Decoding spatiotemporal dynamics of neural oscillations during sleep and their age-related effects on emotional memory consolidation

SOMNEUROLAB

Thea Ng[1,2], Lindsey Mooney[3], Irina Orlovsky[3], Morgan Barnes[3], Cassandra Delvey[3], Lena Gaudette[3], Karolina Rusin[3], Katrina Rodheim[3], Bethany Jones[3], Rebecca Spencer[3,4]

[1]Neuroscience & Behavior Program, Mount Holyoke College, South Hadley
[2]Department of Mathematics and Statistics, Mount Holyoke College, South Hadley
[3]Neuroscience & Behavior Program, University of Massachusetts Amherst, Amherst
[4]Department of Psychological and Brain Sciences, University of Massachusetts Amherst, Amherst

INTRODUCTION:

Slow oscillations (SOs) and sleep spindles (SPs) are crucial for sleep-dependent memory consolidation, yet their role in coordinating long-range cortical communication and how aging affects this function remains poorly understood. Prior studies focused on local dynamics due to limited electrode coverage. Using high-density polysomnography (PSG), this study explores the spatiotemporal dynamics of SOs and SPs, specifically their repeated directional propagation across the cortex and how these propagations are modulated across different frequency ranges, which may represent a potential mechanism to support long-range memory transfer. We also investigate how aging alters the stability of this cortical connectivity during sleep. By applying computational modeling, we further aim to clarify the relevance of SO and SP metrics to memory processes.

METHODS:

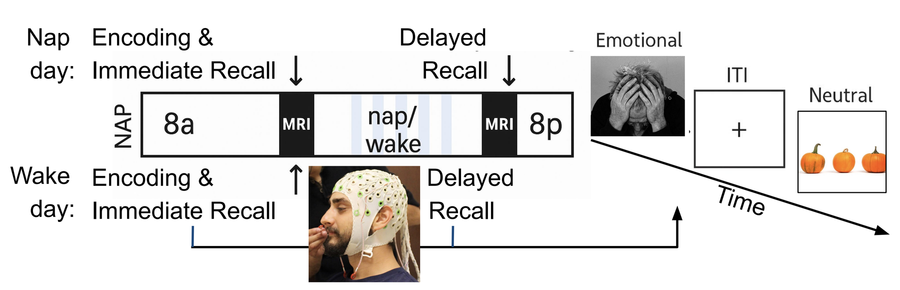


Fig. 1. Experimental paradigm and memory task design

- **Experiment**: Healthy young (N=15, YA) and older adults (N=15, OA) completed immediate and delayed recall tasks for emotional recognition memory on both nap and wake days. High-density PSG (122 electrodes; Fs = 500 Hz) was collected between tests.
- **Behavioral Analysis:** Unequal variance signal detection and drift-diffusion models (DDM) modeled the mechanism underlying memory consolidation. Sensitivity (D_a) and drift rate (v) were used as measure of memory strength in each model.
- **Spectral Analysis:** Multi-Gaussian curve fitting improved topographical measurements in SO and SP peak frequencies and powers following IRASA. Hierarchical clustering was used to classify the electrodes into two groups based on frequency.

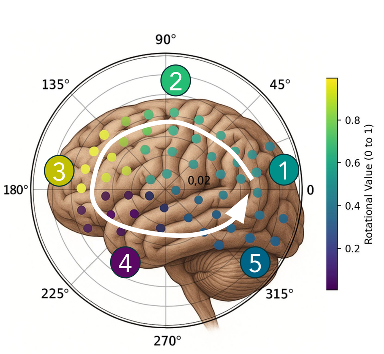


Fig. 2. Electrode rotational map in normalized polar coordinates.

- **Event Detection:** For SO detection, we filtered EEG (0.16–1.25 Hz), extracted 0.8–2 s half-waves, selected events with top 30% troughs and peak-to-peak amplitudes. For SP detection, we used Convolutional Neural Networks (Mofrad et al., 2022) to improve the detection of co-occurring events across electrodes.

