Using multivariate pattern analysis to investigate memory reactivation during sleep

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Introduction

- New memory traces are reactivated during post-learning sleep (Wilson & McNaughton, 1994; Maquet et al., 2004)
- **However, we lack direct, temporally-precise evidence of reactivation in the human EEG**
- **We searched for such evidence shortly after giving learning-related cues during slow-wave sleep**

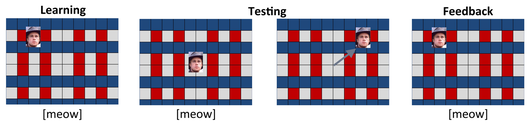
Procedure

Wake Classifier Training

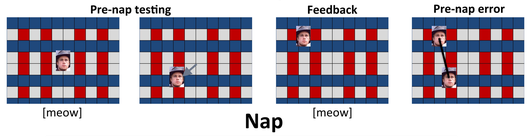
Sound – face/place overlearning

During overlearning – 100% correct 2x. After the nap – 81% correct.

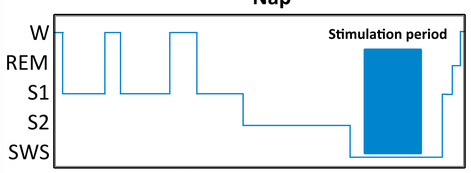
Face/place – spatial location learning



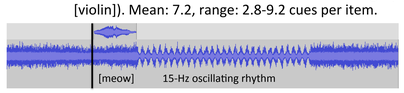
Pre-nap test



Nap

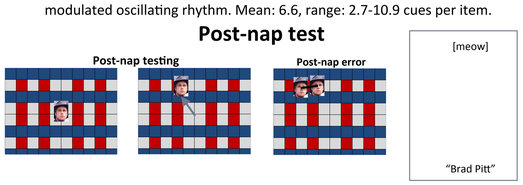


Experiment 1: Cued half of the sounds associated with each category (e.g. [meow], [violin]). Mean: 7.2, range: 2.8-9.2 cues per item.



Experiment 2: Cued ALL sounds, with half followed by 2s, 15 Hz amplitude-modulated oscillating rhythm. Mean: 6.6, range: 2.7-10.9 cues per item.

Post-nap test

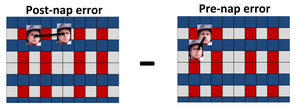


Participants: Thirty-three (Exp 1: 17 18-33, 8 female; Exp2: 16, 19-33, 11 female) subjects refrained from caffeine and alcohol leading up to the study and awoke one hour earlier than normal.

Sound cues during sleep improve spatial memory

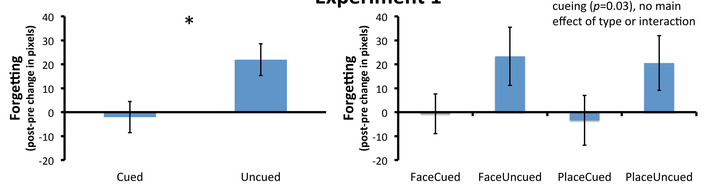
Behavioral measures

Forgetting: difference in error across the nap



* = $p < 0.05$; † = $0.05 < p < 0.1$

Experiment 1



2-way ANOVA: Main effect of cueing (p=0.03), no main effect of type or interaction

Pattern classification analysis strategy

Overview

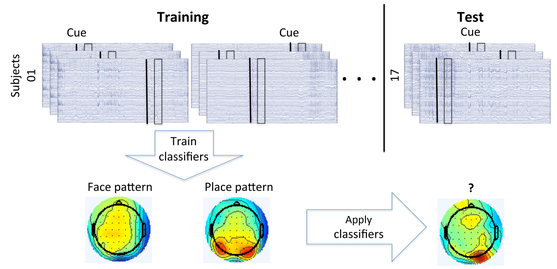
Types:
- Wake (data not shown)
- Sleep
- Wake → sleep (data not shown)

Alignment types:
- Cue-locked time bins
- SO trough-locked time bins
- SO trough-locked phase bins

Features for all (64) electrodes:
- Voltage values
- Hilbert-transformed power at 5 frequencies: 2-4, 4-8, 8-16, 16-30, 30-59 Hz

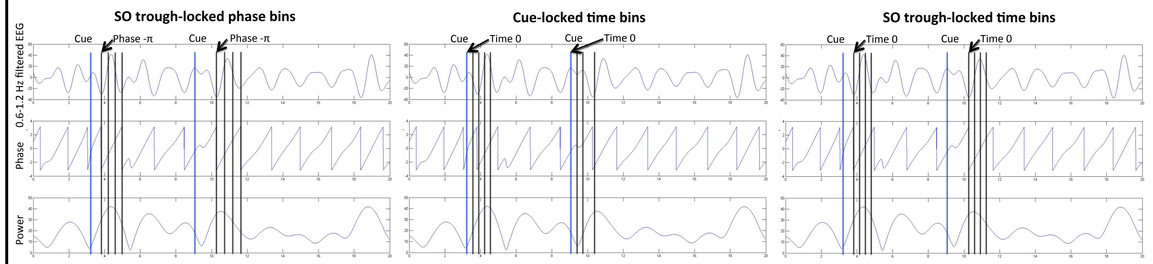
Classifier

We trained a separate logistic regression classifier for each bin across all 64 electrodes. The electrode values (voltage or power) were z-scored within each bin to highlight differences across electrodes. We trained the classifier on all subjects except one and tested on the withheld subject (i.e. leave-one-subject-out classification).

