# Investigating hippocampus-midbrain functional connectivity during consolidation in the context of reward and curiosity-motivated learning


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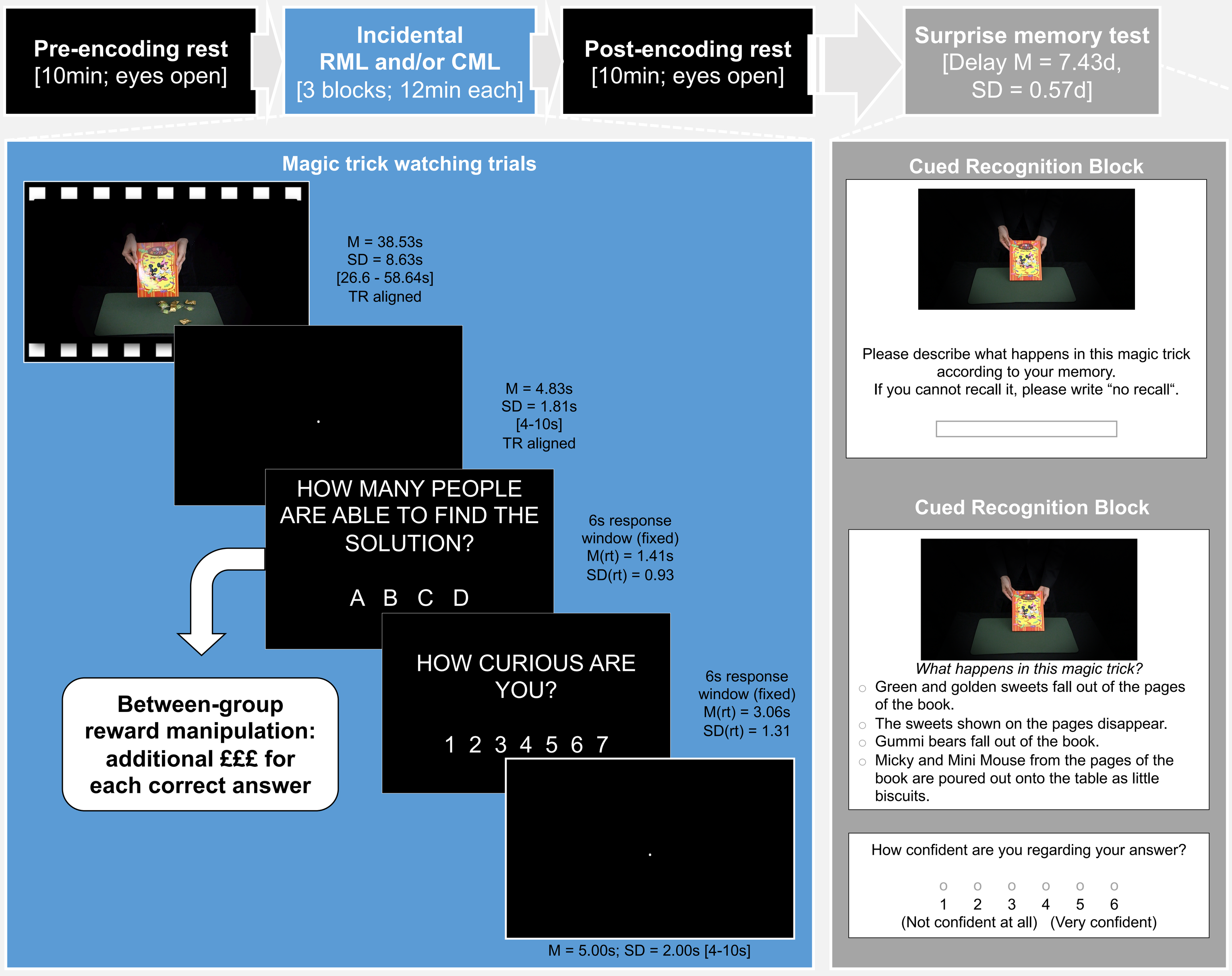
## BACKGROUND