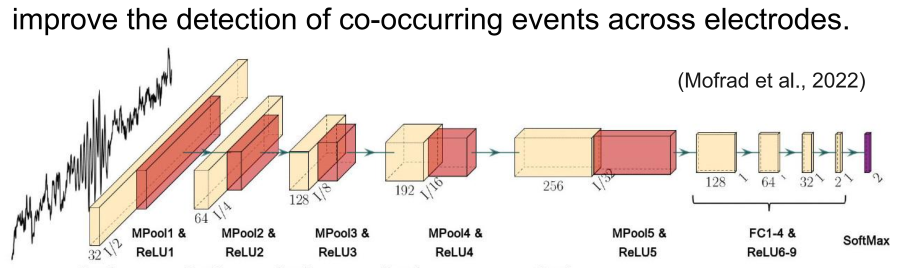


Fig. 3. The detection of spatially clustered sleep spindles using Convolutional Neural Networks (CNN).

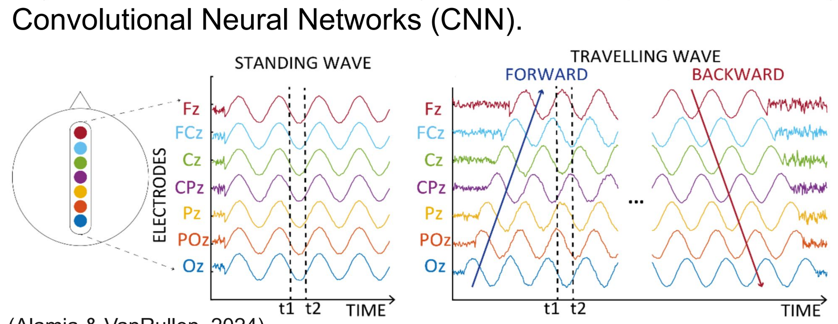


Fig. 4. Visualization of standing waves and two common types of planar traveling waves (TWs).

- **Cortical Connectivity:** Cross-correlation was used to calculate the spatial correlation between each pair of electrodes within +1.5s of the oscillation center (SP peak, SO trough), where the maximum correlation within +0.2s time lag was extracted. 2000 pairs of events and non-event epochs were selected for analysis.
- **Traveling Waves (TWs):** We modeled the propagation of SOs and SPs by extracting the instantaneous phase of each oscillation at each time point. The local traveling direction at each electrode was estimated using the spatial derivative of phase across neighboring electrodes, while the traveling speed was estimated by its temporal derivative. The consistency of wave propagation across electrodes was quantified using Phase Gradient Directionality (PGD), while the consistency of direction across trials was quantified by the axial mean vector length (MVL), defined as modulus of the second trigonometric moment.

