Hippocampus and vmPFC contribute to spacing effects at long timescales

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Introduction

- It is widely acknowledged that spacing learning out over time improves memory[1], and yet it is not clear why spaced learning leads to such benefits.
- Recent evidence from rodents and humans has shown that spaced learning is associated with greater activity pattern similarity in the medial prefrontal cortex[2,3].
- However, previous studies have focused only on short timescales, with repetitions occurring within a single experimental session (and day).

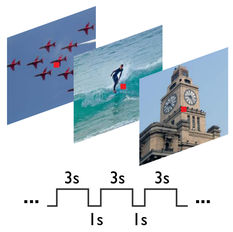
What happens in the brain that allows spaced learning over long timescales to improve memory?

Experimental Design

Natural Scenes Dataset [4]

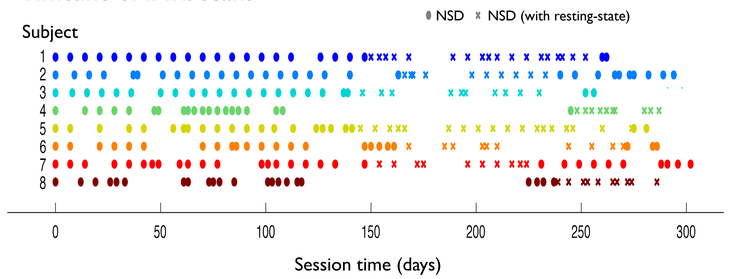
Continuous recognition task

"Have you seen this image before?"
"Yes" or "No"



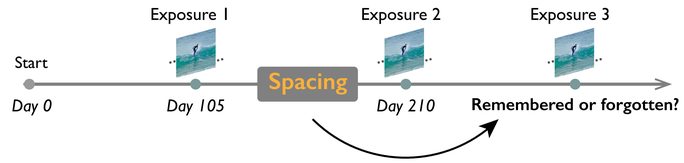
- 8 human subjects
- 30-40 sessions of 7T fMRI distributed over a year per subject
- ~10,000 images presented up to 3 times

Timeline of fMRI scans



Behavioral Results

Timeline of an example image



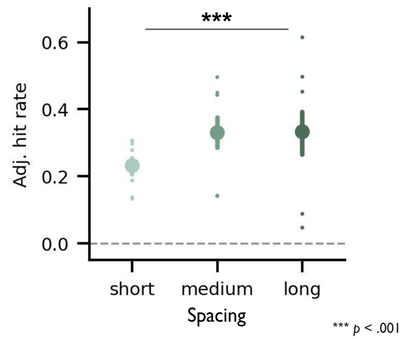
Memory outcome ~ Spacing + E1 onset + E2-E3 lag + FA rates + (1|Subject)

Spacing:
- Short: within-day
- Medium: across-day short (mean: 18 d)
- Long: across-day long (mean: 122 d)

(Items with E2-E3 lag > 1 day)

Spaced learning across long timescales enhances subsequent recognition, with a spacing ranging from 4s to 288 days.

Memory increases as a function of spacing

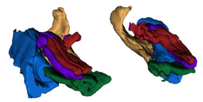


*** $p < .001$

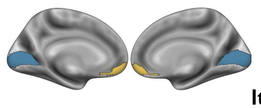
fMRI Analysis

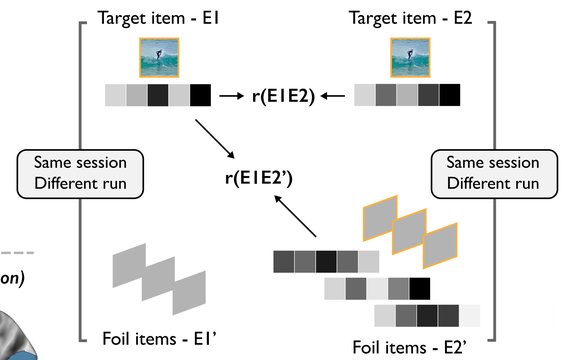
Regions of interest

Medial temporal lobe



vmPFC and V1 (control region)