Motivation as a psychological force drives behaviour and can emerge intrinsically (i.e. through curiosity or interest) or from external rewards like money. Though psychology sees a strong distinction between these types of incentives, neuroscientific studies have repeatedly shown that both rewards are processed in the same reward network in the brain.[1] Additionally, both have shown to facilitate encoding by dopaminergic midbrain (VTASN) projections to the hippocampus (HPC). [2-4] Reward-motivated learning (RML) effects only occur after long delays[5], whereas curiosity-motivated learning (CML) effects can be found after short and long delays[6] suggesting that RML & CML rely on different post-encoding mechanisms. While multiple studies found that post-encoding functional connectivity (FC) between HPC and midbrain ("consoliDopa") is associated with RML[4,7], it is unclear whether consoliDopa also supports CML.

**Research questions:**
Does consoliDopa differ in RML & CML? Do individual differences in consoliDopa predict encoding success and curiosity-motivated learning enhancement (CMLE) differently in RML & CML?

## METHOD

- fMRI data was collected during during a pre-encoding rest phase, an incidental RML and/or CML task, and a post-encoding rest phase. The sample consisted of 50 healthy adults aged 18-37 ($M$ = 25.3, $SD$ = 5.19; 14 males) of which each N = 25 were assigned to the control and reward group, respectively.




- During the incidental RML and/or CML task, participants watched 36 magic trick videos whilst performing judgements for which performance-dependent monetary reward was manipulated. Additionally, participants rated their curiosity regarding each magic trick.
- One week later, there was a surprised memory test consisting of a cued recall block and a four-alternative forced choice recognition memory test (including confidence ratings) using still images of the magic tricks as cues.

