Supplementary Materials for 'Neurofeedback reveals cognitive states supporting waking human hippocampal ripples'

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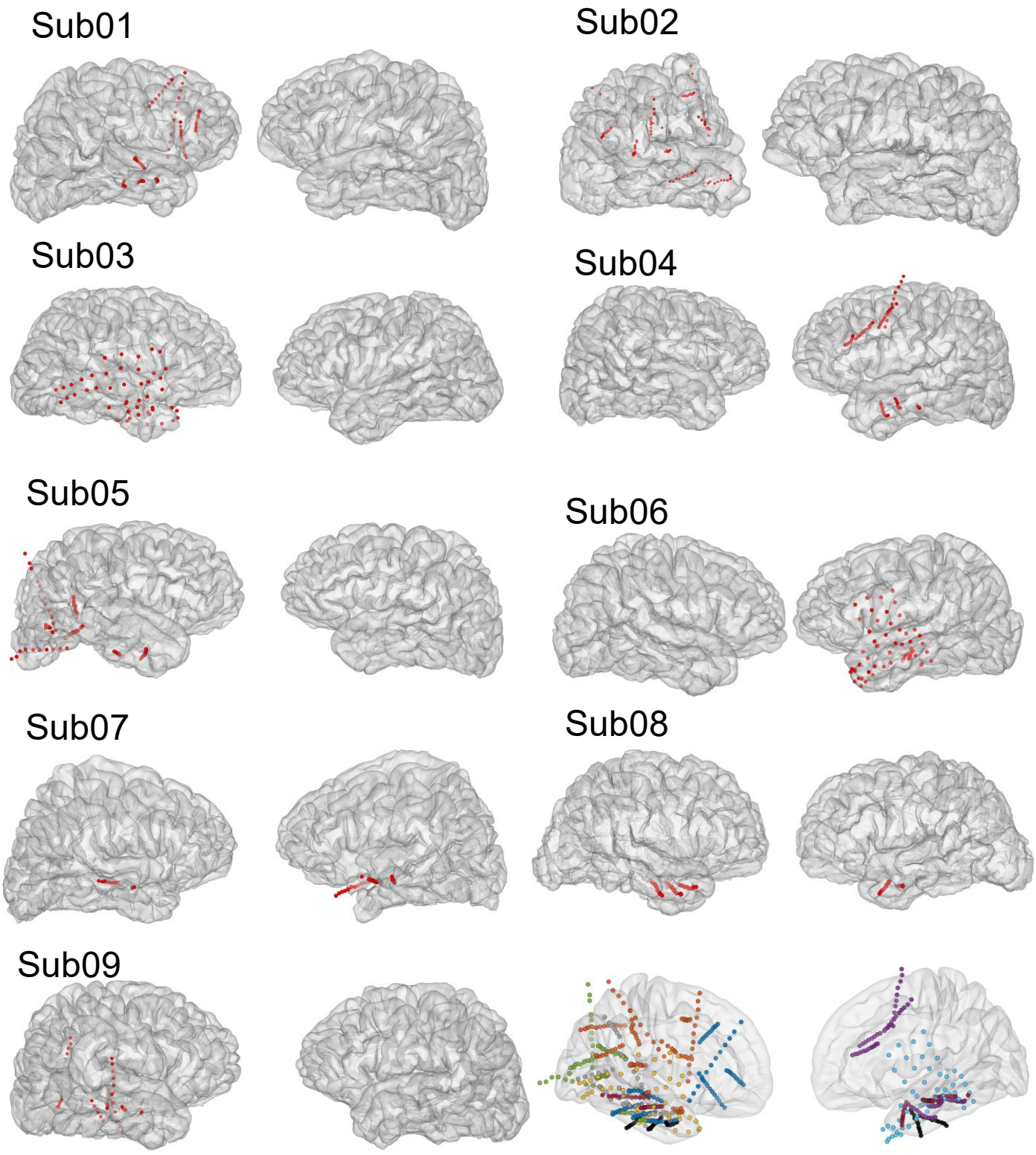
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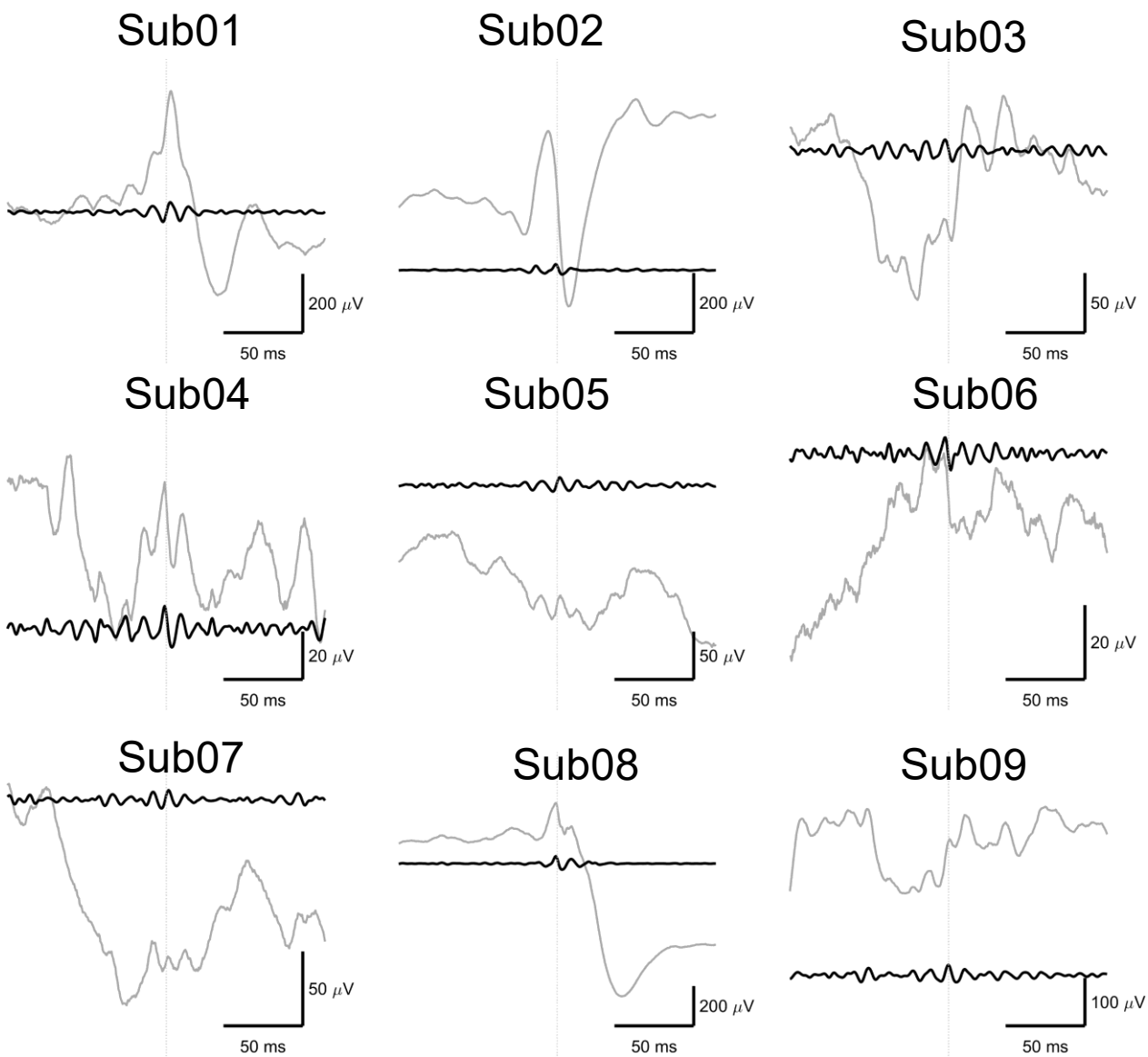
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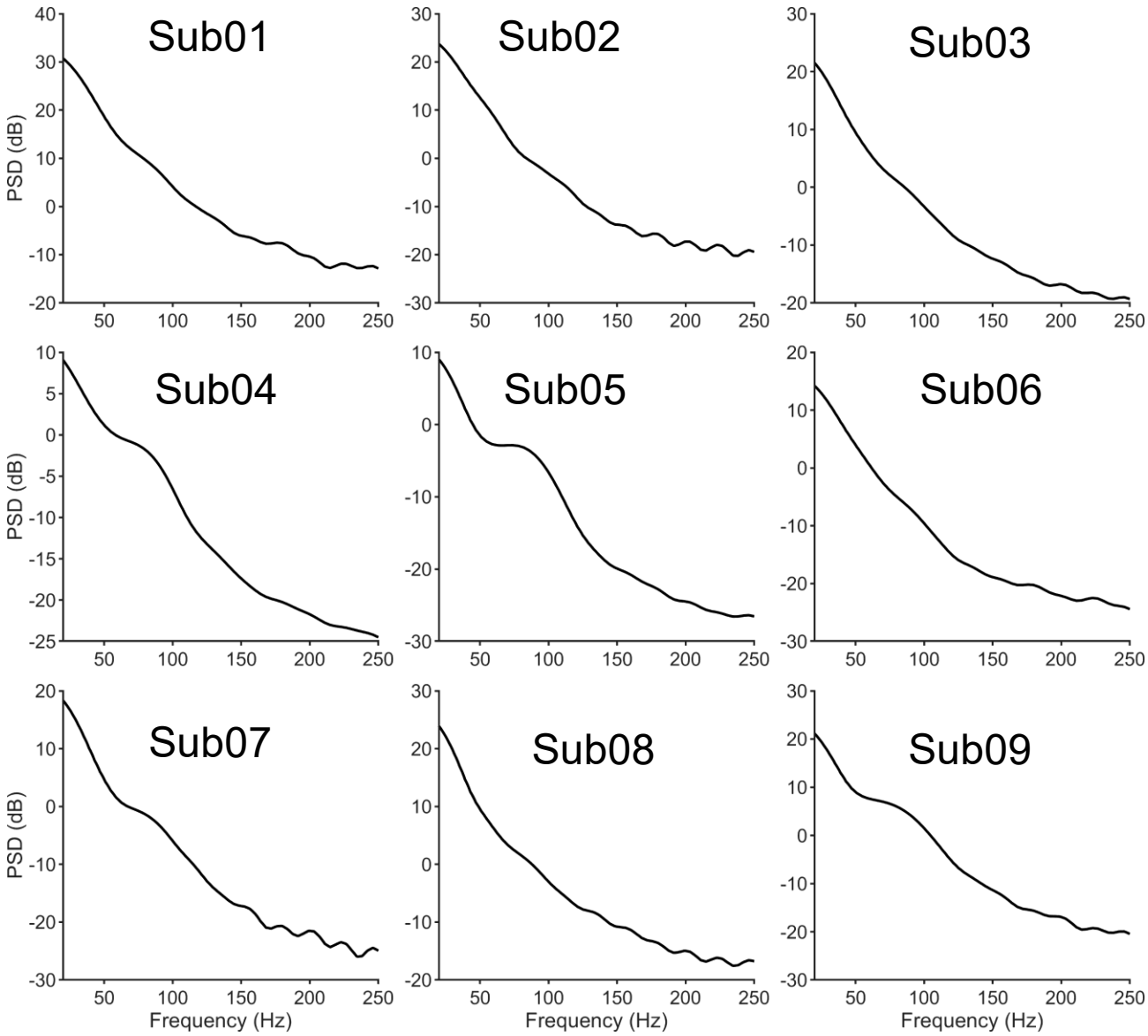
Supplementary Figures 1 to 12
Supplementary Table
Supplementary Method



