How Sleep Rhythms affect System Memory Consolidation and Synaptic Plasticity

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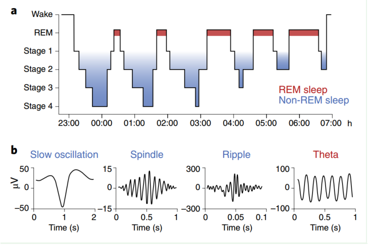
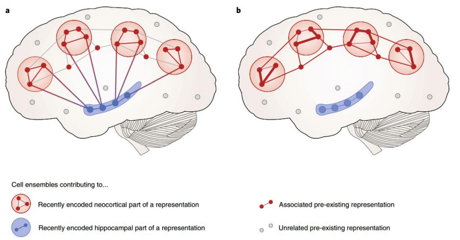
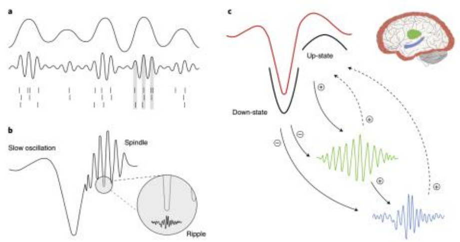
Overview

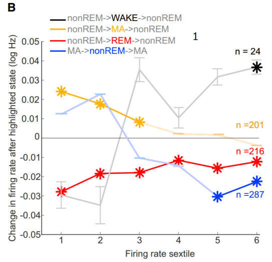
Sleep rhythms have a critical and active role in **system memory consolidation**, and the underlying mechanism is related to the **temporal oscillation coordination**, especially the **nested wave structure** such as the coupling of **SWA, spindle** and **ripples**.

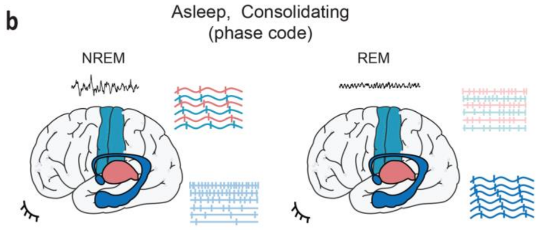






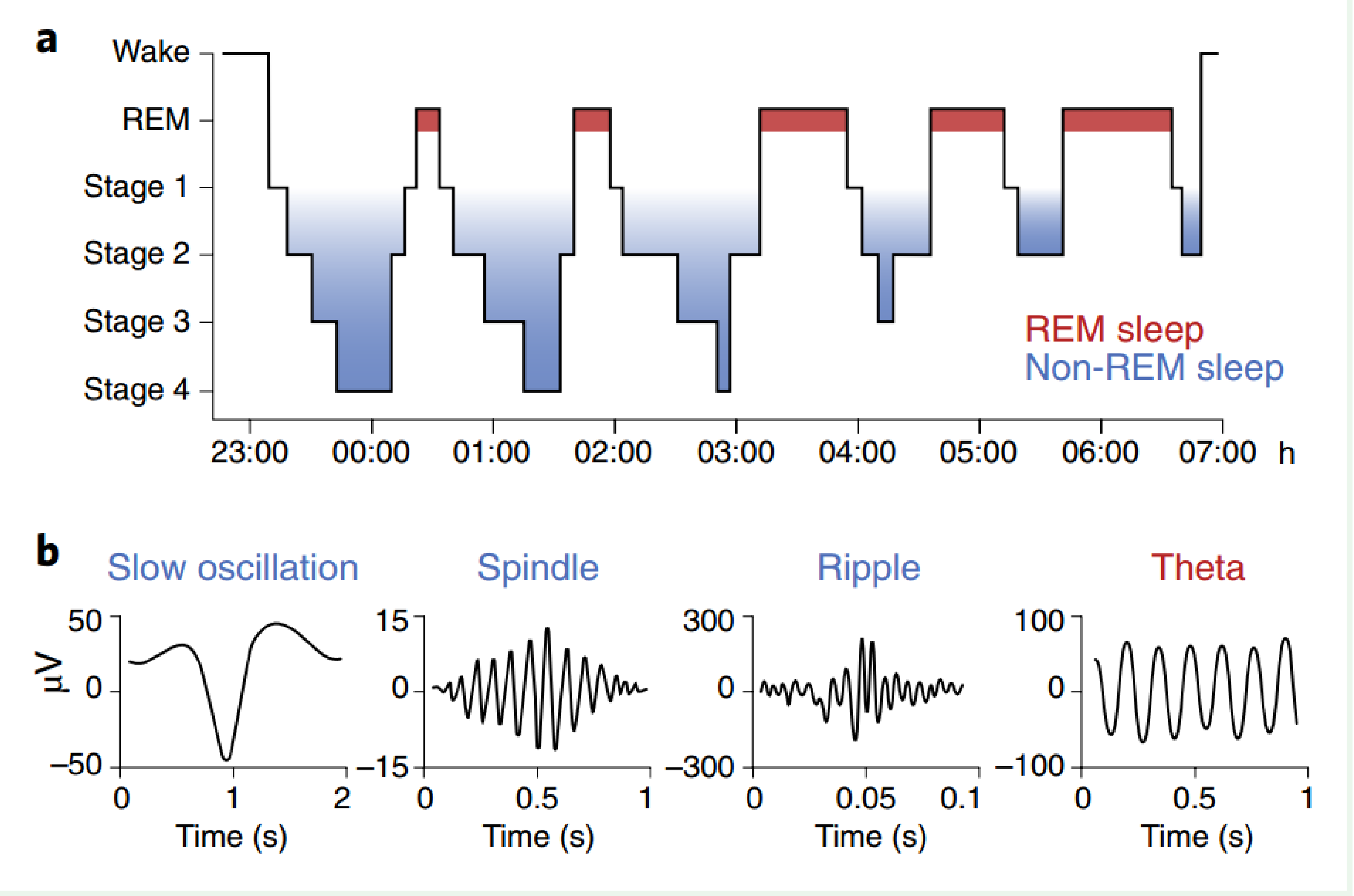
- Background
- Sleep Oscillation Effect (SWA)
- Potential Mechanism (STDP, Resonance)
- Summary (Discussion, Up and Down of Sleep)