**fMRI PRE-PROCESSING AND ANALYSES**

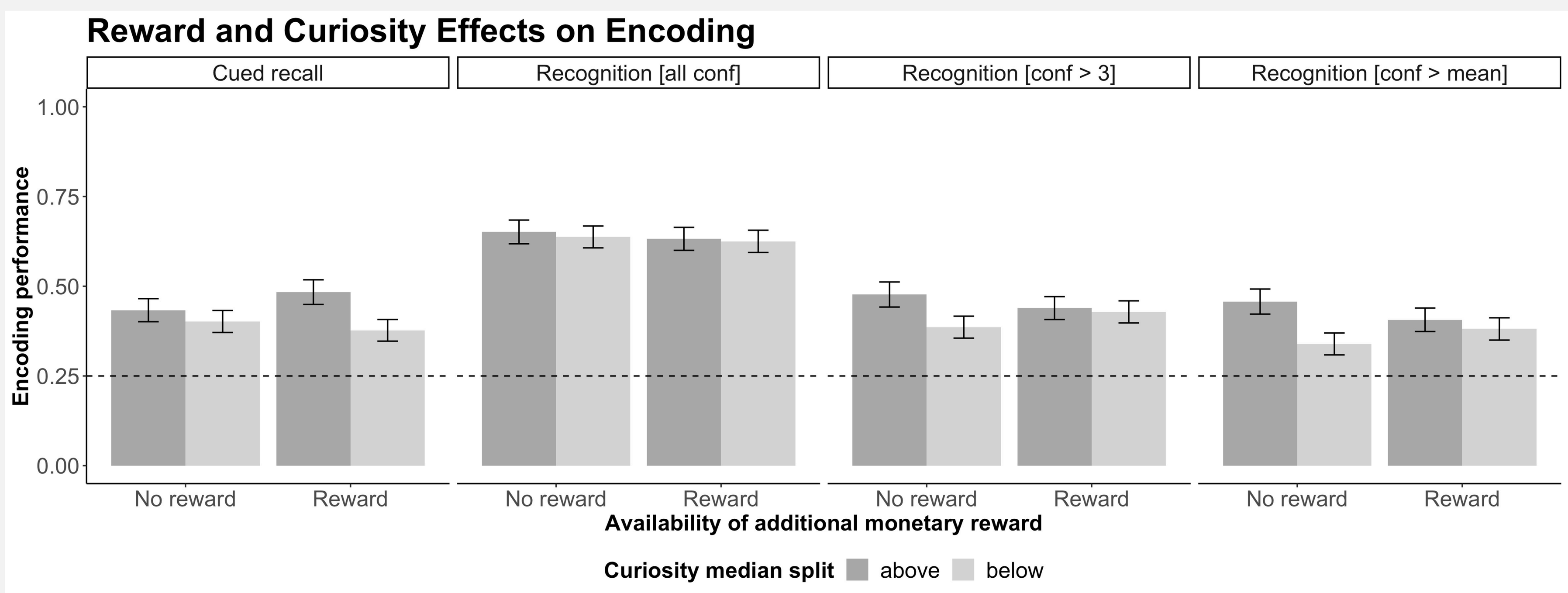
- Based on the memory test, a magic trick was coded as **recalled** if the change that occurred was described. A trick was coded as **recognised** if the correct option was selected. Based on behavioural pilots[8], further thresholding was performed depending on reported **confidence (conf) > 3**. Due to low ratings (M = 3.8, SD = 1.7), the subject **mean conf** was used as additional threshold.
- Encoding performance was analysed using **Generalised Linear Mixed Effects Models (GLMMs)** specifying reward (effect coded) and curiosity (as continuous variable) and their interaction as fixed effects and random effects for intercepts and slopes for subject and random intercepts for stimulus.
- fMRI time series were pre-processed (despiked, $B_0$-distortion, slice-timing and head-motion corrected, aligned with anatomy and MNI template, smoothed, scaled) before regressing out sources of noise (motion ventricle principle components, local white matter). All analysis were carried out using AFNI & R.
- The **anterior HPC (aHPC)** was used as seed region for FC analysis. The bilateral **midbrain ROI** was defined by identifying voxels within a combined VTA/SN mask showing significant FC ($p_{FWE} < 0.05$) with the aHPC during pre-encoding rest. Voxel time courses within the ROIs were averaged and correlated separately for pre- und post-encoding rest.
- Correlation coefficients were Fisher's Z transformed. Change in FC between aHPC and midbrain (consoliDopa") was calculated and correlated with behavioural measures of learning (items encoded and CMLE, i.e. curiosity beta values from the GLMM) and tested for reward-effects).

## RESULTS

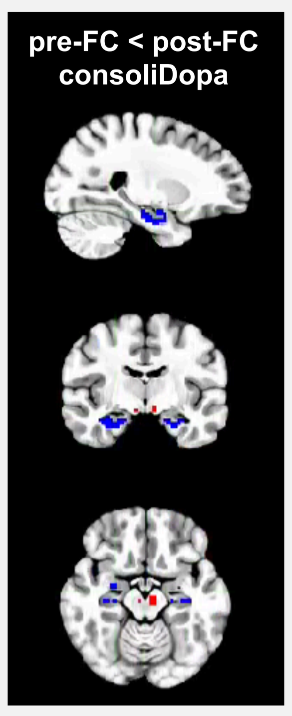
**ENCODING PERFORMANCE**

- Behavioural results showed recollection-based memory enhancements (cued recall/recognition above conf threshold) for curiosity: if participants were more curious about about a magic trick, they were more likely to encode it. Neither reward nor interaction effects were observed.