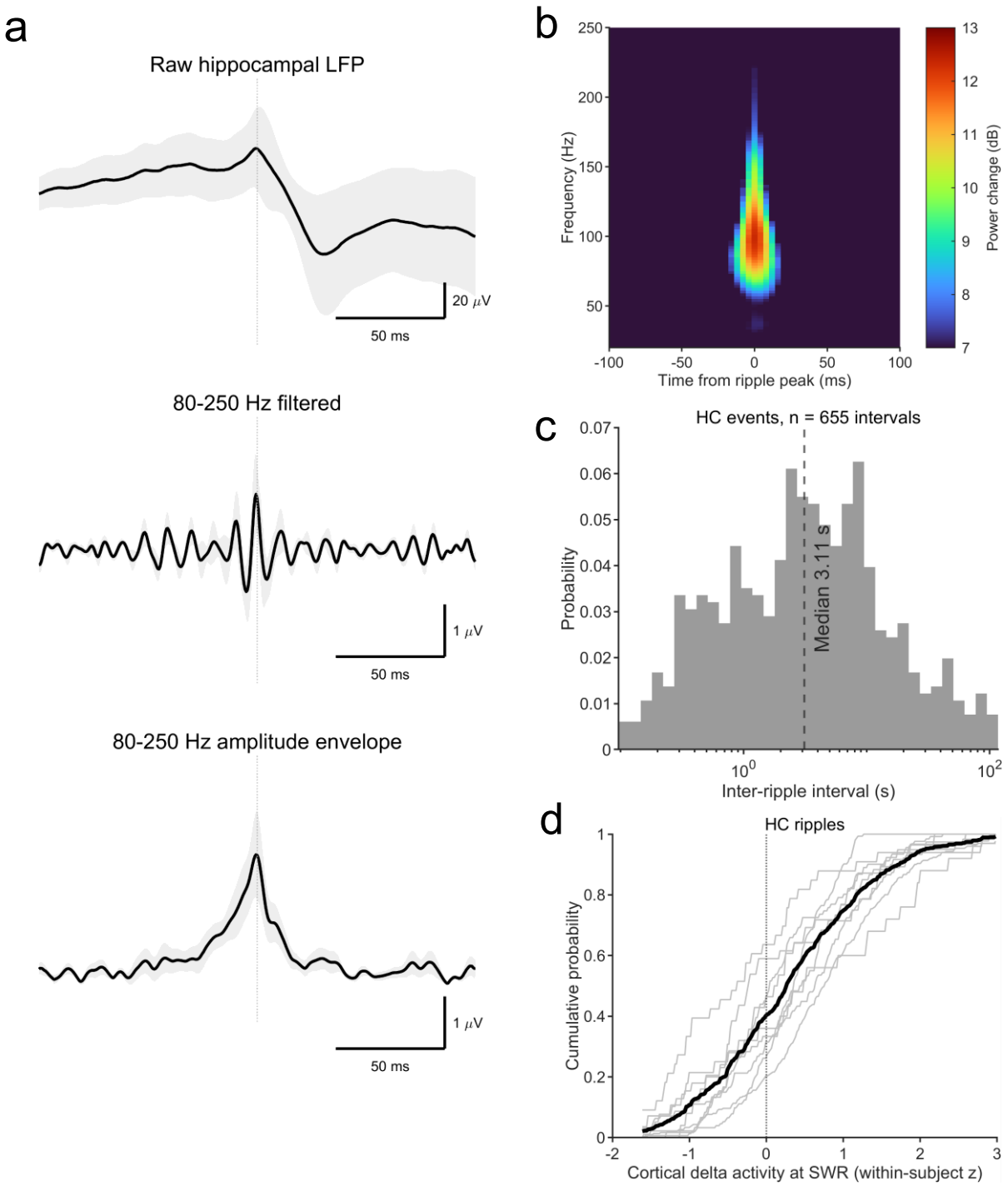
Supplementary figure 1 Electrode locations across participants. Cortical surface reconstructions and implanted electrode locations are shown for each participant. Red dots indicate electrode contacts on the individual cortical surfaces. The lower-right panel shows electrode locations from all participants projected onto a common standard cortical surface, with electrode colors indicating participant identity.