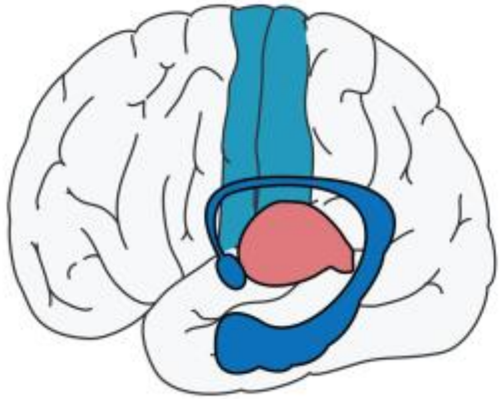


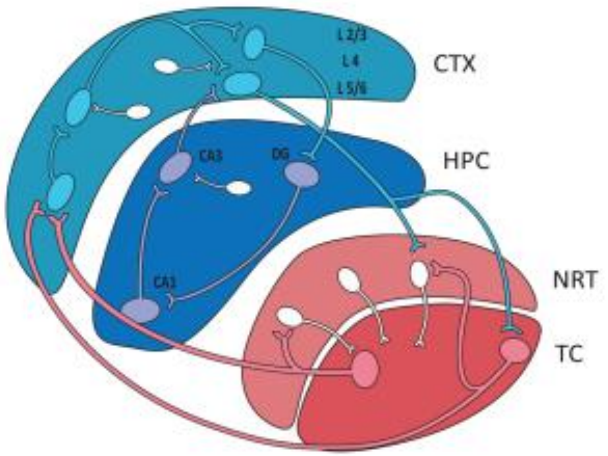


Background: Sleep Oscillations

(Klinzing et al., 2019) [1]
(Puentes-Mestril et al., 2019) [9]





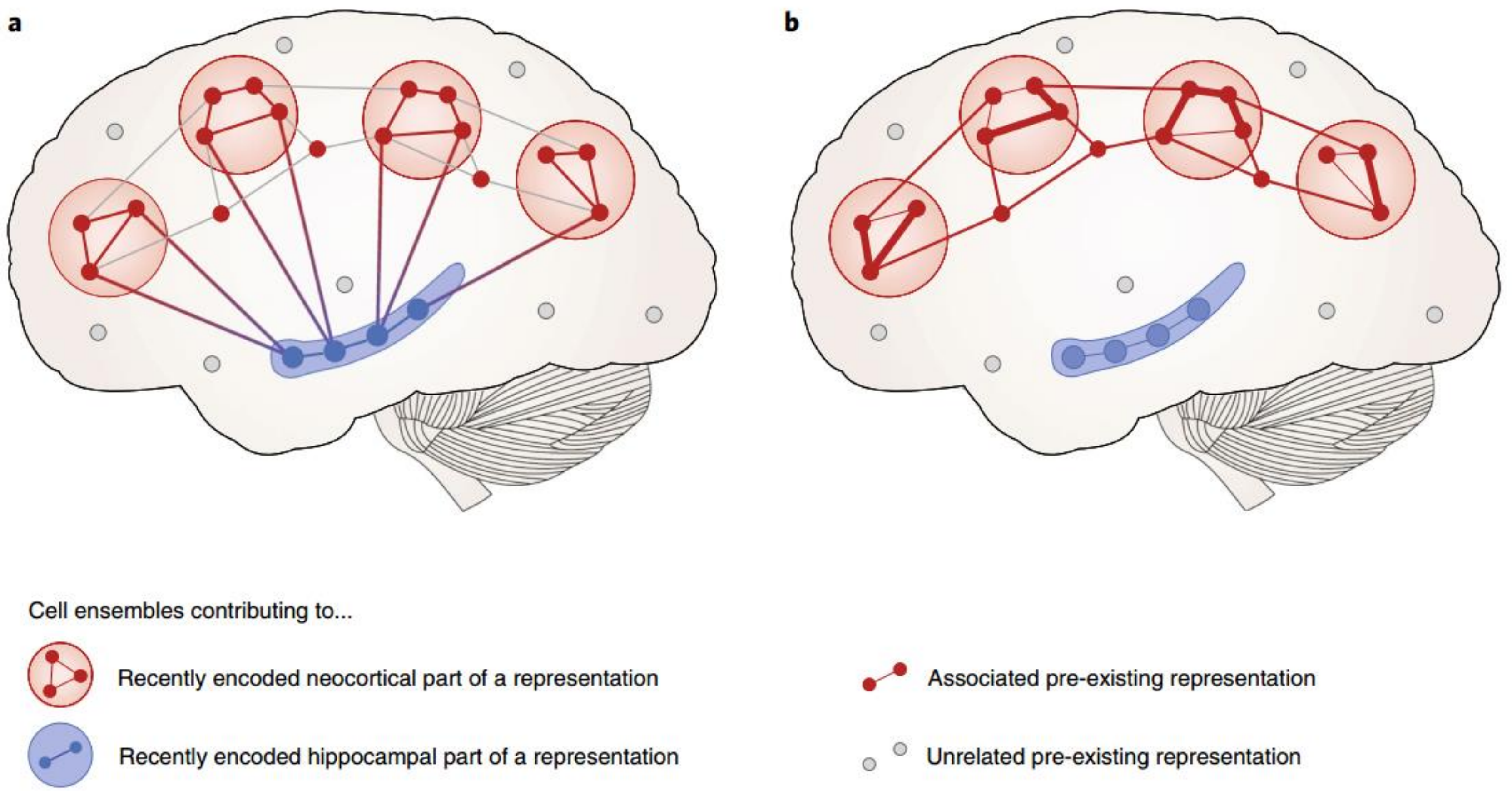


Sleep architecture and sleep oscillations.
(a) Human sleep profile with the **depth of sleep** (NREM consists of Stage 1-4);
(b) Some **typical tracings** of sleep rhythms. (Note the difference in amplitude and time scale).

CTX =cortex; **HPC** = hippocampus;
NRT = thalamic reticular nucleus; **TC** = thalamocortical relay nucleus.