| | Cued recall | | Recognition [all conf] | | Recognition [conf > 3] | | Recognition [conf > mean] | |
|---|---|---|---|---|---|---|---|---|
| | OR [95% CI] | p value | OR [95% CI] | p value | OR [95% CI] | p value | OR [95% CI] | p value |
| Intercept | 0.58 [0.33 – 1.00] | 0.050 | 1.96 [1.33 – 2.90] | 0.001 | 0.64 [0.42 – 0.99] | 0.044 | 0.54 [0.35 – 0.82] | 0.004 |
| Reward | 0.92 [0.72 – 1.18] | 0.527 | 0.88 [0.74 – 1.04] | 0.125 | 0.94 [0.75 – 1.18] | 0.590 | 0.97 [0.84 – 1.14] | 0.739 |
| Curiosity | **1.14 [1.05 – 1.25]** | 0.002 | 1.02 [0.93 – 1.11] | 0.712 | 1.06 [0.98 – 1.15] | 0.129 | **1.11 [1.02 – 1.21]** | 0.015 |
| Interaction | 1.03 [0.95 – 1.11] | 0.523 | 1.02 [0.94 – 1.11] | 0.664 | 0.99 [0.91 – 1.06] | 0.699 | 0.97 [0.90 – 1.05] | 0.464 |