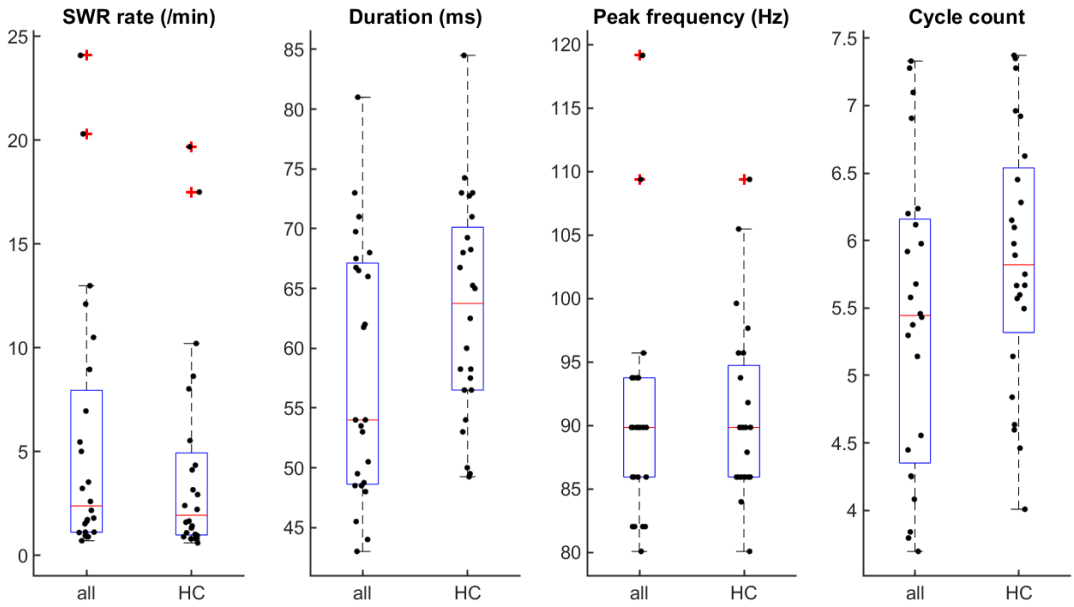
Supplementary figure 2 Representative ripples across participants. Representative hippocampal Ripple events detected from each participant are shown together with scale bars. Gray traces indicate the hippocampal local field potential , and black traces show the corresponding Ripple-band filtered signal.



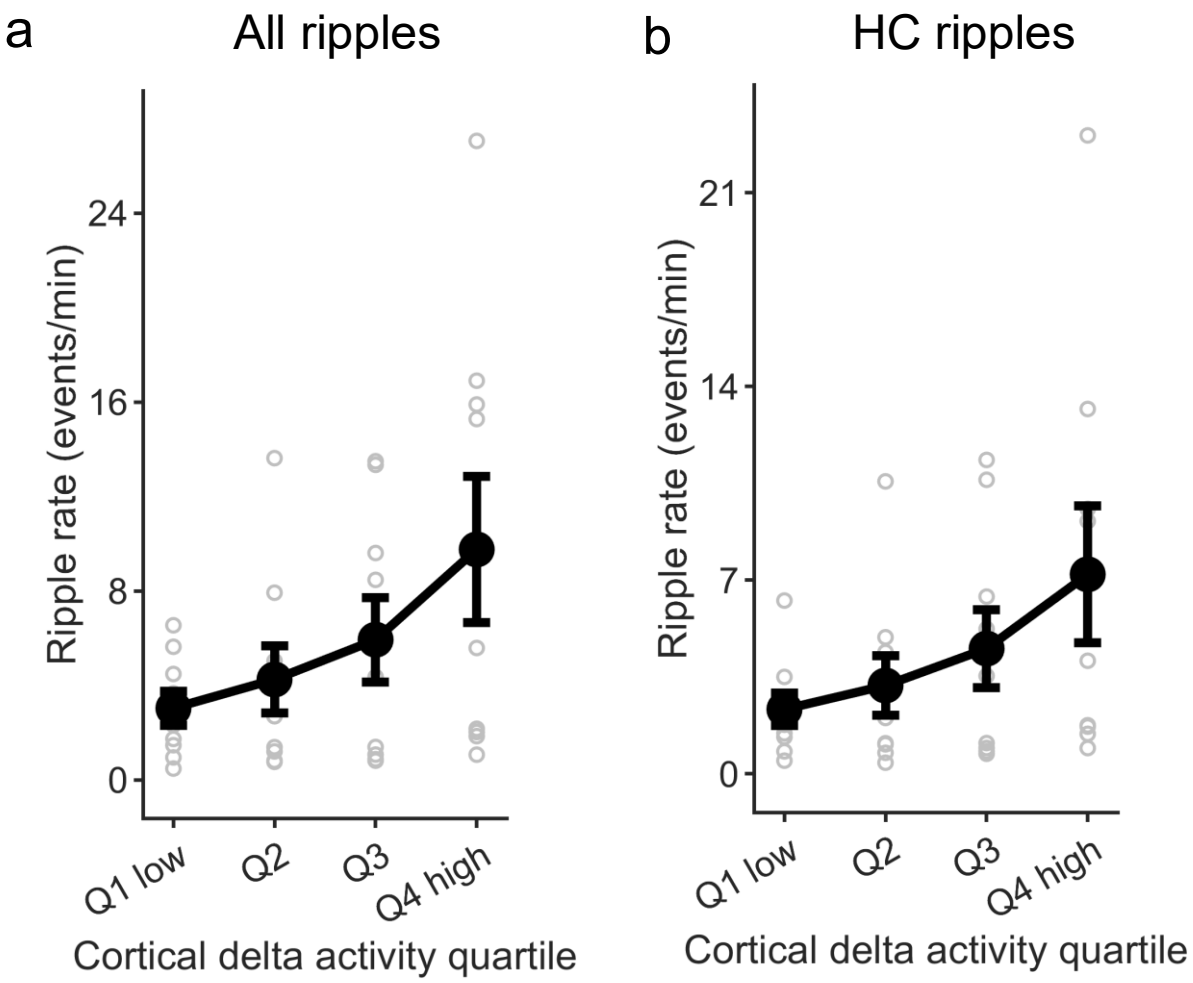
Supplementary figure 3 Individual-participant ripple power spectra. Mean power spectral density (PSD) of detected hippocampal Ripple events is shown separately for each participant. The x-axis indicates frequency (Hz), and the y-axis indicates PSD (dB).



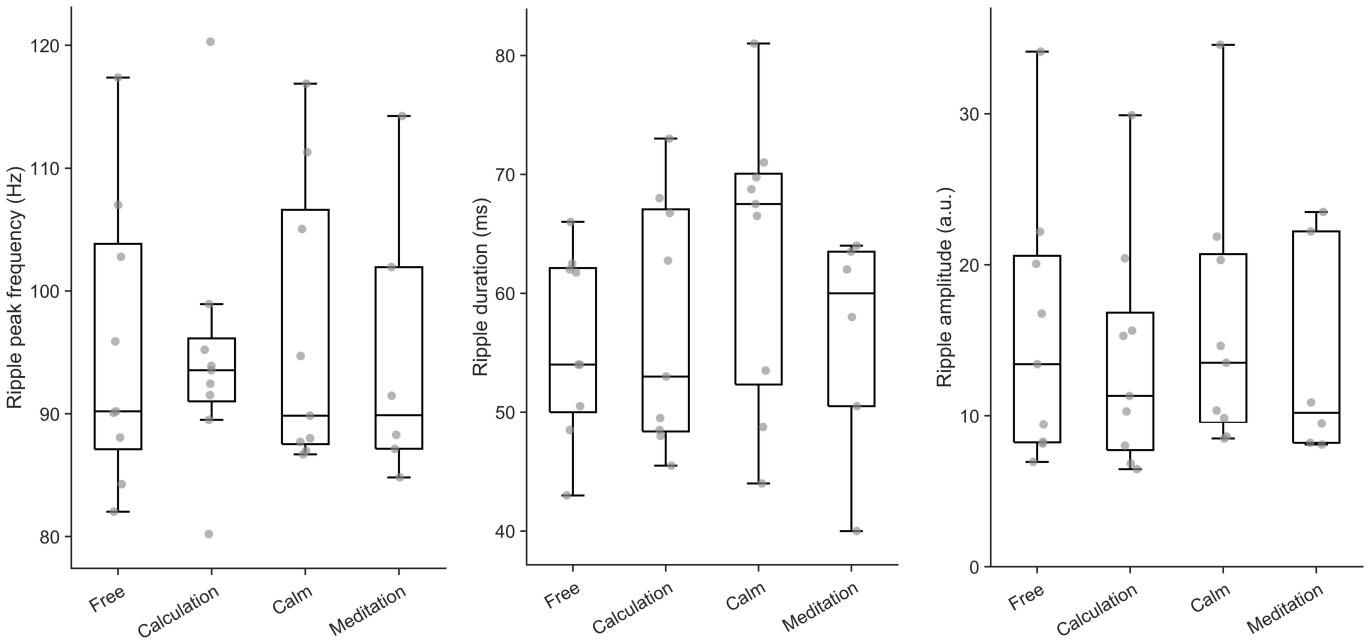
Supplementary figure 4 High-confidence ripple characteristics. **a**, Average waveforms of high-confidence (HC) Ripple events. Top, raw hippocampal local field potential (LFP); middle, Ripple-band-filtered signal (80–250 Hz); bottom, Ripple-band amplitude envelope. Solid lines indicate the mean across HC Ripple events, and shaded areas indicate ±1 s.e.m. **b**, Mean time–frequency representation of HC Ripple events, with color indicating power (dB). **c**, Distribution of inter-Ripple intervals for HC Ripple events. The x-axis shows the inter-Ripple interval on a logarithmic scale (s), and the y-axis shows relative frequency. **d**, Empirical cumulative distribution of cortical delta-band power sampled at the time of HC Ripple events. Gray lines indicate individual participants, and the black line indicates the group mean across participants.



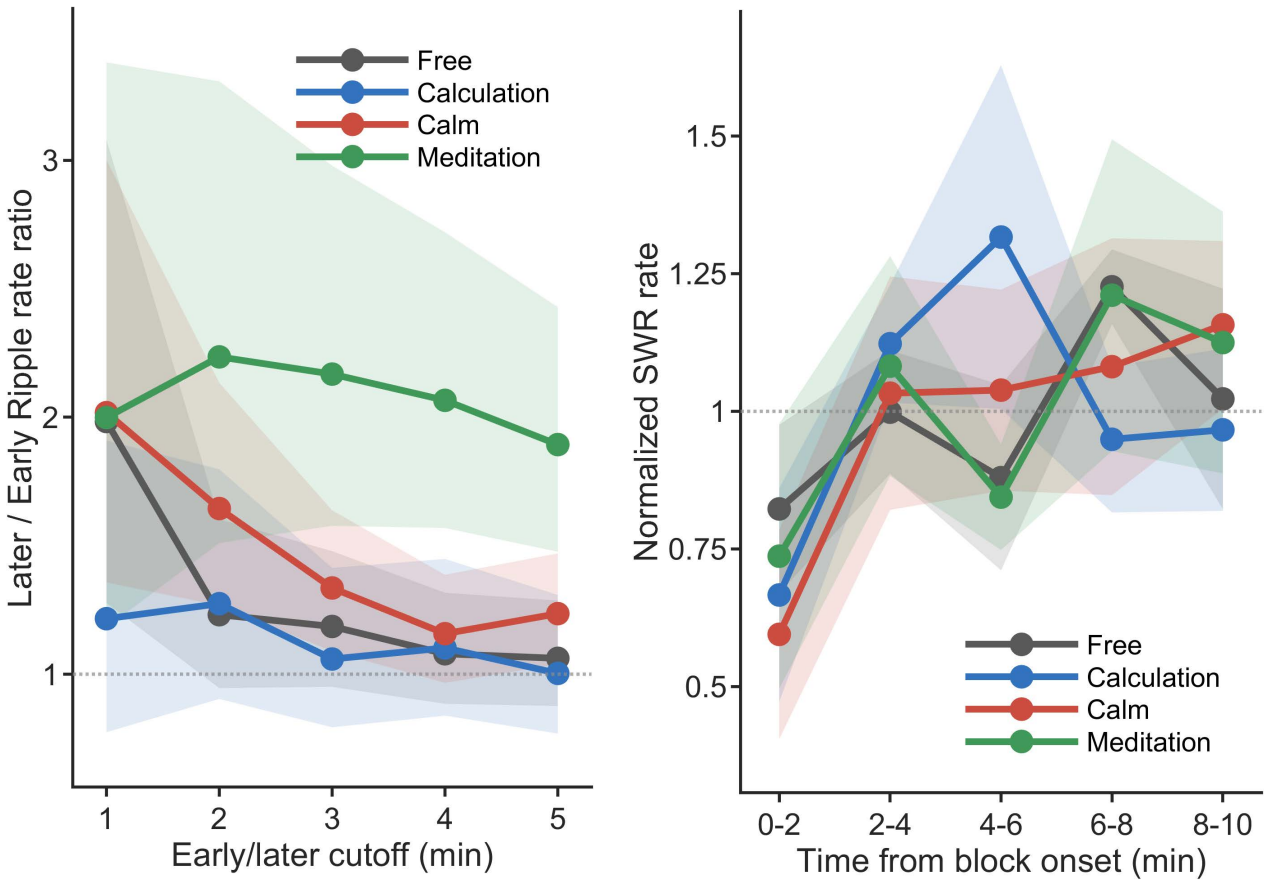
Supplementary figure 5 Comparison of ALL and high-confidence Ripple characteristics. Characteristics of Ripple events detected across all participants and the three primary neurofeedback conditions (Free, Calculation and Calm) are compared between the ALL and high-confidence (HC) event sets. From left to right, box plots show Ripple rate (events min^{-1}), event duration (ms), peak frequency (Hz) and oscillatory cycle count. Distributions are shown separately for ALL and HC Ripples.



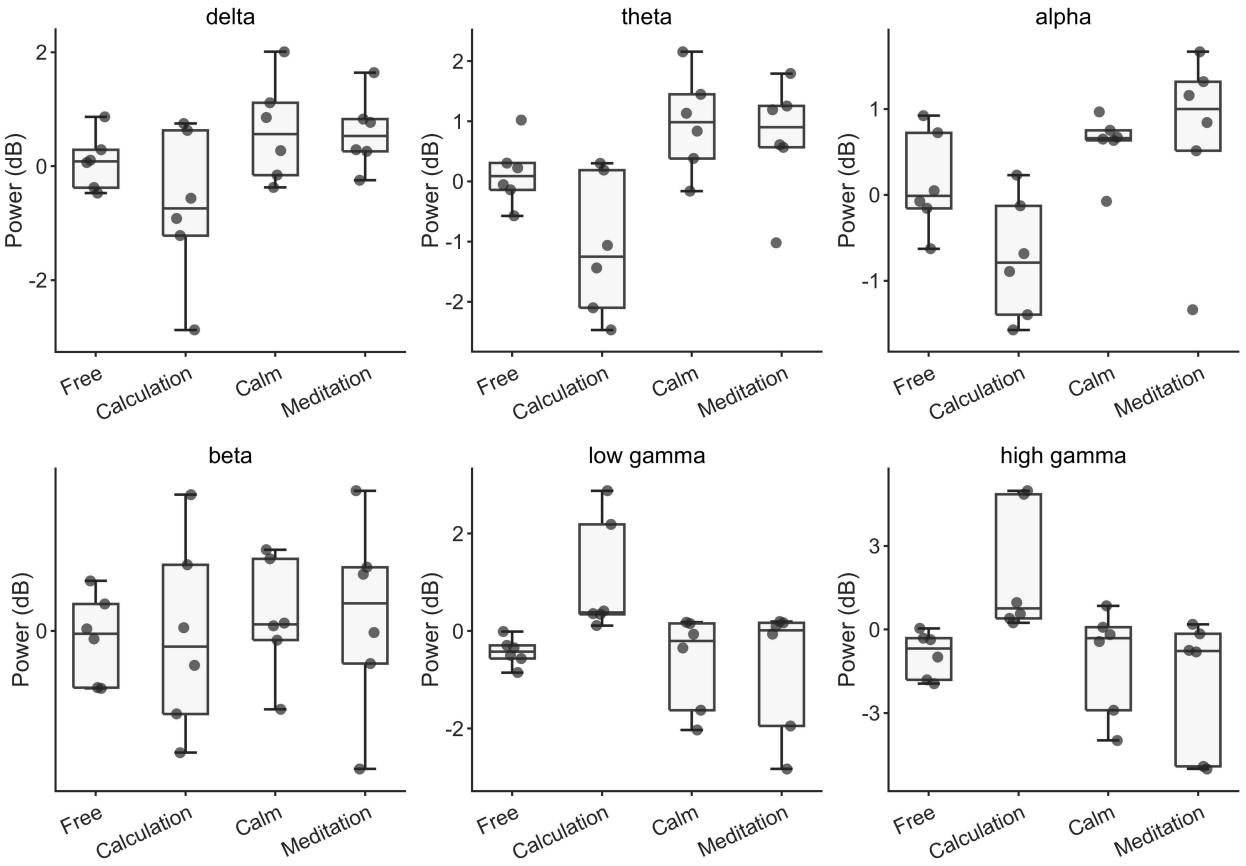
Supplementary figure 6 Physiological validation of Ripple detection using cortical delta states. Valid data from the Free, Calculation and Calm conditions were divided into non-overlapping 2-s windows and pooled within each participant. Windows were ranked according to mean cortical delta-band power and divided into participant-specific quartiles (Q1–Q4), from the lowest to the highest delta activity. Ripple rate within each quartile was calculated as the number of detected Ripple events divided by the total valid observation time in that quartile, thereby accounting for differences in state occupancy. **a**, Ripple rates across delta-power quartiles for all detected Ripples (ALL). **b**, Corresponding analysis for the high-confidence (HC) Ripple subset. Gray lines and symbols indicate individual participants, and black symbols with error bars indicate the group mean ± s.e.m.