Background: System Memory Consolidation

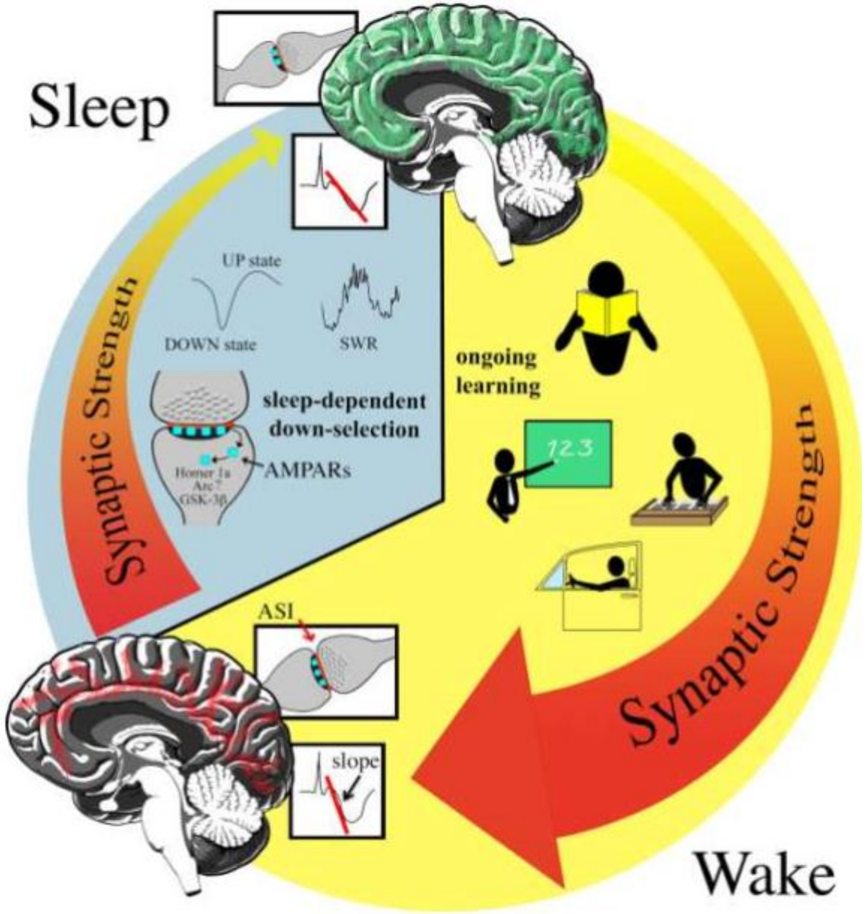
(Klinzing et al., 2019) [1]

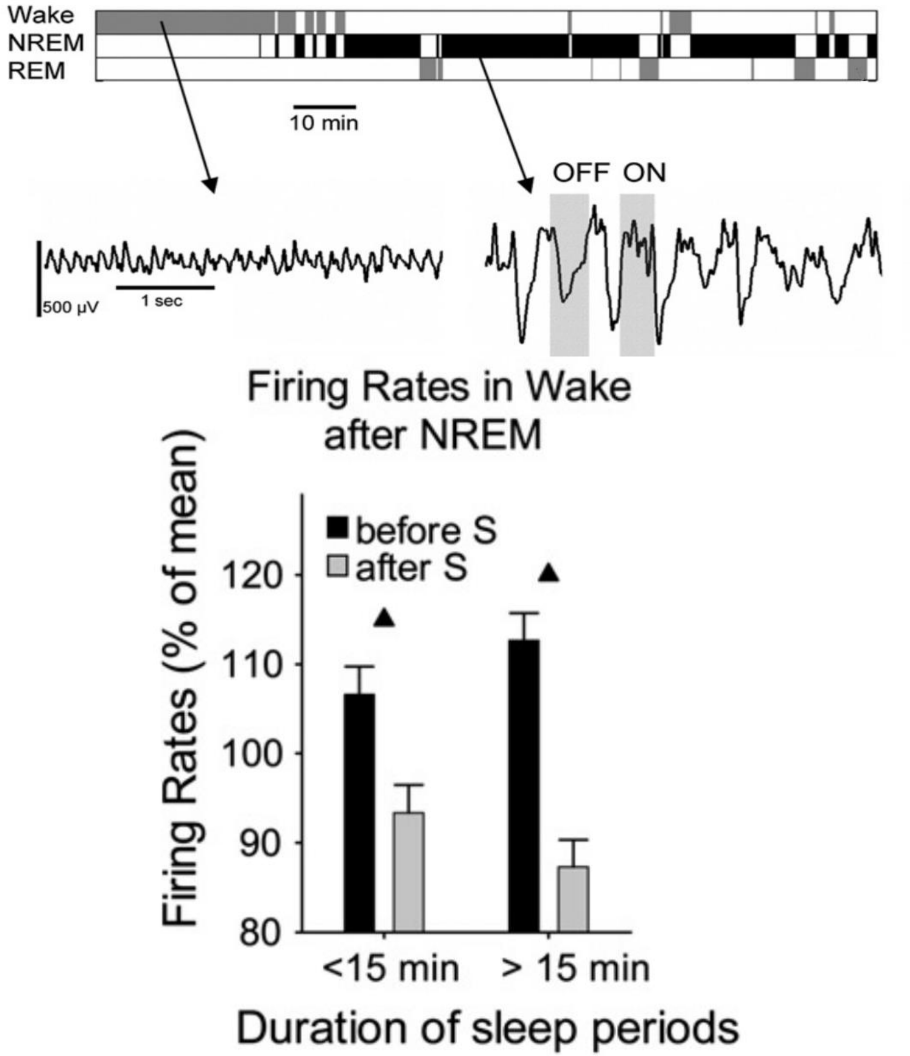


Medial Temporal Hippocampal (MTH) system.
(a) A newly encoded representation in cortex is **indexed by** features in hippocampus;
(b) System Memory consolidation results in a **systems-level** reorganization of the representation.
(Selective **strengthening**, **weakening** and **creating synaptic connections**)