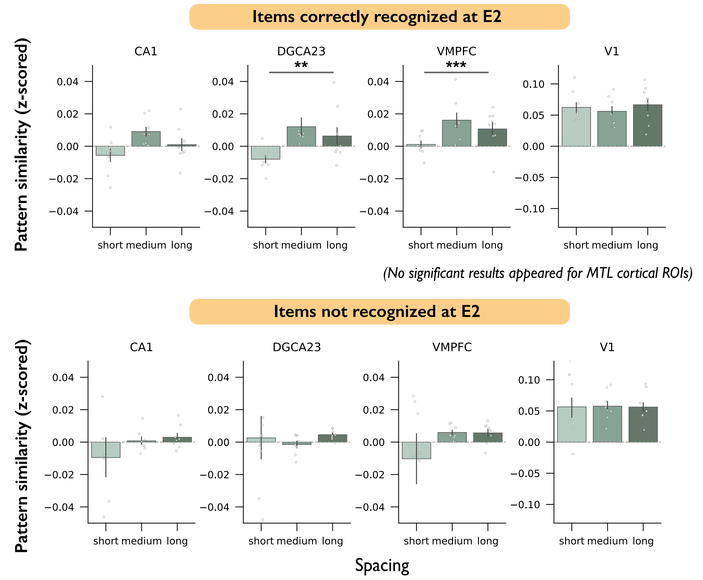


Item-specific similarity = r(E1E2) - median(r(E1E2'))

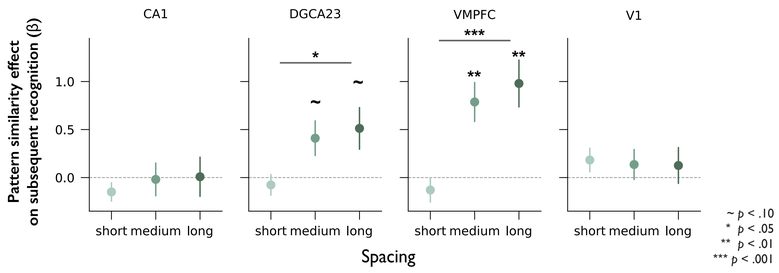
References:
1. Ebbinghaus H (1885). Über das Gedächtnis: Untersuchungen zur Experimentellen Psychologie. Duncker & Humblot.
2. Glas A, Hübener M, Bonhoeffer T, Goltstein PM (2021). Spaced training enhances memory and prefrontal ensemble stability in mice. Current Biology.
3. Feng K, Zhao X, Liu J, Cai Y, Ye Z, Chen C, Xue G (2019). Spaced learning enhances episodic memory by increasing neural pattern similarity across repetitionn. Journal of Neuroscience,
4. Allen EJ, St-Yves G, Wu Y, Breedlove JL, Prince JS, Dowdle LT, Nau M, Caron B, Pestilli F, Charest I, Hutchinson JB, NaselarisT, Kay K (2021). A massive 7T fMRI dataset to bridge cognitive neuroscience and artificial intelligence. Nature Neuroscience.

fMRI Results

Spaced learning enhances item-specific pattern similarity in DGCA23 and vmPFC but only for items correctly recognized at E2.



Pattern similarity in DGCA23 and vmPFC predicts subsequent recognition for medium/long spacing (across-day), but not short spacing (within-day).



Summary

- Spacing effect operates over long timescales, from seconds to months.
- Spaced learning is associated with greater item-specific pattern similarity in DGCA23 and vmPFC but is dependent on memory states during second exposure.
- Subsequent recognition is predicted by item-specific similarity in DGCA23 and vmPFC, but only for spaced (across-day) learning.

Spaced learning enhances neural pattern similarity in DGCA23 and vmPFC, thus strengthening memory and increasing the probability of subsequent recognition.