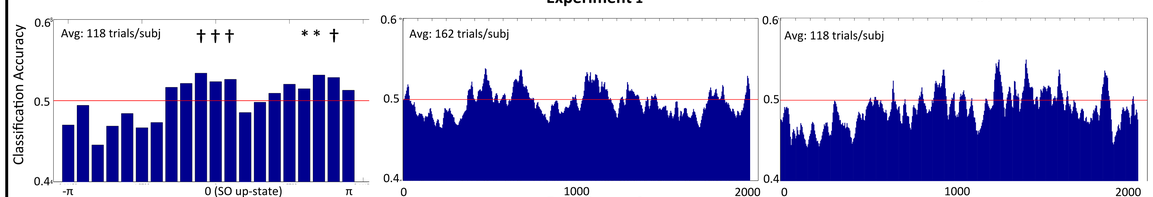


Goal: successfully discriminate sleep cues previously associated with faces vs. places.
Predictions: classification accuracy will be greatest during slow oscillation up-states when we expect reactivation to occur.

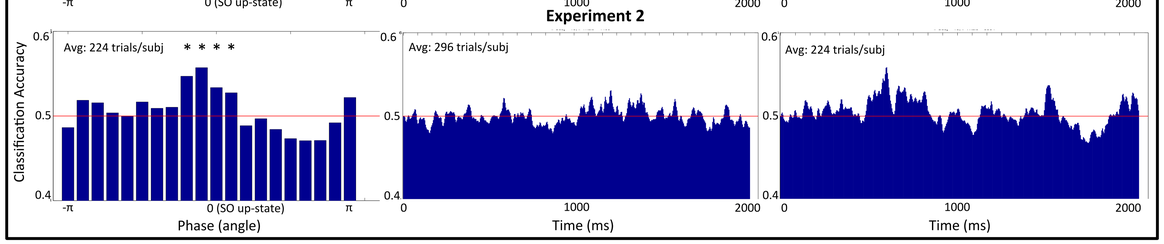
Sleep



Experiment 1



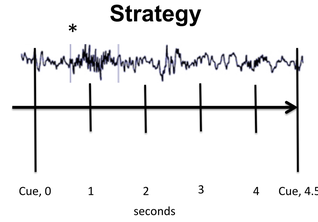
Experiment 2



Post-cue spindles predict memory

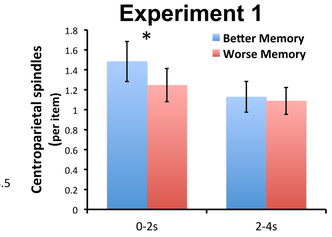
Sleep spindles are short bursts (0.5-3s) of activity between 11-16 Hz during NREM sleep. Correlational (Cox et al.,2012; Diekelmann & Born, 2010) and causal (Mednick et al., 2013) evidence suggests they play a role in memory consolidation.

Strategy

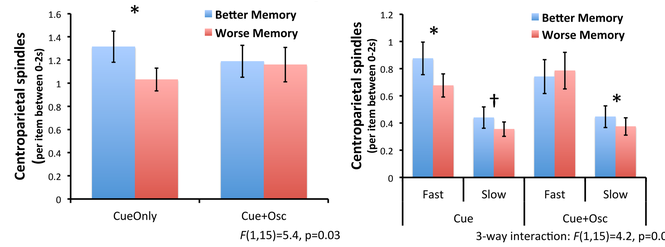


* Counted as spindle starting between 0-1s.

Experiment 1



Experiment 2



Summary

- Cueing benefits memory (Rudoy et al., 2009)
- Information-related activation was consistently discriminable during slow oscillation up-states
  - Consistent with ripples (Mölle et al., 2006) and pattern ensemble reactivation (Gulati et al., 2014) occurring preferentially during slow oscillation up-states
- Post-cue sleep spindles predict memory
  - Oscillating sounds altered this normal predictive effect

Future Directions

- Wake → sleep transformation – do learning-related patterns re-emerge during sleep or does reinstatement constitute a different pattern?
- Is there a consistent temporal relationship between pattern reinstatement and sleep spindles?
- Does reinstatement predict memory on an item-by-item or subject-by-subject level?

References

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Acknowledgements

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