Background: SHY

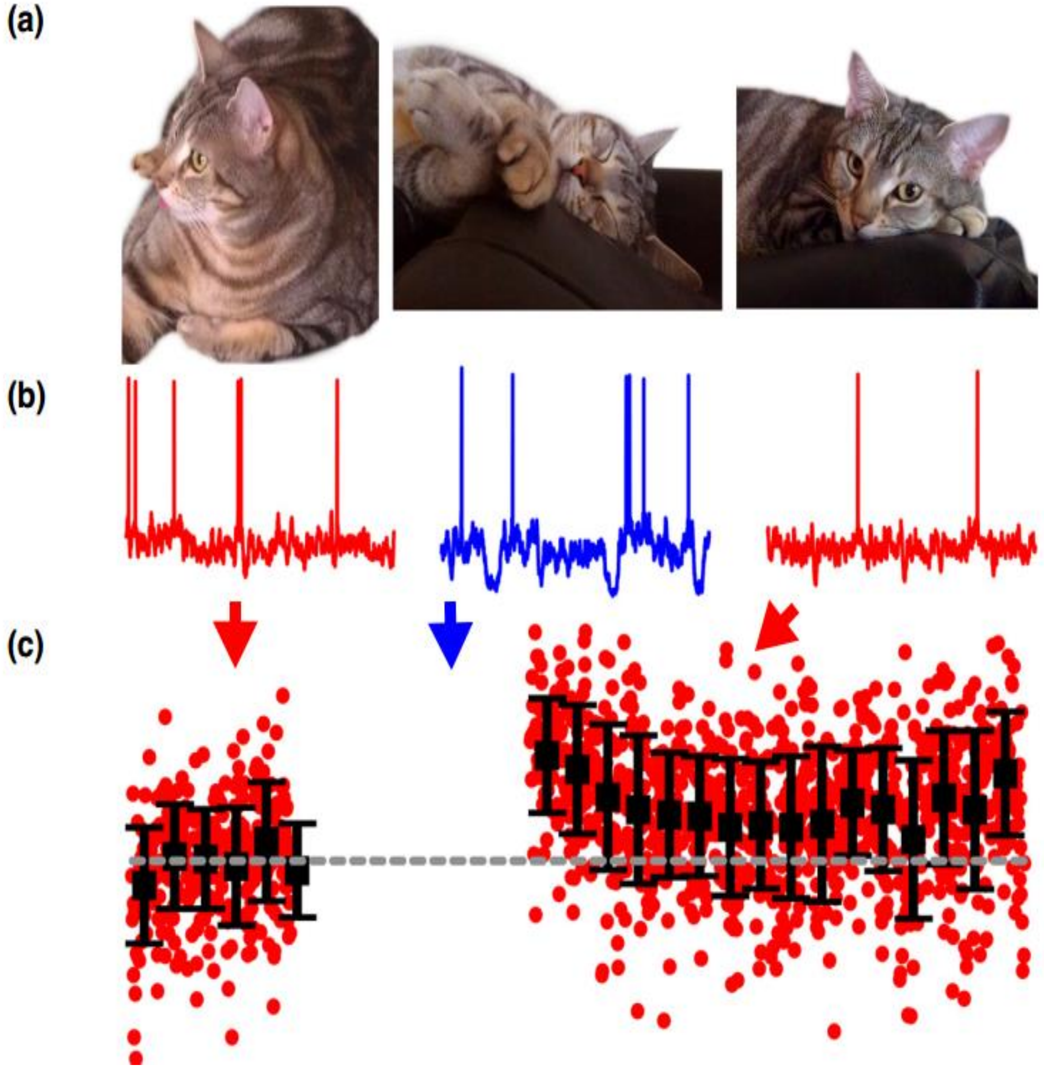
(Tononi et al., 2019) [2]
(Tononi et al., 2009) [3]





Synaptic Homeostasis Hypothesis (SHY) and supporting evidence
Left: SHY predicts the **net effect** on synaptic strength of **awake** and **sleep** brain states.
Right: Cortical neuronal firing rates **decrease** after NREM sleep (<15mins: short sleep; >15mins: long sleep).

Effect: SWA Alone



Slow Wave Activity (**SWA**) induces **LTP**.

(a) A alternation between **wake–SWA–wake** states in a cat;

(b) Intracellular activities of **cortical neuron** in somatosensory cortex with/without **stimulation**;

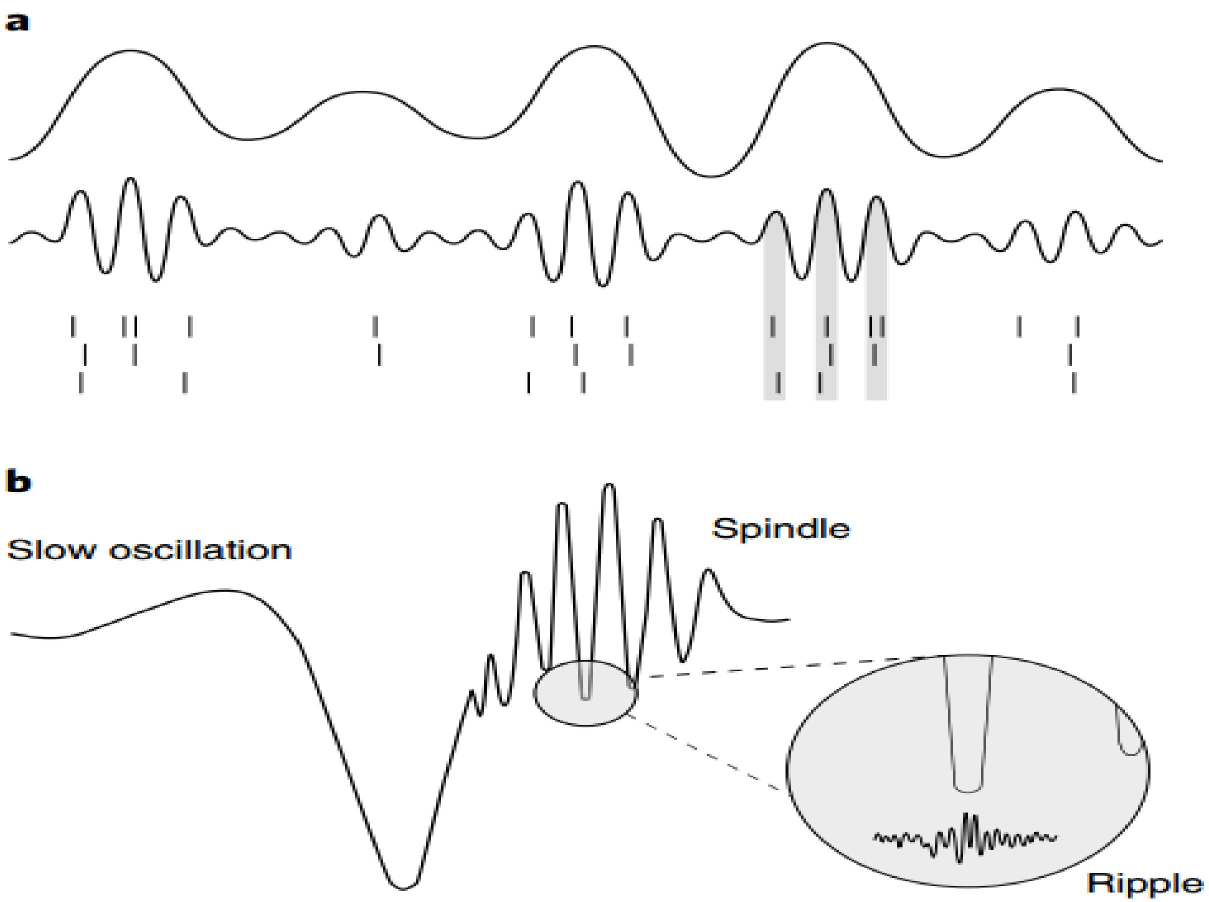
(c) After SWA, first component of somatosensory **EPSP increases** (middle empty: no stimulation applied);