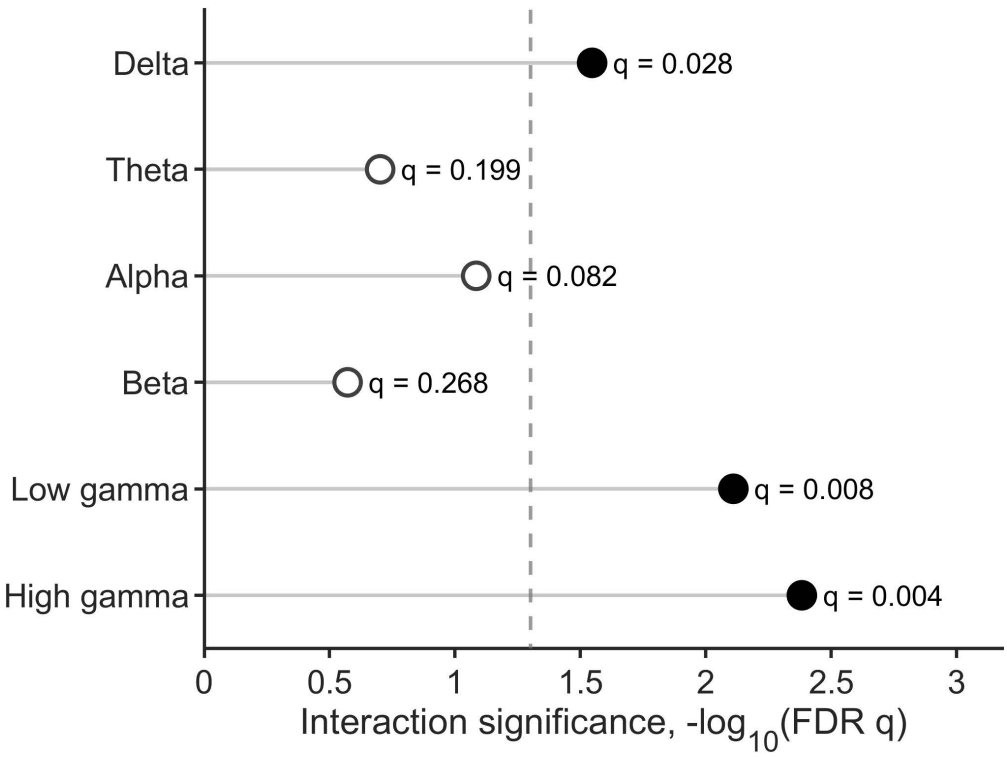
Supplementary figure 7 Condition-dependent Ripple characteristics. Ripple characteristics are shown separately for each neurofeedback condition across participants. From left to right, box plots show Ripple peak frequency (Hz), Ripple duration (ms) and peak amplitude (a.u.).



Supplementary figure 8 Temporal dynamics of Ripple expression during neurofeedback. Left, Later/Early Ripple rate ratios for each cognitive condition calculated using alternative Early/Later cutoff boundaries from 1 to 5 min after block onset. The x-axis indicates the Early/Later cutoff (min). **Right**, Temporal profile of normalized Ripple rate calculated in consecutive 2-min bins for each condition. Lines and error bars indicate the mean ± s.e.m. across participants.The x-axis indicates time from block onset (min).

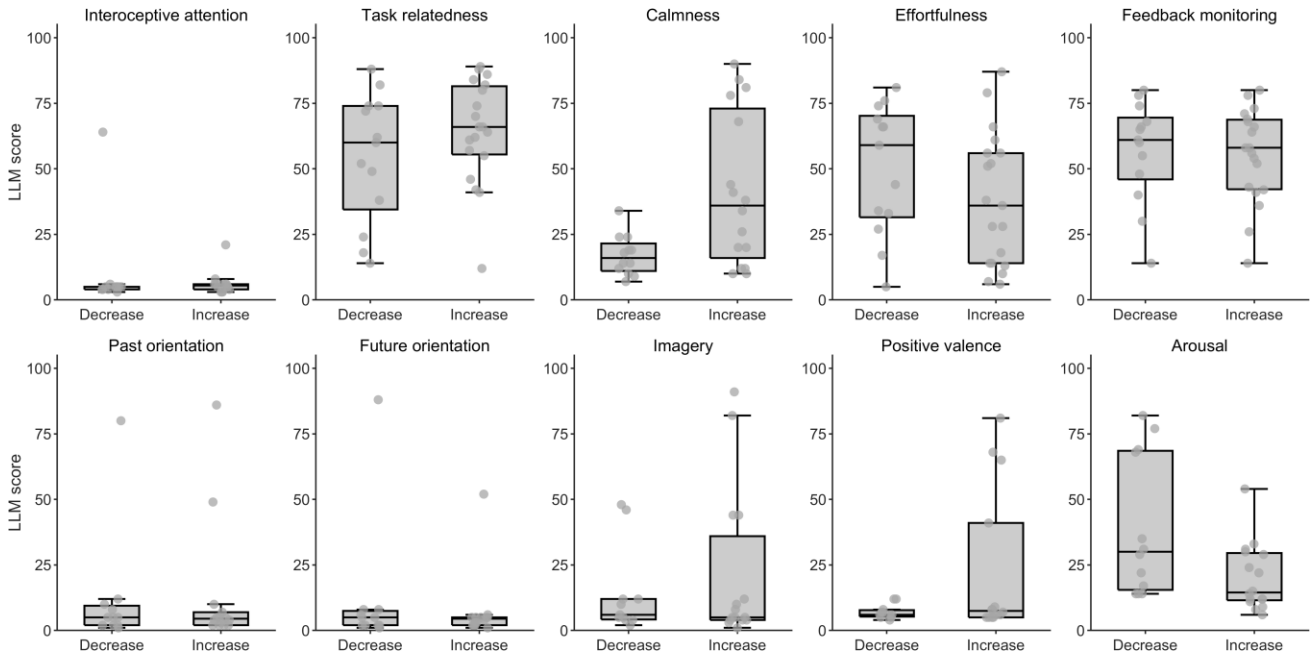


Supplementary figure 9 Condition-dependent cortical spectral power. Cortical spectral power is shown across neurofeedback conditions for six frequency bands: delta, theta, alpha, beta, low gamma and high gamma. The y-axis indicates band power (dB). Individual points represent participant-level values, with box plots summarizing the distribution across participants for each condition.

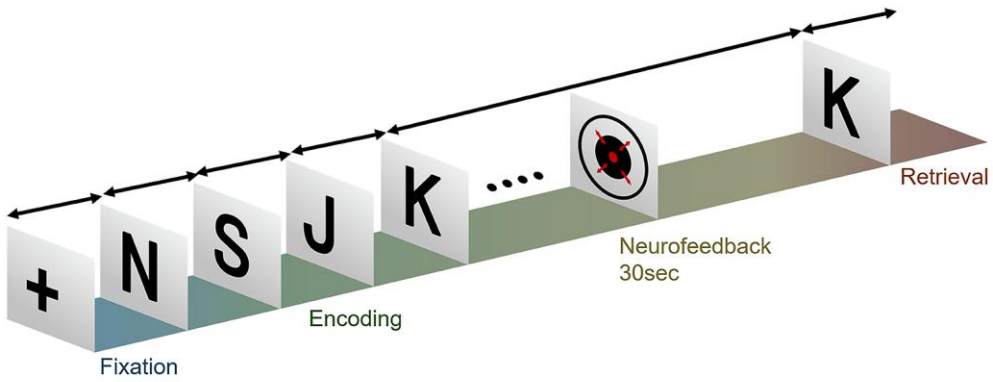


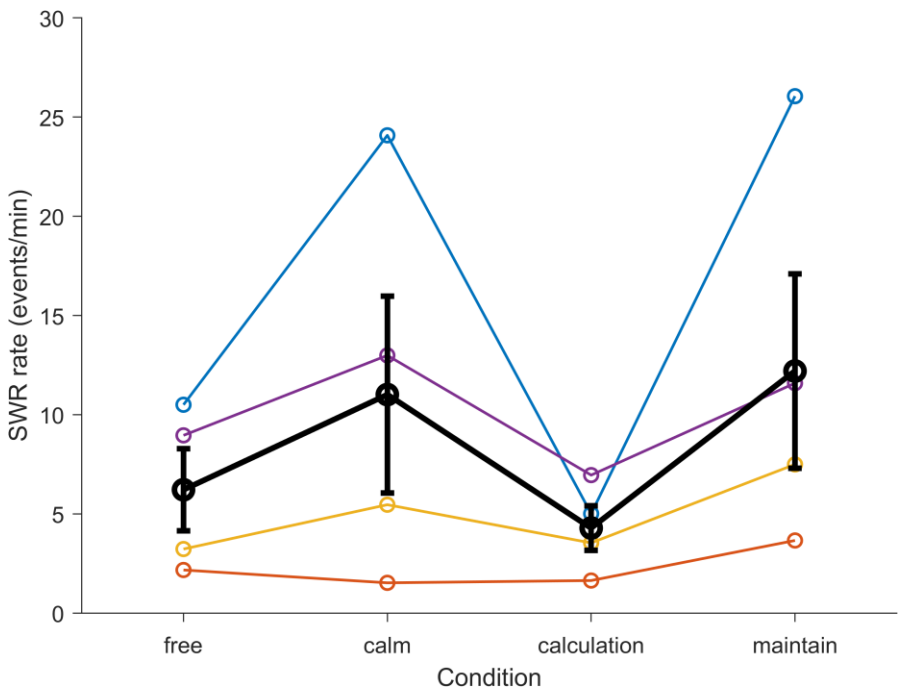
Supplementary figure 10 Condition-dependent modulation of the relationship between cortical spectral power and hippocampal Ripple occurrence.

Interaction significance for each frequency band was assessed by likelihood-ratio comparison between linear mixed-effects models with and without a band-power-by-condition interaction term. P values were corrected across the six frequency bands using the Benjamini–Hochberg false-discovery-rate procedure. The x axis shows −log10(FDR-adjusted q), with the dashed vertical line indicating q = 0.05. Filled circles indicate significant interactions after FDR correction, whereas open circles indicate non-significant interactions. Significant band-power-by-condition interactions were observed for delta, alpha, low-gamma and high-gamma power, but not for theta or beta power.



Supplementary figure 11 LLM-derived cognitive scores for increase- and decrease-associated strategies. Box plots show scores for the ten cognitive dimensions derived from participants' free-text reports using the large-language-model analysis, separately for strategies associated with perceived decreases and increases in the neurofeedback signal.





Supplementary figure12 Real-time Ripple neurofeedback during working-memory maintenance.

In a separate exploratory experiment, four participants performed a working-memory task while receiving real-time Ripple neurofeedback during the 30-s maintenance period. Each participant completed 3 blocks × 20 trials, with task load individually adjusted within the 60–80% range. Online Ripple detection and visual feedback were successfully maintained throughout the maintenance interval, demonstrating the technical feasibility of applying the neurofeedback paradigm during active memory retention. **Lower**, Ripple rates during the working-memory maintenance period are shown for the four participants together with their Ripple rates during the Free, Calculation and Calm neurofeedback conditions. Given the small sample size and exploratory design, these data were not used to draw conclusions regarding behavioral effects of Ripple modulation..

ID	Age	Side of hippocampal electrode implantation	Duration of intracranial monitoring [days]
Sub01	20s	Right	10
Sub02	30s	Right	9
Sub03	20s	Right	11
Sub04	20s	Left	12
Sub05	20s	Right	13
Sub06	20s	Left	11
Sub07	50s	Right	9
Sub08	50s	Left	10
Sub09	20s	Right	13

Supplementary table Participant characteristics and intracranial EEG recording details.