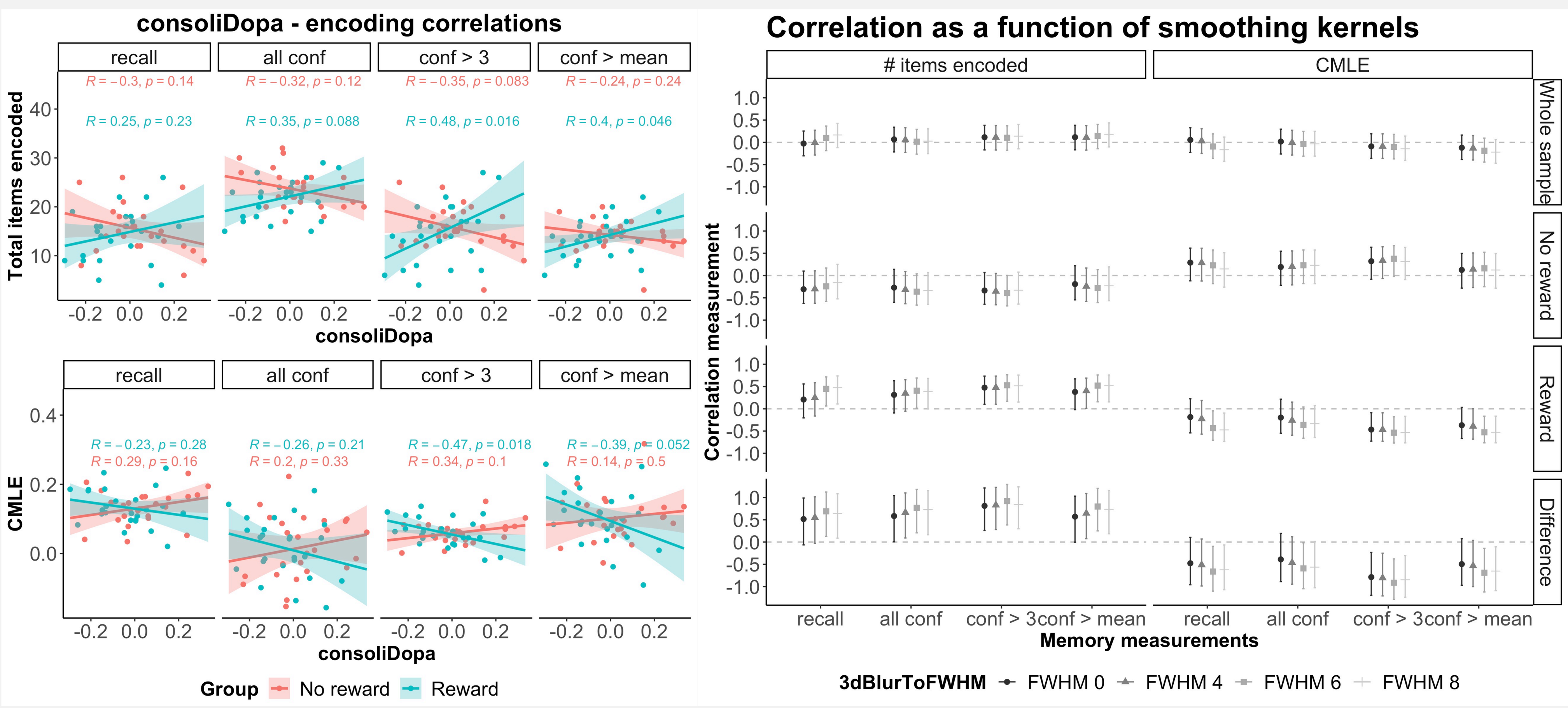

**consoliDopa (smoothing kernel FWHM = 4)**




- While consoliDopa was not significantly different from zero neither in the whole sample nor within the groups (all $p$ > 0.103), the control group showed higher values ($M_C$ = 0.039, $M_R$ = -0.044, $p$ = 0.046).
- Correlating consoliDopa with behavioural measures of learning no effects of consoliDopa on absolute number of items encoded (all r < |0.13|, all $p$ ≥ 0.363). Investigating the correlations separately within each group, however, there was a positive relationship whereas correlation coefficients were negative in the control group (all cor diffs > 0.55, p ≤ 0.06).
- With respect to the effects of consoliDopa on CMLE, again, there were no effects on whole sample level (all r < |0.11|, all $p$ ≥ 0.441). However, within the control group, CMLE correlated positively with consoliDopa whereas opposite effects were observed in the reward group (all cor diffs < -0.46, p ≤ 0.11).

**smoothing**

- Running the same pre-processing and analysis pipeline with different smoothing kernels (FWHM = 4, 6, 8) as well as no smoothing (FWHM = 0) showed that the effects were robust.




## CONCLUSION & FUTURE DIRECTIONS

Results from previous studies showing that consoliDopa predicts encoding were partially replicated[4]: Only in reward group, we observed positive correlations between consoliDopa and the number of items encoded suggesting that the memory-facilitating effects of consoliDopa only occur in the context of RML and cannot be generalised to CML.

Likewise, the relationship between CMLE and consoliDopa was only observed in the reward group and negatively directed suggesting that the higher the influence of curiosity on encoding, the less important consoliDopa becomes.

The results of this study suggest that RML and CML indeed rely on different post-encoding mechanisms: while RML might be dependent on dopaminergic modulation of HPC activity, this might not either not apply to CML or only to a lesser extent. The negative direction of correlations could even imply that consoliDopa is suppressed in favour of other processes and different networks.

This is in line with suggestions from the PACE (Prediction-Appraisal-Curiosity-Exploration) framework[9] linking curiosity effects on HPC-dependent memory to additional brain areas including ACC (anterior cingulate cortex) and lateral PFC (prefrontal cortex). In fact, especially fronto-parietal attention networks have recently been implicated in incidental and intentional CML during encoding.[10,11]

More analyses will be conducted to further quantify the potential involvements of other networks and regions in post-encoding processes in CML, including the fronto-parietal and default network as well as ACC and lateral PFC and other regions in the reward network.


[1]Murayama (2019). *The Cambridge Handbook on Motivation and Learning.* [2]Lisman & Grace (2005). *Neuron.* [3]Gruber et al. (2014). *Neuron.* [4]Gruber et al. (2016). *Neuron.* [5]Murayama & Kuhbander (2011). *Cognition.* [6]Stare et al. (2018). *Cogn Neuroscience.* [7]Murty et al. (2017) *J Neuroscience.* [8]Meliss & Murayama (2019). *Brain and Cognition.* [9]Gruber & Ranganath. (2019). *TiCS.* [10]Duan et al. (2020). *Brain Structure and Function.* [11]Murphy et al. (2021). CNS conference poster.