Causal role of SWA in **improving memory consolidation**

- (Marshall et al., 2006) [10]
- (Ngo et al., 2015) [11]
- (Papalambros et al., 2017) [12]

Effect: SWA-Spindle-Ripple Coordination

(Klinzing et al., 2019) [1]

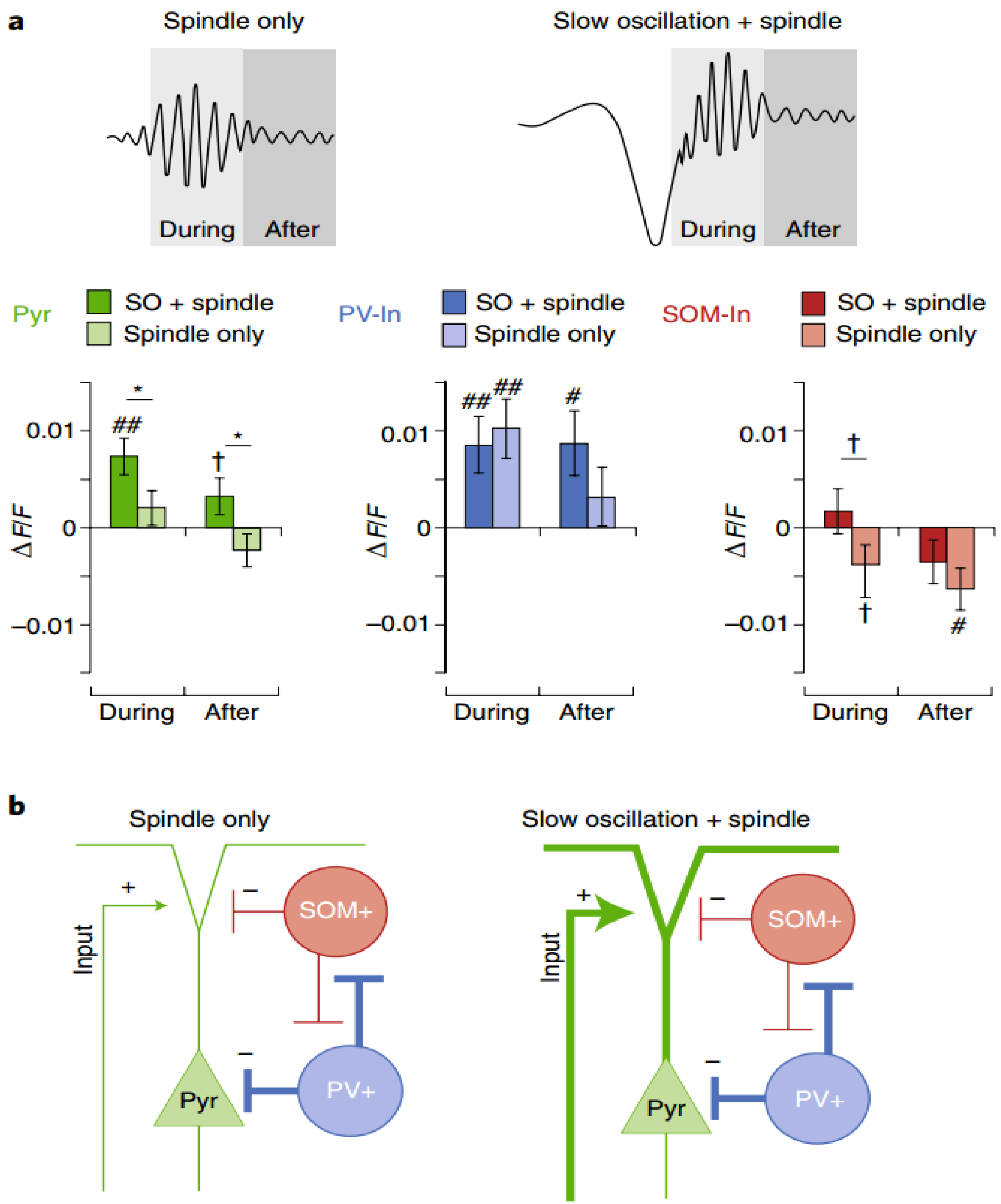


Sleep oscillation coordination **regulates** systems memory consolidation.

(a) The **temporal relationship** between a low-, high- frequency oscillation, and local neural firing;
(b) A **triple-coupling** of oscillations in NREM sleep (**conditions** of facilitated synaptic plasticity);

Effect: SWA-Spindle Coordination

(Klinzing et al., 2019) [1]



Changes of Synaptic plasticity in cortical neurons with/without spindle nesting SWA-up-state coordination.