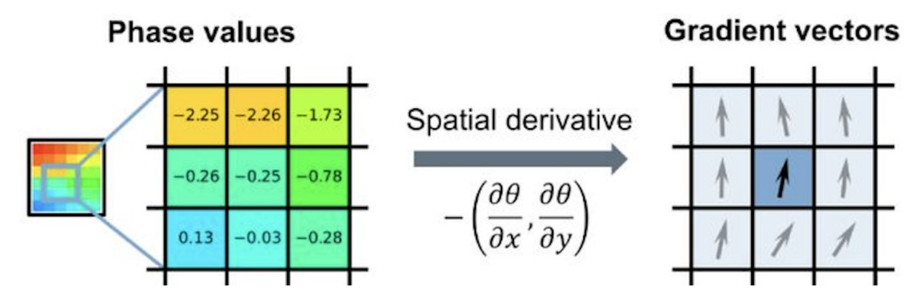
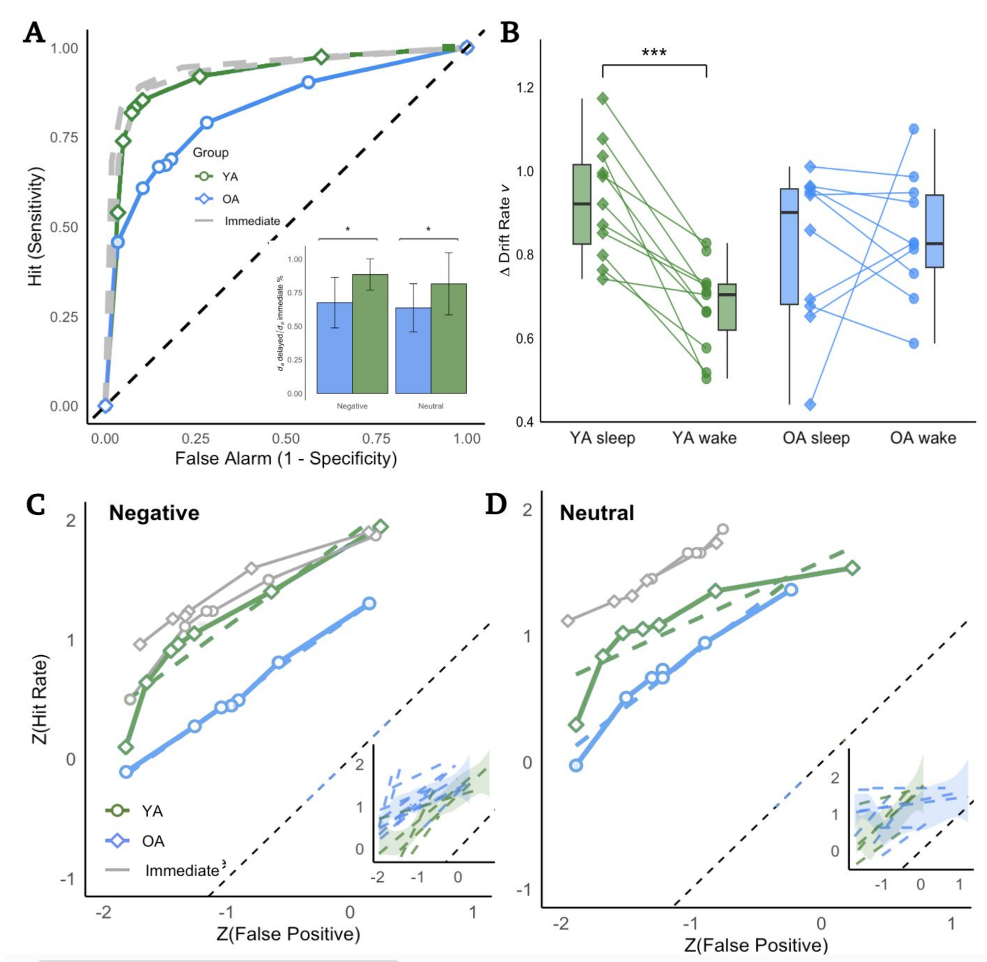


Fig. 5. The detection of traveling waves using phase gradients.

- **Spindle Trains:** Each SP cluster was defined as a sequence of successive SP events with peak times separated by less than 6 seconds.

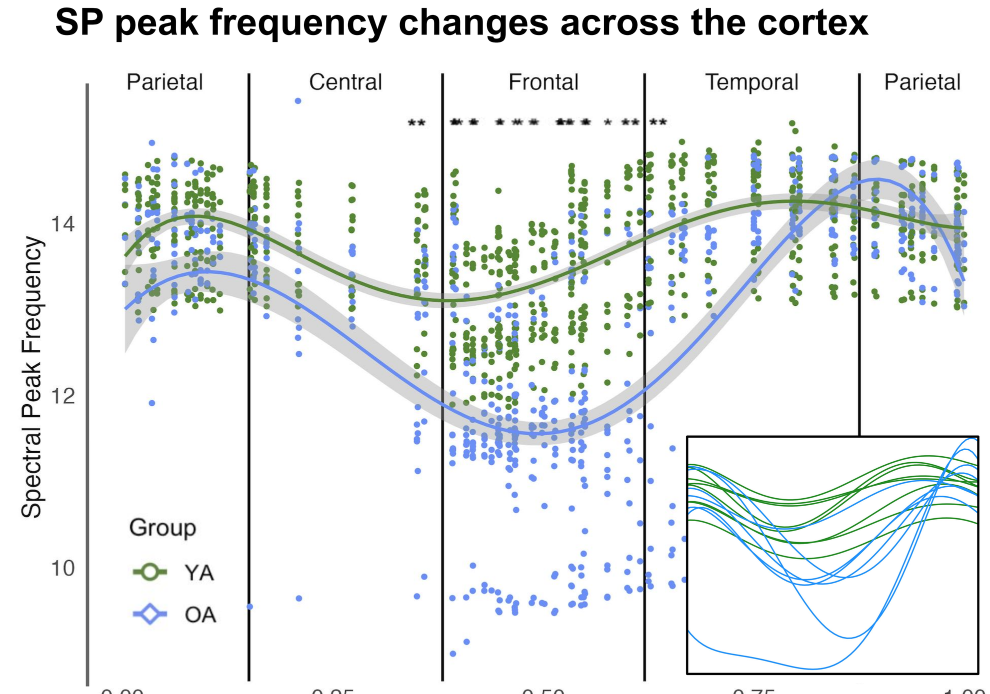
RESULTS:

Post-nap memory change differs by age and emotion



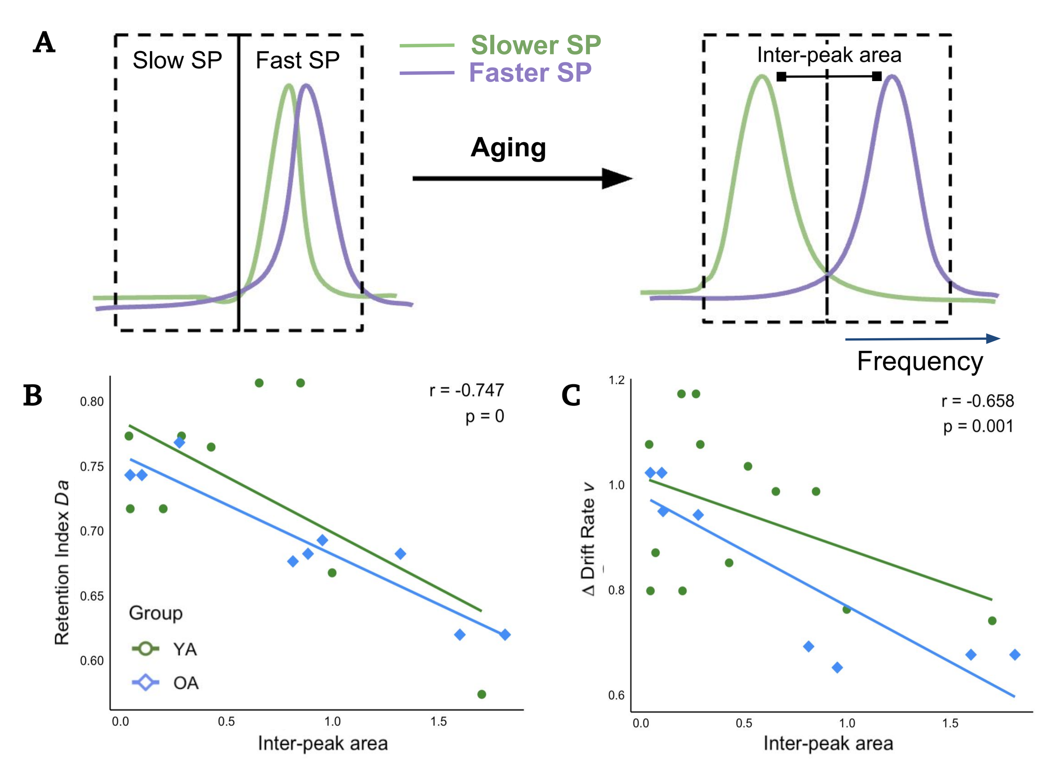
- The post-nap ROC curve for YA is above OA, reflecting greater discriminability and better memory performance in YA following a nap.
- This difference exists in both emotional and neutral memory, with a more pronounced gap in emotional memory (see C, D), where YA performance almost approaches that of immediate recall.
- After accounting for accuracy, reaction time, and confidence, **every individual** in the YA group showed improved memory in delayed recall task on the nap day compared to the wake day (see B). No significant difference was observed in the OA group.

