated with visuospatial memory identified in step 1 to the regression analysis described in step 2. This included activation in rostral anterior cingulate cortex (rACC), dorsal anterior cingulate cortex (dACC), insula, thalamus, visual cortex, posterior cingulate cortex (PCC), and dorsolateral prefrontal cortex (dlPFC; see Table 1).

3. Results

3.1 Descriptive Data

Across all participants, as expected, reported income was higher in adulthood as compared to childhood ($t(42) = 3.4$, $p = .001$). Income to needs ratio at age 9 was positively correlated with income to need ratio in adulthood ($r = 0.32$, $p = .04$), such that lower income at age 9 predicted lower income levels in adulthood. Income to needs ratio at age 9 was also positively correlated with PPVT score (Dunn & Dunn 2007), such that those with lower childhood income levels had lower verbal IQ scores ($r = 0.28$, $p = .04$). Thus, we controlled for adult income to needs ratio and PPVT scores in all analyses. Income at age 9 was not correlated with item recognition (d′), response bias (C), or reaction time (*p*s > .09). RT was correlated with d′, such that faster reaction times predicted better item recognition ($r = 0.30$, $p = .03$).

3.2 Neural Activation during Encoding

During encoding, (task minus baseline contrast, $p < .05$ FWE SVC) a significant activation cluster was identified in the hippocampus (x, y, z = −33, −28, −14). Activation in this region was not related to income or recognition accuracy (d′), and the income x hippocampal activation interaction on recognition accuracy was not significant (*p*s > .09). Activation in other brain regions associated with the Encoding task (Table 1a) were also not significantly related to income or recognition accuracy (*p*s > .06).

3.3 Neural Activation during Recognition

During recognition (task minus baseline contrast, $p < .05$ FWE SVC) a significant activation cluster was identified in the hippocampus, as expected (x, y, z = 33, −13, −11; Figure 2). The association between childhood income and hippocampal activation was at the cutoff for significance, $B = -1.00$, $t = -2.0$, $p = .05$. There was no significant association between recognition accuracy and hippocampal activation, $B = -.42$, $t = -1.2$, $p = .25$, thus the mediation model could not be formally tested, as the proposed mediator (hippocampal activation) was not associated with the proposed outcome (recognition accuracy). However, the interaction between childhood income and hippocampal activation on recognition accuracy (d′) was significant, $B = 0.96$, $t = 2.6$, $p = .01$, suggesting that the association between hippocampus activation and recognition accuracy differs across levels of childhood income. Specifically, as income increased, the association between hippocampal activation and accuracy became stronger and more positive, while as income decreased, the association between hippocampal activation and accuracy became more negative (Figure 3). Adult income and verbal IQ measured on the PPVT, which were entered as nuisance covariates in this analysis, were not associated with hippocampal activation (*p*'s > .69).

Activation in other brain regions associated with the Recognition task (Table 1b) were explored, to determine whether patterns of activation were associated with income or task performance. Activations in the task-related regions, including rACC, dACC, insula, thalamus, visual cortex, PCC, and dlPFC, were not associated with income or recognition accuracy.

3.4 Hippocampal Volume

We repeated the regression analysis described above to examine relationships between hippocampal volume (total, right, and left), childhood income to need ratio, and performance on the visuospatial memory task (d′). No relationships were observed between our variables of interest and hippocampal volume (*p*'s > .21).

4. Discussion

The purpose of this study was to investigate neural mechanisms underlying deficits in visuospatial memory in young adults with a history of childhood poverty. While the relationship between childhood income and visuospatial memory performance mirrored previous reports (Evans & Schamberg 2009; Herrmann & Guadagno 1997) of adults with a history of childhood poverty performing more poorly on a visuospatial recognition task, this relationship did not reach significance in our sample. This is not entirely unexpected, as our study involving complex neuroimaging, included less subjects than the studies that examined cognitive functions only.

The interaction we observed between childhood income and hippocampal function on visuospatial memory performance reveals a novel and interesting link between hippocampal function in association with visuospatial memory performance and history of childhood poverty. We demonstrate here that toward higher levels of childhood income, there was an expected positive association between hippocampal activation and memory performance. Conversely, toward lower levels of childhood income, the association between memory performance and hippocampal activation was negative (i.e. more activation was associated with poorer memory performance). We did not detect an association between neural activation in the hippocampus during encoding and performance on the subsequent recognition task, across all the subjects, in contrast to a previous report of hippocampal engagement in both information encoding and recognition (Wong et al. 2013).

These findings suggest a possible “disconnect” between hippocampal activation as observed on fMRI and performance on a visuospatial recognition task in adults with a history of poverty. One relatively straight forward explanation of our findings is that while increased activation in the higher childhood income participants reflects effective activation of hippocampus (i.e. stronger activation leads to better performance), activation in the lower childhood income participants reflects effort associated with difficulty that is not leading to improved performance. These results link previous findings, which separately documented associations between poverty and poorer memory performance (Farah et al. 2006; Noble et al. 2007), and poverty and hippocampal structure (Hanson et al. 2011). These findings are also consistent with data from the animal literature that rodents raised in conditions to model poverty had less capacity for plasticity in hippocampus, which was related to poorer performance on memory and learning tasks (Hackman, Farah & Meaney 2010).