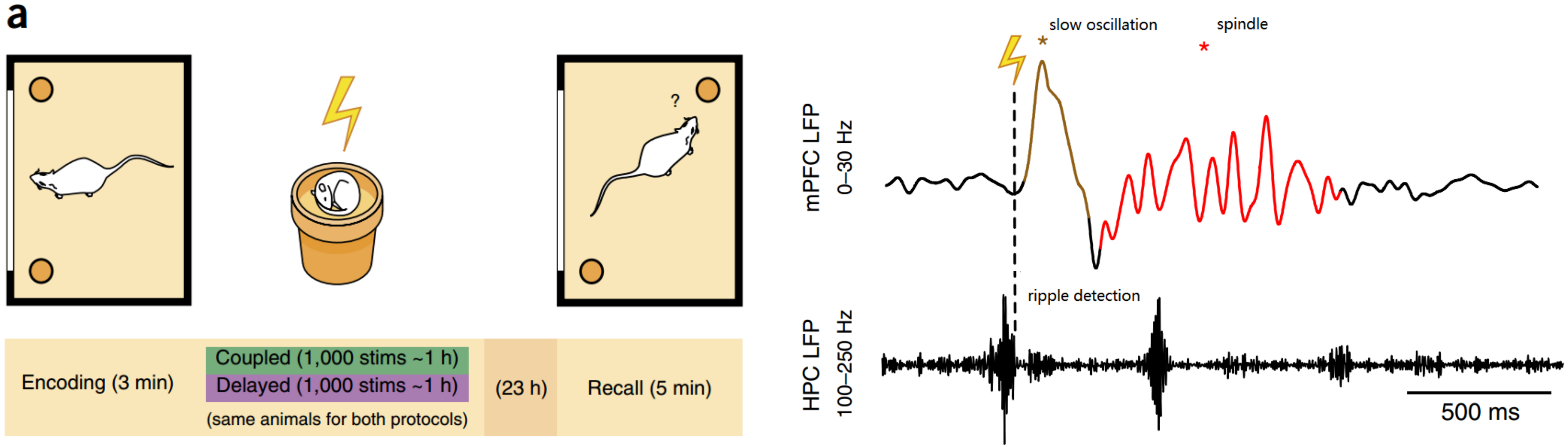
(a) Only SWA+spindle **potentiate** the Pyr cell activity.
Top: Wave situations of "spindles only" and "SWA+spindles";
Down: two-photo calcium imaging indicates the activities of **Pyr**, **PV-In**, and **SOM-In** cells under different conditions.

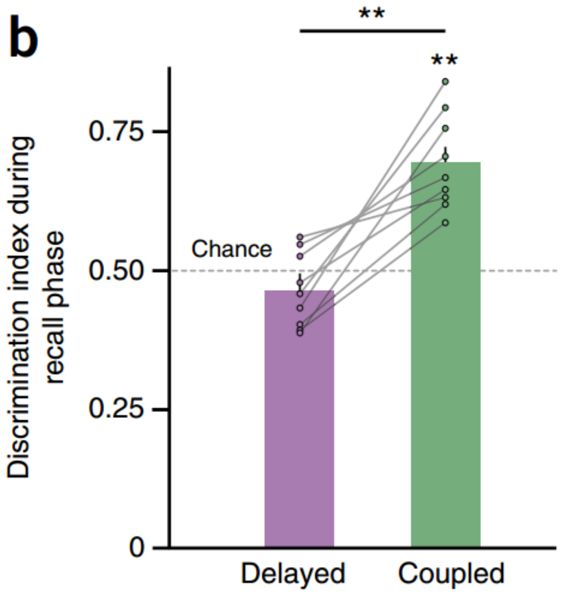
Pyr = cortical pyramidal cell;
PV-In = parvalbumin-positive (PV+) inhibitory interneuron;
SOM-In = somatostatin-positive (SOM+) inhibitory neuron;

(b) The schematic diagram shows above results.
Different settings of the **excitation/inhibition balance** in cortical circuits during spindles **depending on** whether they occur in isolation (**Spindle only**, left) or nest in an SWA up-state (**Slow oscillation + spindle**, right).

(Maingret et al., 2016) [5]

Effect: SWA-Ripple Coordination

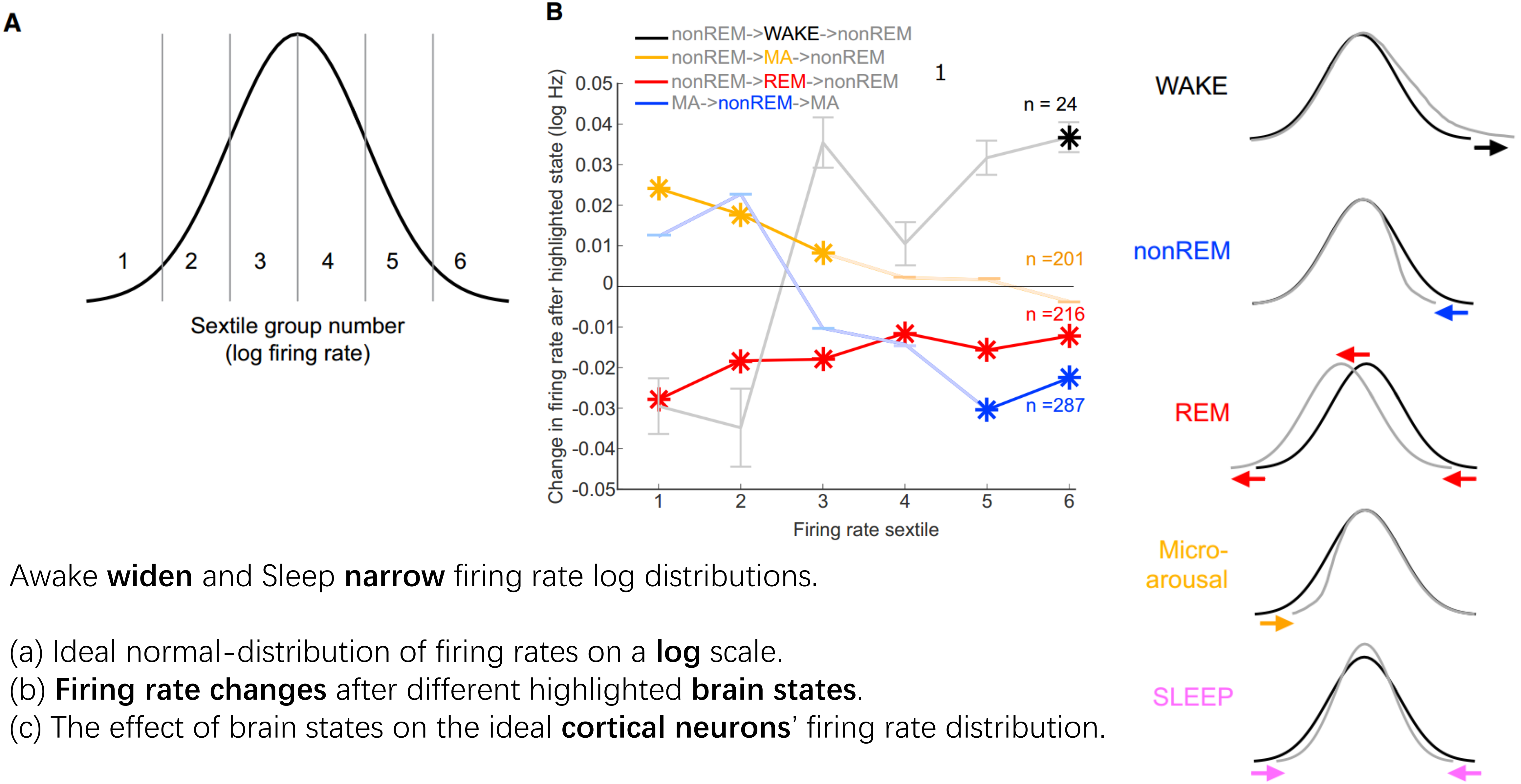




Fine-tuned coupling between SWA and ripples **enhance** memory performance.
(a) Experiment workflow
- **Coupled**: induce-**SWA** stimulation **right after** Ripple Detection.)
- **Delayed**: induce-**SWA** stimulation **in a random delay after** Ripple Detection.)

(b) **Discrimination index** for the displaced object
shows the **SWA-Ripple** boosted memory consolidation.

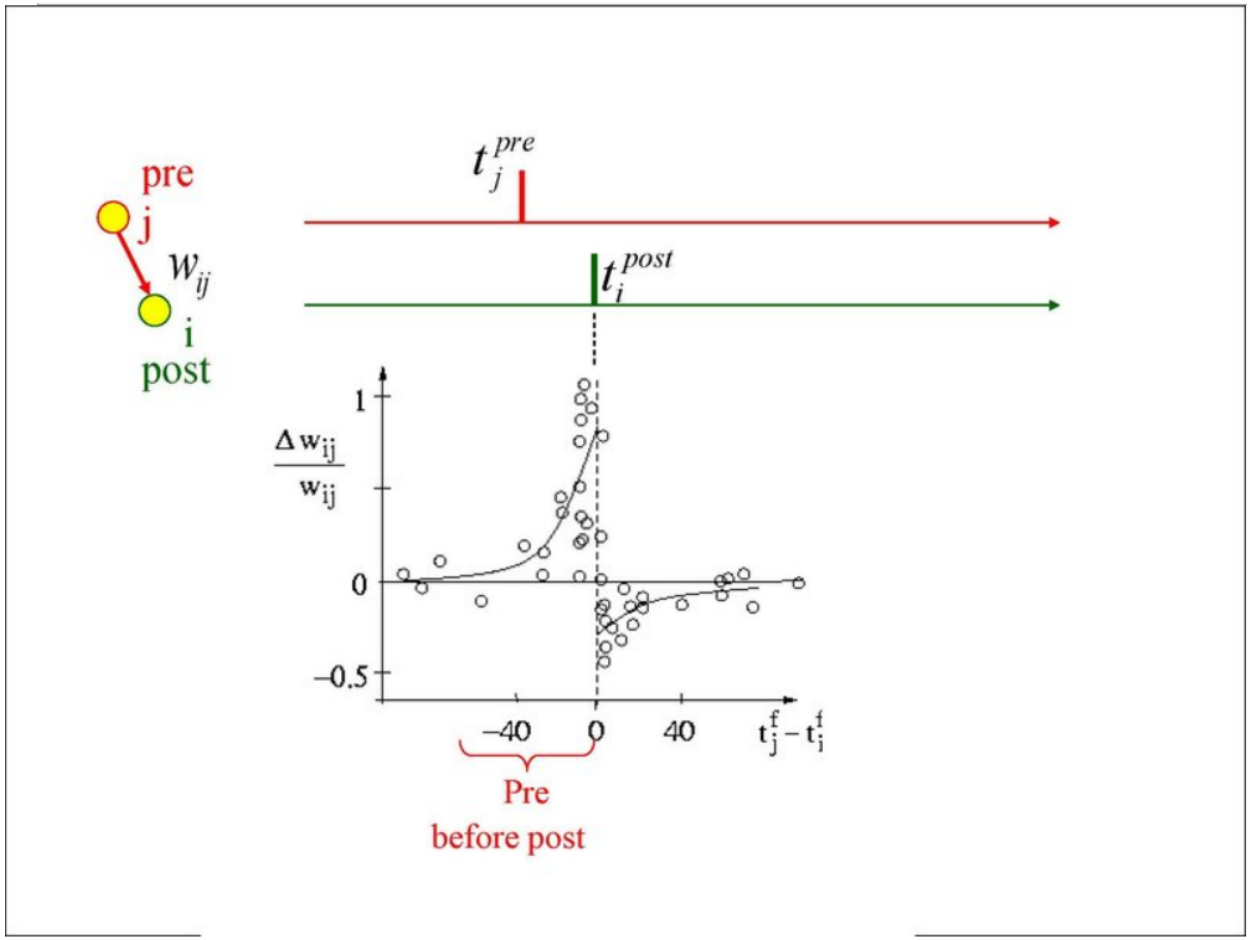
Effect: Sleep Oscillation to Firing rate



Awake **widen** and Sleep **narrow** firing rate log distributions.

(a) Ideal normal-distribution of firing rates on a **log** scale.
(b) **Firing rate changes** after different highlighted **brain states**.
(c) The effect of brain states on the ideal **cortical neurons**' firing rate distribution.

Mechanism: STDP



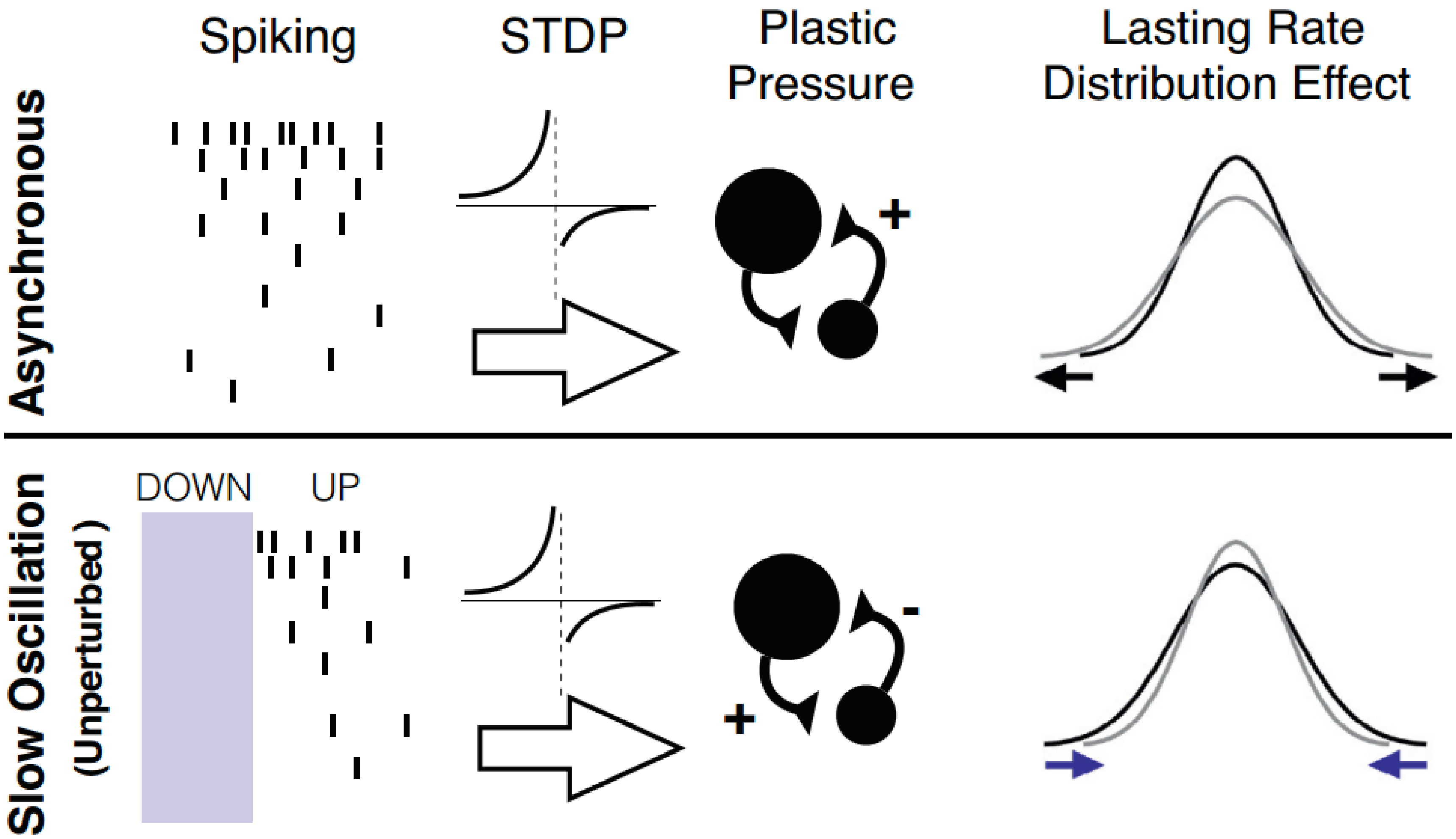
The Spike-timing-dependent plasticity (**STDP**) rule.

STDP is a temporally **asymmetric form** of Hebbian learning induced by temporal relationships between the spikes of pre- and postsynaptic neurons, which can lead to **LTP** and **LTD**.

t_j: the firing time of presynaptic neuron j;
t_i: the firing time of postsynaptic neuron i;

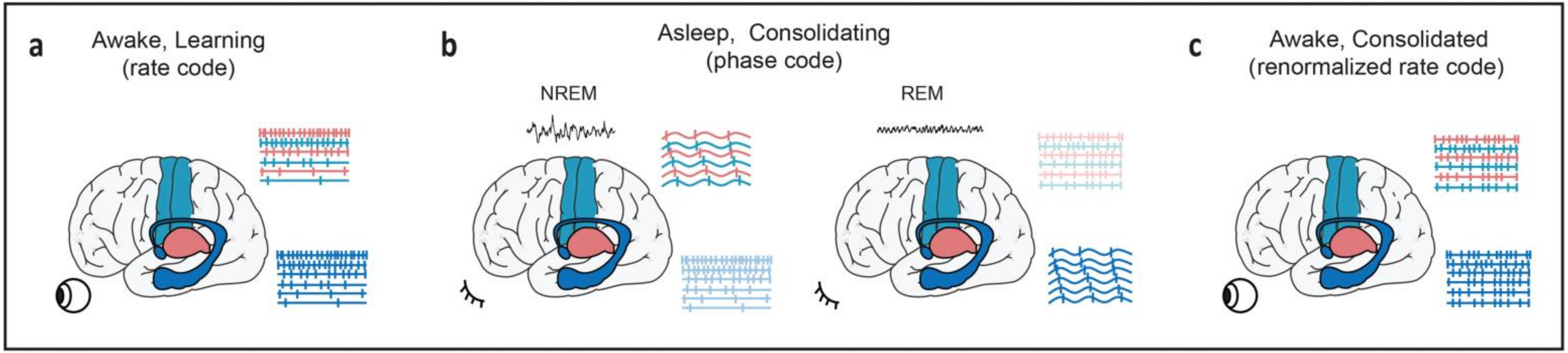
w_ij: the synaptic weight from j to i;
Δw_ij: the change of synaptic weight from j to i;

Mechanism: NREM SWA Regulation



Sleep NREM **SWA** (compared to wake) offers **a synchronous background** in the SWA **DOWN->UP** phases for high- / low- firing rate neurons to change its **plastic pressure** (the tend that synaptic weights would change), so as to mediate the **homeostatic function**.

Mechanism: General Oscillation Resonance



Resonance-based mechanisms for sleep-dependent plasticity.

(a) Awake: neurons **encode new information** by changing its firing rate distribution (**Rate Coding method**).

(b) Asleep: neurons reorganize the representation for system memory consolidation (**Phase Coding method**).
NREM SWA and **REM theta** wave provide the **basis of Resonance**, which generates consistent spike-timing relationships between different neuron groups based on their **intrinsic properties**, like firing rate distribution.

(c) Awake after sleep: as a result of **STDP** during the resonance states,
firing rates are renormalized and **new memory traces** are integrated into the existing cortical network.

Summary: From Sleep Oscillation to Memory Consolidation

- Background
  - Sleep oscillation
    - NREM: Slow oscillation, spindle, ripple
  - System memory consolidation
    - **Two stage model**
    - **Synaptic Homeostasis Hypothesis (SHY)**
- Sleep Oscillation Effect (Up or Down)
  - SWA Alone
  - SWA-Spindle
  - SWA-Ripple
  - SWA-Spindle-Ripple
- Potential Mechanism
  - STDP synaptic plasticity rule
  - Resonance Model for the change of firing rate distribution

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Thank you