SP peak frequency changes across the cortex



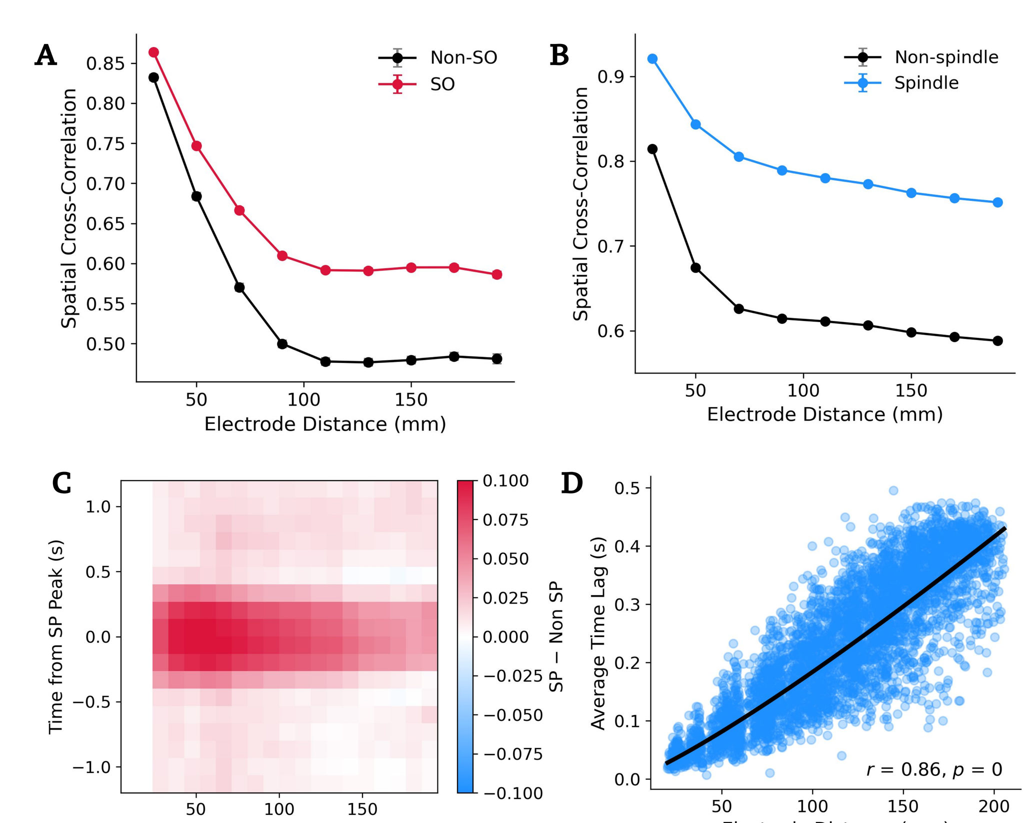
- The frequency of SOs and SPs changes smoothly across the cortex along electrode cycles in YA, rather than localized activity.
- OA exhibit a discontinuity in SP peak frequency, represented as a **'cliff'** between frontal-temporal and centroparietal electrodes.
- This discontinuity may be associated with disrupted long-range communication and increased regional isolation.
- **The traditional 'fast' vs 'slow' spindle classification may be subjective**, as SP frequency varies continuously with age and cortical location, reflecting spatial and developmental gradients rather than distinct subtypes.

