Time-dependent contributions of hippocampus and vmPFC to distributed learning

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Introduction

• Spacing effect: spacing learning out over time improves memory [1].

What is the neural mechanism underlying the spacing effect?

• In rodents, spaced learning is associated with greater ensemble activity pattern similarity in medial PFC [2].

• However, previous studies have focused only on short timescales, with repetitions occurring within a single experimental session (and day).

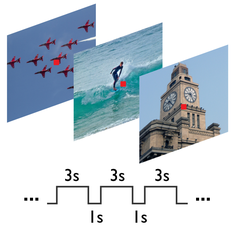
What happens in the brain that allows spaced learning over long timescales to improve memory?

Experimental design

Natural Scenes Dataset [3]

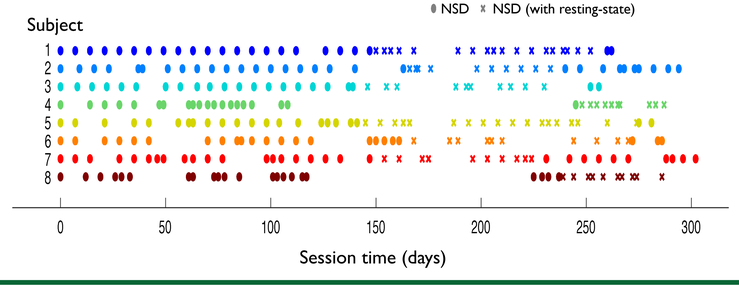
Continuous recognition task

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



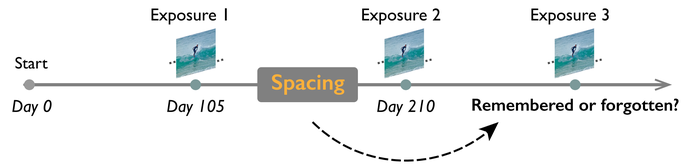
- 8 human subjects
- 30-40 sessions of 7T fMRI distributed over a year per subject
- ~30,000 trials per subject
- ~10,000 images presented up to three times

Timeline of fMRI scans



Behavioral results

Timeline of an example image



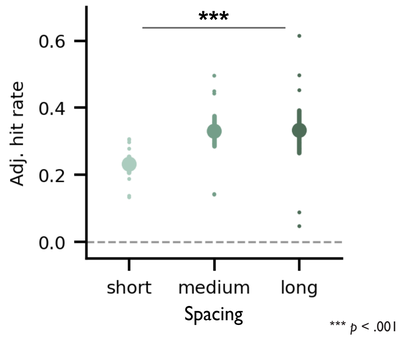
Memory outcome ~ Spacing + E1 onset + E2-E3 lag + FA rates + (1|Subject)

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

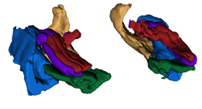


*** $p < .001$

fMRI analysis

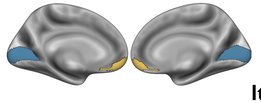
Regions of interest

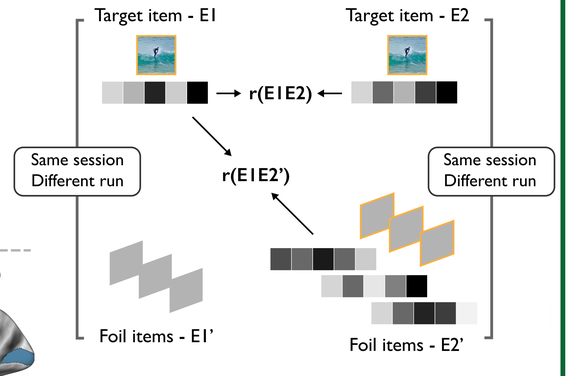
Medial temporal lobe



CA1 DGCA23
ERC PRC PHC

vmPFC and V1 (control region)



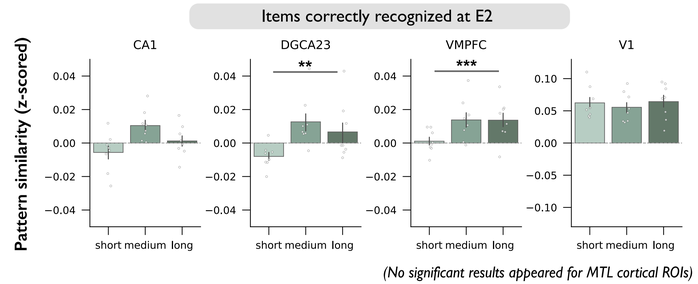


Item-specific similarity = r(E1E2) - median(r(E1E2'))

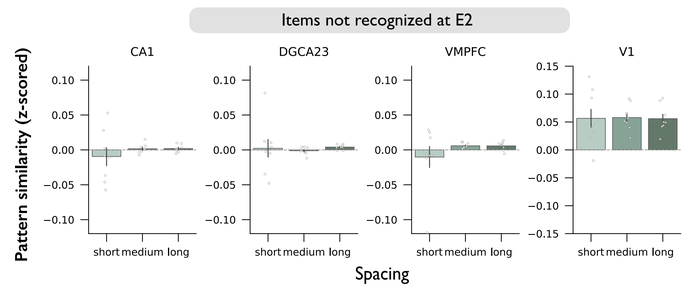
References and Acknowledgments:
1. Ebbinghaus H (1885). Über das Gedächtnis: Untersuchungen zur Experimentellen Psychologie. Duncker & Humblot.
2. Glas A, Hübener M, Bonhoeffer T, Goltstein PM (2021). Spaced training enhances memory and prefrontal ensemble stability in mice. Current Biology.
3. Allen 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.
4. Collection of the NSD dataset was supported by NSF CRCNS grants IIS-1822683 (to K.K.) and IIS-1822929 (to T.N.).

fMRI results

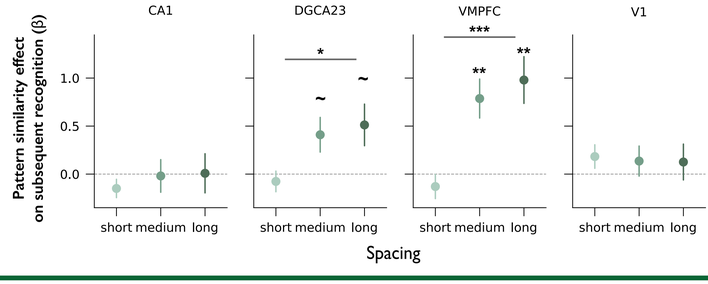
Spaced learning enhances item-specific pattern similarity in DGCA23 and vmPFC but is dependent on memory states during second exposure.



(No significant results appeared for MTL cortical ROIs)



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.
- Subsequent recognition is predicted by pattern 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.