Exploratory analysis aimed to identify activation in other brain regions involved in encoding and recognition, associated with income or recognition accuracy. In our sample, multiple brain regions previously implicated in memory processes, like prefrontal cortex, inferior frontal gyrus, and visual cortex (Preston & Eichenbaum 2013; Wong et al. 2013) were activated during encoding and recognition tasks, but none of these regions were associated with childhood income or recognition accuracy.

There are important limitations of this study. Like the majority of studies examining early life risk factors, our study reveals links and associations, and should not be interpreted as evidence of causation. While the prospective and objective nature of the assessments confer confidence in our findings, they do not exclude the possibility of additional unaccounted factors contributing to the observed associations. Because poverty is a complex construct, encompassing multiple interacting variables like parental education, parenting style, school and home environment, nutrition, etc., it was not possible to isolate a single specific mechanism that influences brain function and cognitive performance. Mediation models may assist with this in the future, but our sample size provided limited power for this type of analysis. It is important to note here, that examining effects of isolated variables might not constitute the single best strategy either, since the interaction between multiple factors within the construct of childhood poverty might be the most salient contributing factor (Evans 2003). In addition, we used a “convenience sample” from an existing longitudinal prospective cohort that had been followed up already for 15 years, and income was only measured at four year intervals beginning at age 9. Therefore, we chose the earliest possible data point available for this cohort. Although income in our sample and similar samples tends to remain stable over time (Evans & Schamberg 2009), we are unable to provide direct evidence of early childhood poverty prior to age 9. We did not examine performance on other (non-visuospatial) memory tasks or other cognitive tasks, and do not know whether deficits in performance and/or the related differences in brain function would extend to other tasks. In addition, since subjects were tested only once as young adults, we were unable to investigate whether the reported deficits would persist into later adulthood.

Despite the limitations, this is the first study to our knowledge to document differences in the associations between brain function and visuospatial memory performance in healthy young adults as a function of childhood income levels. We used prospective data collection over the course of a longitudinal study, which is a significant advantage over previous studies using retrospective data. Our real time data collection allowed for assessment of income at multiple time points across development. Although it has long been known that poverty is related to a number of negative outcomes in adulthood, this is the first study demonstrating associations between visuospatial memory deficits associated with differences in hippocampal function during encoding and recognition, occurring independent of current adult income. Given prior reports of hippocampal recruitment associated with better memory performance (Wong et al. 2013; Bergmann et al. 2016), these results suggest that early experiences of poverty set disadvantaged children on a trajectory of altered neurological functioning that, among other things, may result in compromised memory later in life. Future investigations will need to examine specific mechanisms underlying the links between poverty, neural function, and cognitive performance.

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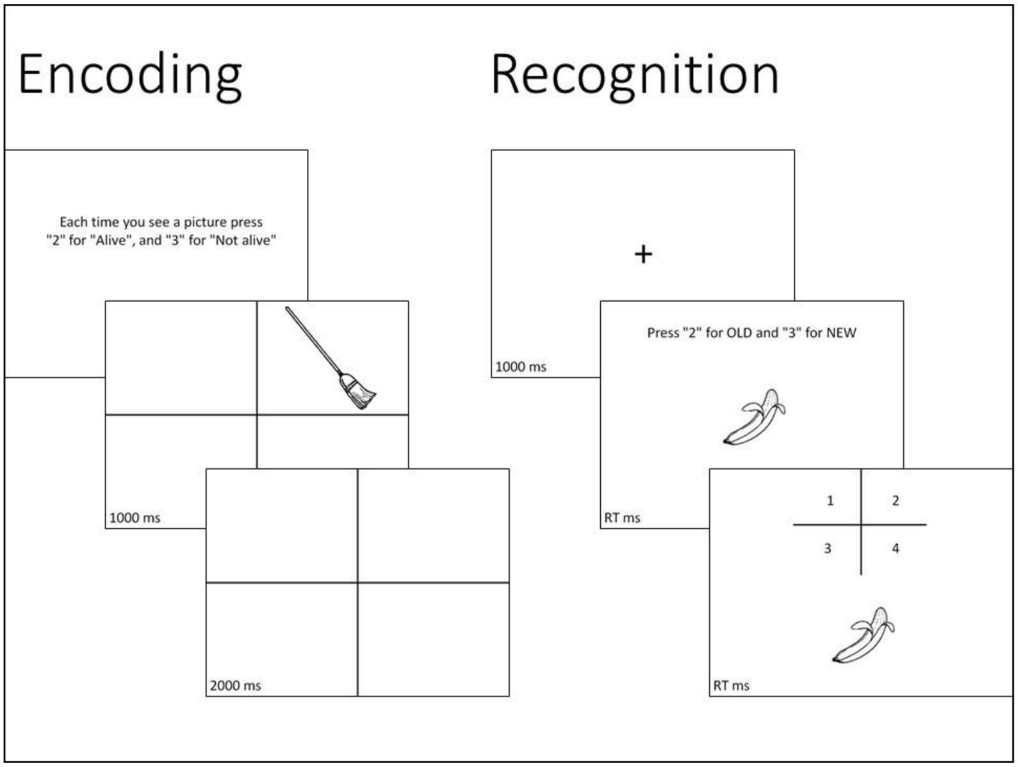

Figure 1.
Example trials from Encoding and Recognition

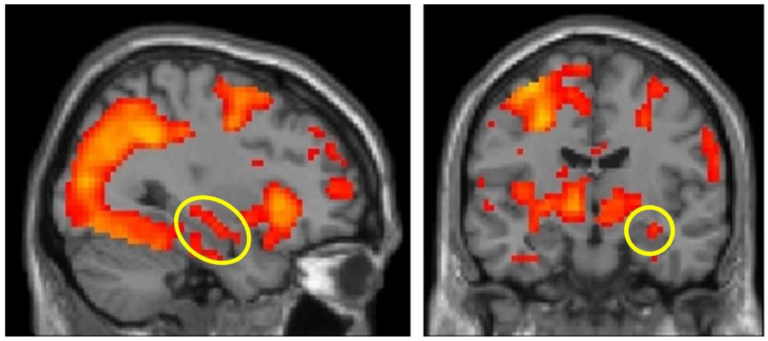

Figure 2.
Neural activation during recognition. Activation in the circled hippocampal region of interest was extracted for further analysis.

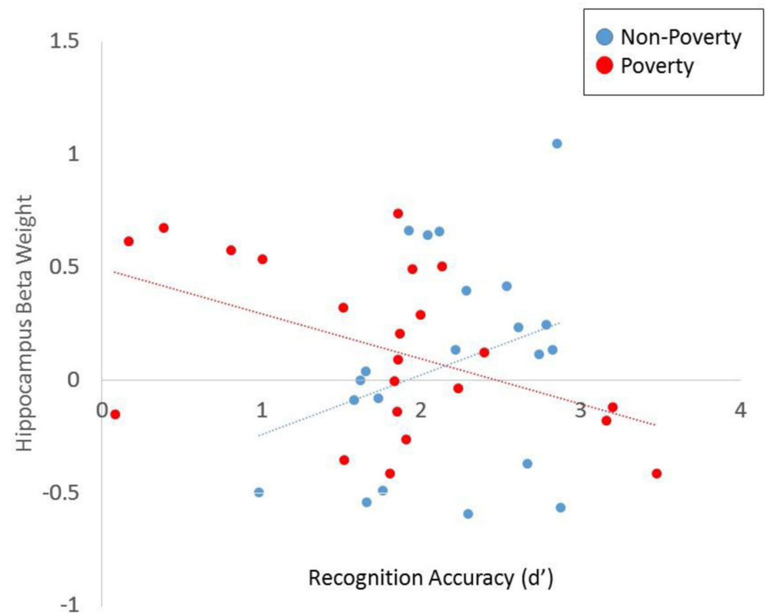

Figure 3.
Results of regression analysis demonstrating variations in the association between accuracy and hippocampal activation across income levels. For illustrative purposes, we divided participants into two groups (non-poverty, poverty) based on the continuous income measure, to graph the income x hippocampal function interaction on d′. The non-poverty group (blue dots) represent adults with no history of poverty, while the poverty group (red dots) represent those who reported living below the poverty line at age 9.

Table 1

Significant regions of activation during A) Encoding and B) Recognition (k = 10 contiguous voxels, alpha level = .001$_{uncorr}$). Abbreviated regions include anterior cingulate cortex (ACC), dorsal ACC (dACC), rostral ACC (rACC), middle frontal gyrus (MFG), posterior cingulate cortex (PCC), prefrontal cortex (PFC) dorsolateral PFC (dlPFC), inferior frontal gyrus (IFG), orbitofrontal cortex (OFC).

A. Encoding

All Trials - Baseline

Region	***x, y, z***	***z***	***k***
Insula	−39, −4, 10	7.07	185
dlPFC	−36, −25, 52	12.5	848
Hippocampus	−33, −28, −14	4.13	16
MFG	−24, 32, 43	−5.62	96
dACC	−3, 8, 49	9.91	415
PCC	3, −37, 43	−7.54	1391
Visual Cortex	6, −76, 1	12.73	2539
rACC	9, 50, −8 24, 32, 37	−6.73 −5.50	767 185

B. Recognition

All Trials - Baseline

Region	***x, y, z***	***z***	***k***
dlPFC	−45, 5, 37	10.24	513
Insula	−39, −4, 7	5.07	179
Thalamus	−18, −31, 1	7.59	308
PCC	−15, −70, 52	−9.04	872
rACC	−12, 47, −5	−5.19	508
dACC	−6, 11, 46	11.76	282
Visual cortex	−3, −91, 4	9.57	3243
Hippocampus	33, −13, −11	4.08	41