SP & SO Frequency Gaps Predict Memory Performance



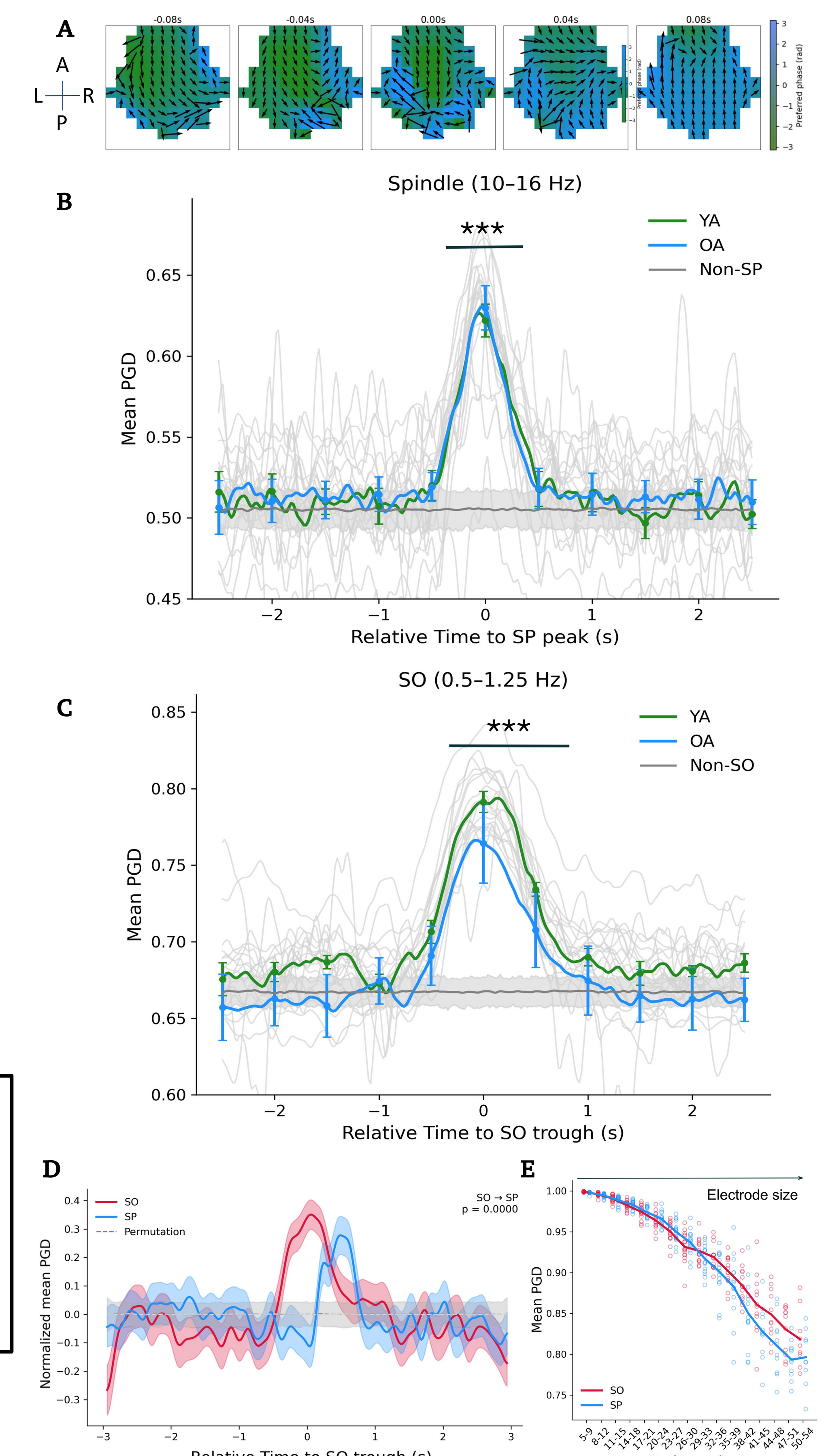
- An **increased** frequency gap between 'slower' frontal-temporal and 'faster' centroparietal SPs predicts **poorer** memory performance in both YA and OA.
- Similar associations are found between SO frequency gradients and post-nap memory performance.
- **Q:** What does the consistency of SO and SP frequency gradients imply about the importance of connectivity across brain regions?