Supplementary method Prompt used for LLM-based evaluation.

You are a research assistant responsible for structuring and evaluating free-text reports obtained after a hippocampal sharp-wave ripple (SWR) neurofeedback experiment.

The free-text reports may contain a mixture of the following types of information:

1. What the participant was generally thinking about during neurofeedback

2. What the participant was thinking about when they felt that the feedback became larger

3. What the participant was thinking about when they felt that the feedback became smaller

Evaluate these components separately.

[A. during_nf]

This category provides an overall assessment of the participant's actual thought content, emotional state, attentional state, and mental strategies during neurofeedback.

In addition to general descriptions of the participant's experience during neurofeedback, any content described as an increase_strategy or decrease_strategy should also be included in during_nf, because these strategies represent mental activities that were actually performed during neurofeedback.

Assume that each free-text report contains at least some description of thought content or mental state. Therefore, during_nf must always be evaluated.

[B. increase_strategy]

Evaluate the thought content, emotional state, attentional state, or mental strategy that the participant reported as being associated with an increase in the feedback signal.

This includes not only definite statements but also uncertain or tentative expressions such as:

* became larger

* increased

* went up

* I felt that it became larger

* I think it became larger

* it may have become larger

* it probably became larger

* it was relatively large

The reported association with an increase does not need to be stated with certainty.

For example:

"I think it became larger when I was not thinking about anything."

This statement should be classified as an increase_strategy.

In this case, the strategy to be evaluated is "not thinking about anything."

Do not incorporate the outcome expression "became larger" itself into the strategy score.

[C. decrease_strategy]

Evaluate the thought content, emotional state, attentional state, or mental strategy that the participant reported as being associated with a decrease in the feedback signal.

This includes not only definite statements but also uncertain or tentative expressions such as:

* became smaller

* decreased

* went down

* I felt that it became smaller

* I think it became smaller

* it may have become smaller

* it probably became smaller

* it was relatively small

The reported association with a decrease does not need to be stated with certainty.

For example:

“I feel that it became smaller when I was doing calculations.”

This statement should be classified as a decrease_strategy.

In this case, the strategy to be evaluated is “doing calculations.”

Do not incorporate the outcome expression “became smaller” itself into the strategy score.

[Important classification principles]

* Do not incorporate the outcome itself, such as “became larger” or “became smaller,” into the strategy scores.

* The content to be evaluated as a strategy is the thought content, emotional state, attentional state, or mental strategy that was associated with an increase or decrease in the feedback signal.

* Even if the report contains uncertain expressions such as “I feel,” “I think,” “may have,” or “probably,” extract the content as a strategy if a subjective association with an increase or decrease is described.

* Do not infer or add content that is not present in the free-text report.

* Do not use information other than the free-text report, such as the experimental condition name or participant ID, in the evaluation.

* Any content extracted as an increase_strategy or decrease_strategy must also be included in during_nf.

* Do not classify the same statement as both increase_strategy and decrease_strategy without supporting evidence.

* If it cannot be determined whether a statement is associated with an increase or a decrease, do not assign it to either strategy category based on speculation.

* If a statement corresponding to an increase_strategy or decrease_strategy is present, set present=true.

* If no corresponding statement is present, always return:

  present=false

  evidence_text=null

scores=null

* If a strategy description is present but a particular evaluated feature is not evident in that strategy, assign a score of 0 for that feature.

* during_nf must always be evaluated, and both evidence_text and scores must be returned.

[Evaluation dimensions]

interoceptive_attention:

The degree to which attention is directed toward breathing, heartbeat, internal bodily sensations, bodily state, or related interoceptive information.

task_relatedness:

The degree of orientation toward an explicit task, including calculation, reading, experimental instructions, task performance, performance outcomes, or the task goal of manipulating the feedback signal.

calmness:

The degree of calmness, relaxation, tranquility, restfulness, or a meditative state.

effortfulness:

The degree of cognitive effort or mental load, including trying hard to think, intentionally exerting control, concentrating excessively, or strongly directing conscious attention.

feedback_monitoring:

The degree to which the participant continuously observed or checked the size of the circle, the visual feedback signal, or changes in the feedback signal.

memory_past_orientation:

The degree to which the content concerns past events, personal experiences, recollections, autobiographical memory, or episodic memory.

future_orientation:

The degree to which the content concerns future plans, future events, predictions, or planning.

imagery:

The degree to which the participant concretely represents or imagines visual scenes, spatial layouts, sounds, movements, or other perceptual content that is not actually being presented.

positive_valence:

The degree of positive emotional valence, including enjoyment, pleasantness, reassurance, satisfaction, or happiness.

Do not automatically interpret mere calmness or low arousal as positive valence.

arousal:

The degree of tension, excitement, impatience, alertness, activation, or emotional elevation.

Distinguish arousal from cognitive effort itself.

[Scoring procedure]

Give the highest priority to content that is explicitly stated in the report.

Even when a feature is not explicitly described, inference is permitted if it can be reasonably inferred from the context, wording, behavior, attentional focus, emotional state, or strategy used.

Do not require strictly explicit statements. Score each dimension continuously within a range that is psychologically and cognitively reasonable.

As a general rule, each score should be an integer from 1 to 100.

For during-NF experience, do not use a score of 0.

Use null only when the report is completely unrelated to the dimension or when the available information is so limited that even a reasonable inference is impossible.

Do not assign null merely because the description is brief or because the relevant feature is not explicitly mentioned.

If a feature is judged to be almost entirely absent, assign a low score of approximately 1-15 rather than null.

A score of 100 should be used when the feature is directly and clearly described and constitutes a dominant, central characteristic of the category.

Scores from 1 to 99 should be determined according to the clarity, strength, specificity, repetition, and relative importance of the supporting content within the overall description.

Do not preferentially use representative values such as 25, 50, or 75.

Do not round scores to increments of 5, 10, or 25.

When appropriate, use any integer value that reflects the content, such as 17, 38, 62, or 84.

Reflect differences between reports numerically, and do not mechanically assign identical scores to descriptions that differ in strength.

[evidence_text]

For each category, extract the original text that served as the basis for the evaluation exactly as written, without modification, summarization, or paraphrasing.

If multiple separate passages provide supporting evidence, return them as separate elements in an array.

For during_nf, extract all relevant statements judged to describe what the participant was doing or experiencing during neurofeedback.

If there is no statement corresponding to increase_strategy or decrease_strategy, set evidence_text to null.

Output only the specified JSON structure.

Do not output any explanatory text outside the JSON.