Cortical connectivity increases during oscillation events



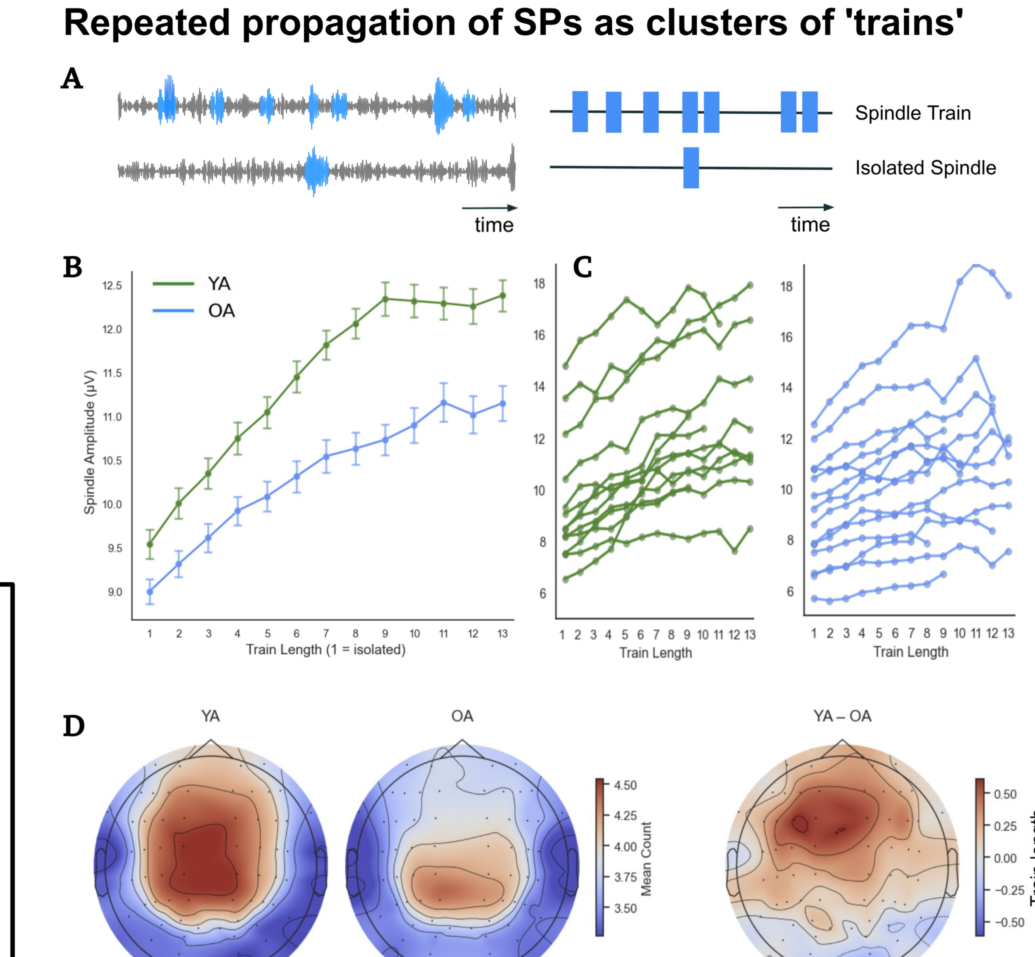
- Cortical connectivity significantly **increases** during SO & SP events compared to the baseline epochs during nREM sleep.
- This increase in connectivity is concentrated at the **peak** of SPs and the **up-state** of SOs.
- **Q:** Which type(s) of connectivity are characteristic of SOs & SPs?
  – Simultaneous connectivity – Unidirectional propagation – PAC
- The time lag of SO and SP signals between electrodes **increases** with inter-electrode distance, following a power law distribution.

The directionality of SOs & SPs as traveling waves



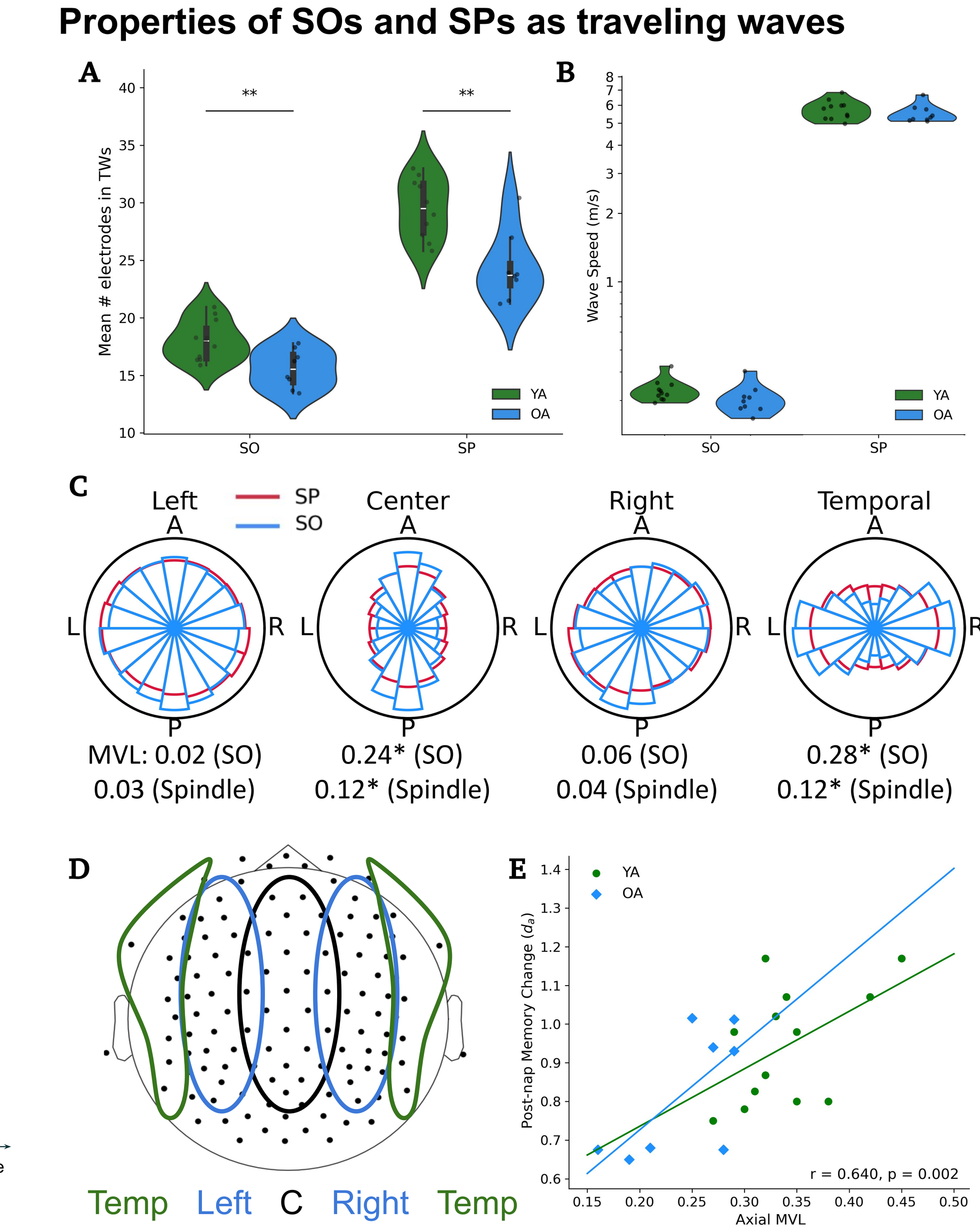
- **Unidirectional connectivity** of SP signals peaks at the SP peak, whereas that of SOs remains elevated throughout the entire up-state.
- The directionality of SPs is modulated by the directionality of SOs.
- Directionality decreases as the spatial extent of a TW increases.

Repeated propagation of SPs as clusters of 'trains'



- As SP train length **increases**, the amplitude, duration, and frequency of SPs consistently **increase**, while trains occur more frequently in the frontal-central region of YAs than in OAs.
- Prior studies link increases in these metrics to improved memory.
- YA benefit more from having multiple SP events repeatedly propagating within a short timeframe, leading to stronger waves.

Properties of SOs and SPs as traveling waves



- SO & SP TWs propagate across **broader** cortical areas in YA.
- TWs in central regions show a strong preference for anterior-posterior propagation compared to other directions.
- **Higher** directional consistency of SO and SP propagation predicts **better** memory performance in YA and OA.

CONCLUSIONS:

- The repeated temporal coupling between the **peak** of SP amplitude and the SO **up-state** across the cortex is critical:
  1. It enables maximal coordinated, unidirectional propagation of SOs and SPs, supporting long-range information transfer.
  2. It facilitates cross-frequency **modulation** from SOs to SPs, potentially enhancing information integration.
- Disruptions in propagation gradients, consistency, and cortical involvement are related to impaired memory performance.
- Traditional definitions of 'fast' and 'slow' SPs are often subjective. SP frequency varies by age and cortical region.
- Precise spatiotemporal coordination along anterior-posterior axis during the propagation of sleep oscillations is crucial for effective memory consolidation, highlighting the functional importance of large-scale neural coordination during sleep.
- Future sleep-memory studies should include spatiotemporal structures in their analysis.

SO-SP Coupling Meta-anal:

REFERENCES: