

Investigating Neuronal Network Dynamics Supporting Memory in the Human Brain



Thesis

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Abstract

Abstract to write here

Contents

List of Abbreviations	8
1 Introduction	10
1.I Theta oscillations in mammals	10
1.II What about theta oscillations in humans?	10
1.III Hypotheses and aims of this work	10
2 Assessing associative memory in human participants	11
2.I Conceptual introduction	11
2.I.1 Inference as an extension of associative memory	11
2.I.1.a Definition of associative memory and inference	11
2.I.1.b Conservation across species	11
2.I.1.c Two-stages model: short-term and long-term memory .	11
2.I.1.d Rodent paradigms	11
2.I.1.e Human paradigms	11
2.I.2 The role of the hippocampal network in associative memory . . .	11
2.I.2.a Animal studies	11
2.I.2.b Human lesion studies	11
2.I.2.c Indirect recordings of brain electrical activity in humans (fMRI, MEG)	11
2.I.2.d Direct recordings of brain electrical activity in humans .	11
2.II Investigating associative memory in humans using a social community task	12
2.II.1 Rationale and behavioural paradigm	12
2.II.2 Variants and controls	12
2.II.2.a Simple and complex tasks	12

2.II.2.b	Scientific rationale for population diversity	12
2.II.2.c	Stimulus types and controls	12
2.II.2.d	Additional visual controls	12
2.III	Quantifying behavioural performance	12
2.III.1	Participant demographics	12
2.III.2	Performance metrics	12
2.III.2.a	Group-level performance	12
2.III.2.b	Inter-individual variability and performance profiles . . .	12
2.III.2.c	Across-group comparisons	12
2.III.3	Possible confounds and their resolution	12
2.III.3.a	Demographic and cognitive contributors	12
2.III.3.b	Standardised cognitive testing	12
2.IV	Summary: why this behavioural context justifies a neural two-stage memory investigation	12
3	Neural activity in the online human hippocampus is paced by a 2-Hz rhythm	13
3.I	Conceptual introduction	13
3.I.1	Why search for a human analogue of rodent theta?	13
3.I.2	Hypothesis	13
3.I.3	Analytical overview	13
3.II	Hippocampal 2-Hz tracks mnemonic engagement	13
3.II.1	Prominent 2-Hz bursts structure hippocampal LFPs	13
3.II.1.a	Recording hippocampal LFPs with depth EEG in humans	13
3.II.1.b	Hippocampal LFPs are paced by a 2-Hz oscillation . . .	15
3.II.1.c	Hippocampal 2-Hz oscillations are transient	18
3.II.1.d	Validation of 2-Hz oscillations	18
3.II.2	Hippocampal 2-Hz is selectively evoked in the memory task . . .	18
3.II.2.a	Hippocampal 2-Hz power increase with task engagement	18
3.II.2.b	Hippocampal 2-Hz bursts are evoked by mnemonic cues	18
3.II.2.c	Hippocampal 2-Hz oscillations are not evoked by motor activity	18

3.III Hippocampal neuronal activity is preferentially modulated at 2-Hz	19
3.III.1 Hippocampal neurons are paced at 2-Hz	19
3.III.1.a Basic firing properties of hippocampal neurons reveal 2-Hz rhythmicity	19
3.III.1.b Hippocampal neurons prefer 2-Hz oscillations	19
3.III.2 Hippocampal gamma oscillations are preferentially modulated at 2-Hz	19
3.III.2.a Gamma activity correlates with spiking activity	19
3.III.2.b Hippocampal gamma activity is preferentially coupled to 2-Hz phase	19
3.III.2.c Holo-Hilbert amplitude modulation analysis confirms prevailing 2-Hz hippocampal modulation of gamma activity	19
3.IV Hippocampal 2-Hz synchronizes neuronal activity across MTL regions	20
3.IV.1 2-Hz oscillations are preferentially observed in the MTL	20
3.IV.1.a 2-Hz power dominates in the MTL and particularly in the hippocampus	20
3.IV.1.b Prominent 6-8Hz oscillations in the non-MTL were detected using tmEMD	20
3.IV.1.c 2-Hz oscillations are not directly evoked by mnemonic cues outside the hippocampus	20
3.IV.2 MTL neurons are paced at 2-Hz	20
3.IV.2.a Basic firing properties of MTL neurons reveal 2-Hz rhythmicity	20
3.IV.2.b MTL neurons prefer 2-Hz oscillations in the hippocampus	20
3.IV.3 Hippocampal 2-Hz synchronizes MTL gamma oscillations	21
4 Neural activity in the offline human hippocampus	22
4.I Conceptual introduction	22
4.I.1 The two-stage model of memory	22
4.I.2 Hypothesis	22
4.I.3 Analytical overview	22
4.II Hippocampal physiology across sleep stages	22
4.II.1 Hippocampal 2-Hz features REM sleep but not SWS	22
4.II.2 Hippocampal ripples feature SWS and rest sessions	22

4.II.2.a	Detection of hippocampal ripples	22
4.II.2.b	Basic properties of the ripples	22
4.II.2.c	Ripples properties across sleep stages	23
4.II.2.d	Hippocampal neurons are modulated by ripples	23
4.II.2.e	Ripples propagate to the MTL	23
4.III	Neuronal coactivity motifs in 2-Hz bursts reactivate in post-learning hippocampal ripples	23
4.III.1	Measuring reactivation using neuronal coactivity motifs	23
4.III.1.a	2-Hz bursts coactivity motifs reactivate in post-learning ripples	23
4.III.1.b	Reactivation is relevant for behavioural performance	23
4.III.2	Measuring reactivation using gamma coactivity motifs	23
4.III.2.a	Gamma coactivity motifs are physiologically meaningful	23
4.III.2.b	Gamma coactivity motifs are rigid	23
5	Discussion	24
A	Appendix: Neurophysiological recordings and analysis of oscillations	25
A.I	Data acquisition and preprocessing	25
A.I.1	Participants	25
A.I.2	Electrode models	25
A.I.3	Co-registration and anatomical verification	25
A.I.4	Neurophysiological recordings	25
A.I.5	Detection of IEDs	25
A.II	Decomposing LFPs into oscillatory components	25
A.II.1	Rationale for IMF-based decomposition	25
A.II.2	Mask optimization and criteria	25
A.II.3	Cycle detection and quality control	25
A.II.4	Detection of oscillatory bursts	25
A.III	Other spectral decompositions	25
A.III.1	PSDs estimation (Welch)	25
A.III.2	Aperiodic correction using spectral parameterization	25

A.III.3	Morlet wavelet spectrogram parameters	25
A.III.4	Stimulus-locked spectral amplitude estimation	25
A.III.5	Detection of gamma activity	26
A.IV	Cross-frequency analyses	26
A.IV.1	PAC and phase randomization	26
A.IV.2	HHSAs	26
B Appendix: Analysis of single-neuron activity		27
B.I	Spike sorting and single-unit validation	27
B.I.1	Automated pipeline	27
B.I.2	Manual curation quality criteria	27
B.I.3	Waveform classification	27
B.II	Spike-field relationship	27
B.II.1	PPC and phase randomization	27
B.II.2	Spike-gamma relationship	27
C Appendix: Hippocampal ripples and reactivation		28
C.I	Ripple detection and validation	28
C.I.1	Initial ripple detection	28
C.I.2	Template matching	28
C.I.3	Final detection and quality controls	28
C.I.4	Ripple-triggered averages	28
C.I.5	Characterization of ripple central frequency	28
C.II	Detection of cross-regional coactivity motifs	28
C.II.1	Epochs selection	28
C.II.2	Using single-neurons	28
C.II.3	Using gamma activity	28
C.III	Reactivation of coactivity motifs in hippocampal ripples	28
C.III.1	GLMs	28
C.III.2	Controls	28
D Appendix: Statistical analyses		29

D.I	Bootstrap and permutation tests	29
D.II	GLMs and LMEMs	29
D.III	Cluster-based permutation	29

List of Abbreviations

CI confidence interval

depth EEG depth electroencephalography

ECoG electrocorticography

EMD empirical mode decomposition

fMRI functional magnetic resonance imaging

GLM generalized linear model

HHSA Holo-Hilbert Spectral Analysis

IED interictal epileptiform discharge

IMF intrinsic mode function

ISOMAP isometric mapping

LFP local field potential

LMEM linear mixed-effects model

MEG magnetoencephalography

mEMD masked EMD

MTL medial temporal lobe

PAC phase-amplitude coupling

PPC pairwise-phase consistency

PSD power spectral density

REM rapid eye movement

SWR sharp-wave ripple

SWS slow-wave sleep

tmEMD tailored-masked EMD

UMAP uniform manifold approximation and projection

1 Introduction

1.I Theta oscillations in mammals

1.II What about theta oscillations in humans?

Direct recording of hippocampal activity using depth electroencephalography (depth EEG). History. Methodological considerations and differences between electrode types. There is a gap in knowledge.

1.III Hypotheses and aims of this work

2 Assessing associative memory in human participants

2.I Conceptual introduction

Why behaviour matters for interpreting hippocampal physiology?

2.I.1 Inference as an extension of associative memory

2.I.1.a Definition of associative memory and inference

2.I.1.b Conservation across species

2.I.1.c Two-stages model: short-term and long-term memory

2.I.1.d Rodent paradigms

2.I.1.e Human paradigms

2.I.2 The role of the hippocampal network in associative memory

Keep in mind the framework of the thesis which differentiates short-term and long-term memory. And HPC vs MTL for human studies.

2.I.2.a Animal studies

2.I.2.b Human lesion studies

2.I.2.c Indirect recordings of brain electrical activity in humans (fMRI, MEG)

2.I.2.d Direct recordings of brain electrical activity in humans

2.II Investigating associative memory in humans using a social community task

2.II.1 Rationale and behavioural paradigm

2.II.2 Variants and controls

2.II.2.a Simple and complex tasks

2.II.2.b Scientific rationale for population diversity

2.II.2.c Stimulus types and controls

2.II.2.d Additional visual controls

2.III Quantifying behavioural performance

2.III.1 Participant demographics

2.III.2 Performance metrics

2.III.2.a Group-level performance

2.III.2.b Inter-individual variability and performance profiles

2.III.2.c Across-group comparisons

2.III.3 Possible confounds and their resolution

2.III.3.a Demographic and cognitive contributors

2.III.3.b Standardised cognitive testing

2.IV Summary: why this behavioural context justifies a neural two-stage memory investigation

Transition to Chapter 3: behaviour => neural recordings

3 Neural activity in the online human hippocampus is paced by a 2-Hz rhythm

3.I Conceptual introduction

3.I.1 Why search for a human analogue of rodent theta?

Rodent theta: pacing learning, spatial navigation, and ensemble formation. Human low-frequency variability and the open question

3.I.2 Hypothesis

Human memory is organized by a slower “theta-like” rhythm. This rhythm should appear in active states, structure spikes and gamma, synchronize MTL regions, be modulated by mnemonic engagement.

3.I.3 Analytical overview

Oscillation decomposition (concept). Burst detection (concept). Spike-phase and gamma-phase coupling local and distal (concept). ERP-locked analyses. Point to appendices for methodological details

3.II Hippocampal 2-Hz tracks mnemonic engagement

3.II.1 Prominent 2-Hz bursts structure hippocampal LFPs

3.II.1.a Recording hippocampal LFPs with depth EEG in humans

To characterize hippocampal network activity in humans, we recorded local field potentials (LFPs) directly from the hippocampus using depth EEG. Thirty-five participants

undergoing clinical monitoring for pharmacoresistant epilepsy in two centers (Toulouse and Paris) were included in this study. Electrode implantation followed clinical requirements only. Because the hippocampus is commonly involved in seizure networks (REF), electrodes were often implanted in the hippocampus (Fig. 3.1A). In this manuscript, we focussed on participants with at least one electrode implanted in the hippocampus. Participants were implanted with standard and hybrid depth electrodes (DIXI Medical in Toulouse or Behnke–Fried in Paris). Hybrid electrodes incorporated both macrocontacts and microelectrodes (tetrodes or microwires). For consistency across the two centers, macrocontacts were used to obtain LFPs and common average referencing was applied. Tetrodes were used to identify single-neuron activity next to the macrocontact (Fig. 3.1B) and are used from chapter 3.III.1 of this manuscript. Anatomical localization of each macrocontact was obtained by co-registering postoperative CT with preoperative MRI and mapping contacts to individual hippocampal volumes (Fig. 3.1C,D). For additional methodological details see Appendix A.I.

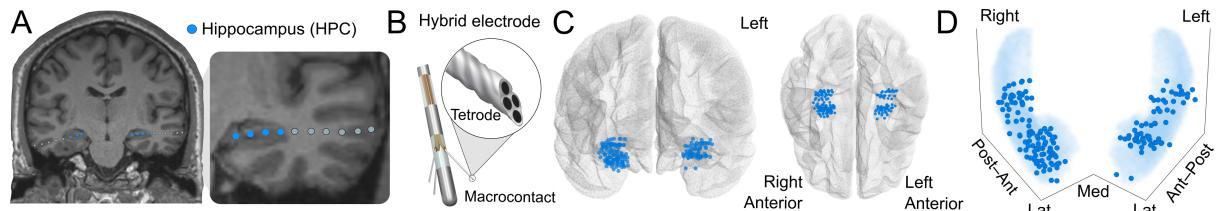


Figure 3.1: Direct electrophysiological recordings from the human hippocampus **(A)** T1-weighted MRI showing contact locations from two representative depth electrodes targeting the hippocampus. **(B)** Each hybrid electrode incorporated tetrodes extending from the macrocontact shaft. **(C and D)** MNI template brain and 3D projection showing hippocampal electrode contact locations across participants (axes: Post–Ant, posterior–anterior; Med–Lat, medio–lateral; Sup–Inf, superior–inferior).

We further verified the location of hippocampal contacts along the antero–posterior and medio–lateral axes of each participant’s hippocampus using their native three-dimensional segmentation (Fig. 3.2A,B). Coverage was denser in the head of the hippocampus than in the body, and virtually no contacts were located in the tail (Fig. 3.2C,D).

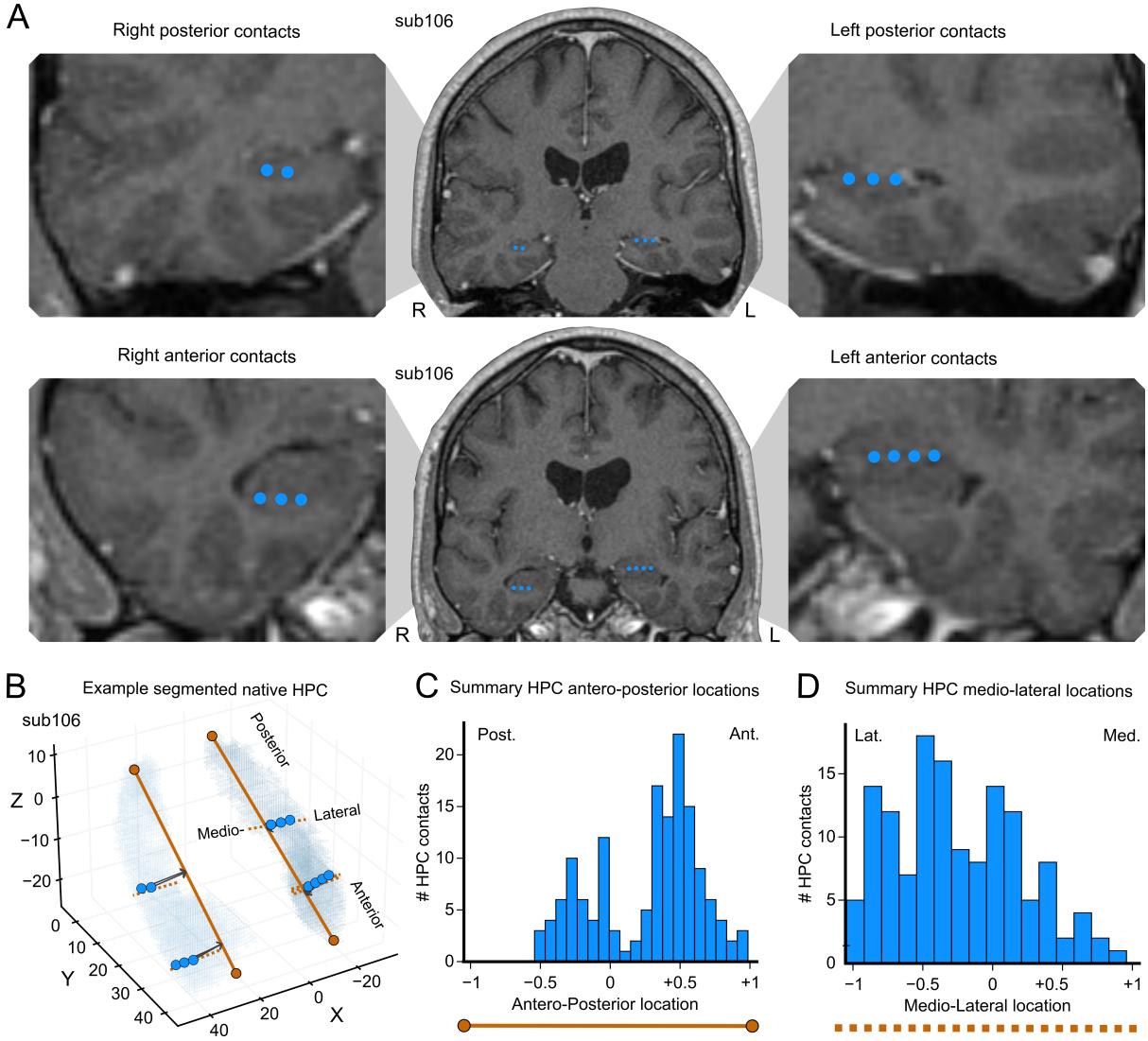


Figure 3.2: Anatomical localization and distribution of hippocampal electrode contacts (A) T1-weighted MRI showing posterior (top) and anterior (bottom) hippocampal electrode contacts. Insets display higher magnifications of the right and left hemispheres. (B) 3D hippocampal volumes segmented from the same subject's MRI with contact locations (blue dots) overlaid. Solid and dotted brown lines mark the detected antero-posterior and medio-lateral axes, respectively. (C and D) Distribution of hippocampal contacts along the antero-posterior (C) and medio-lateral (D) axes across all participants. Of 170 contacts, 105 were located in the right hemisphere.

3.II.1.b Hippocampal LFPs are paced by a 2-Hz oscillation

Analyzing brain oscillations often involves assuming that a given biological signal lies within a strict frequency range. This approach is efficient when this biological phenomenon is well established such as theta oscillations in mice (REF), but it constrains the analysis to prior knowledge. An alternative is to use unsupervised signal decomposition methods such as empirical mode decomposition (EMD). EMD decomposes LFPs into their constituent oscillatory components (referred to as intrinsic mode functions (IMFs)) without assuming fixed frequency bands (REF). However, several factors can

influence the spectral structure of LFPs across macrocontacts and subjects. As a result, the extracted IMFs may overlap in frequency (mode mixing) or may not be detected in a consistent manner across macrocontacts or participants (low consistency) (REF). These issues make it challenging to ensure that IMFs are reliably identified across subjects. To address these limitations, we used a recently introduced version of masked EMD, referred to as tmEMD (REF). This approach introduces controlled masking signals during decomposition to reduce mode mixing and to improve the separation of oscillatory components. In addition, mask parameters are optimized across subjects, which increases the consistency of the detected components at the group level. tmEMD therefore provides a more stable and interpretable decomposition of hippocampal LFPs than standard EMD, particularly in datasets with substantial inter-individual variability. Full methodological details are provided in Appendix A.I.

In participants who were awake and watching screen displays, we detected one oscillation in the human hippocampus with a peak frequency around 6 Hz (peak [80% power band (PB): 6.15 [3.75 – 8.50] Hz]. In addition, we identified two slower rhythms centered near 2 Hz [peak (80% PB): 2.38 (1.25 – 3.50) Hz] and 1 Hz [peak (80% PB): 1.08 (0.65 – 1.50) Hz] (Fig. 3.3).

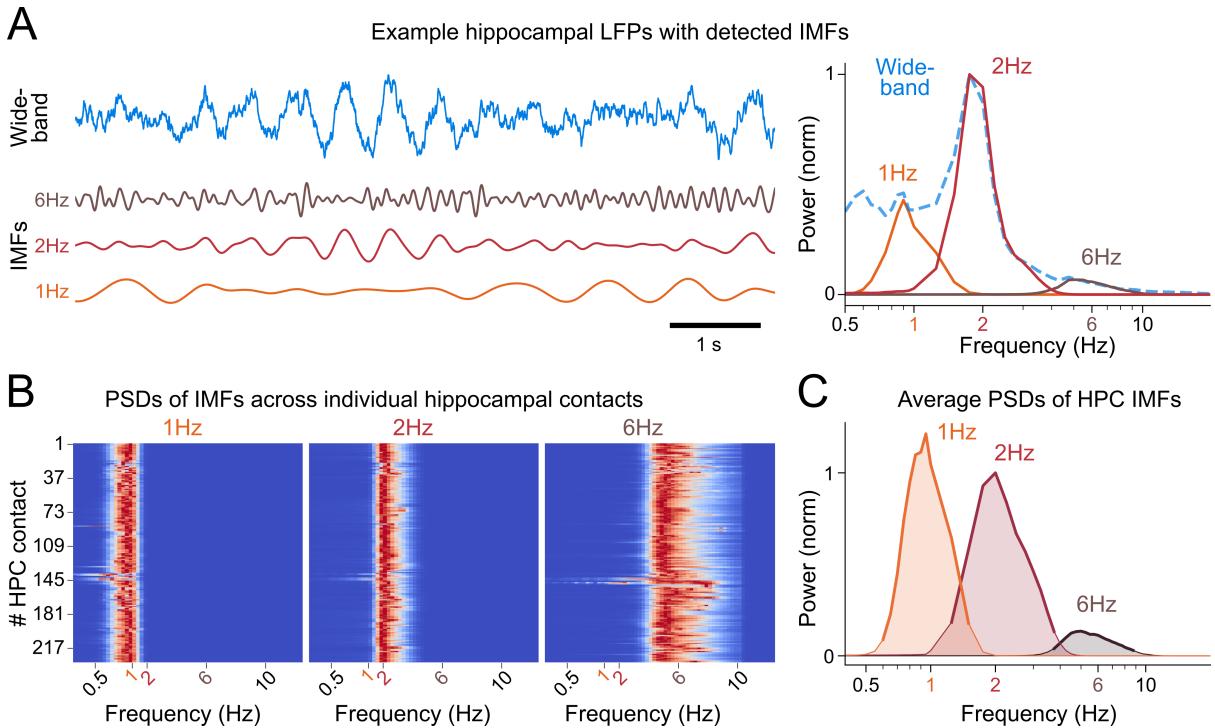


Figure 3.3: Tailored Masked Empirical Mode Decomposition in the human hippocampus **(A)** Left: Example hippocampal wide-band LFPs traces with IMFs. Right: Power spectral density (PSD) of the wide-band signal (dashed line) obtained from macrocontact recording and the corresponding 1-, 2-, and 6-Hz IMFs. **(B)** Heatmaps showing power distributions of 1-, 2-, and 6-Hz IMFs across all hippocampal contacts, illustrating that IMFs were consistently detected across participants. **(C)** Average power spectral densities across hippocampal contacts, normalized to the maximal 2-Hz power, showing that IMFs exhibited low mode mixing (thick lines indicate 80% power bands).

Though we were able to detect 6-Hz oscillations in the human hippocampus, the most prominent oscillation visible in the raw LFPs traces were at 2 Hz (Fig. 3.3A). These 2-Hz

oscillations were visible on both macrocontacts and tetrodes (Fig. 3.4).

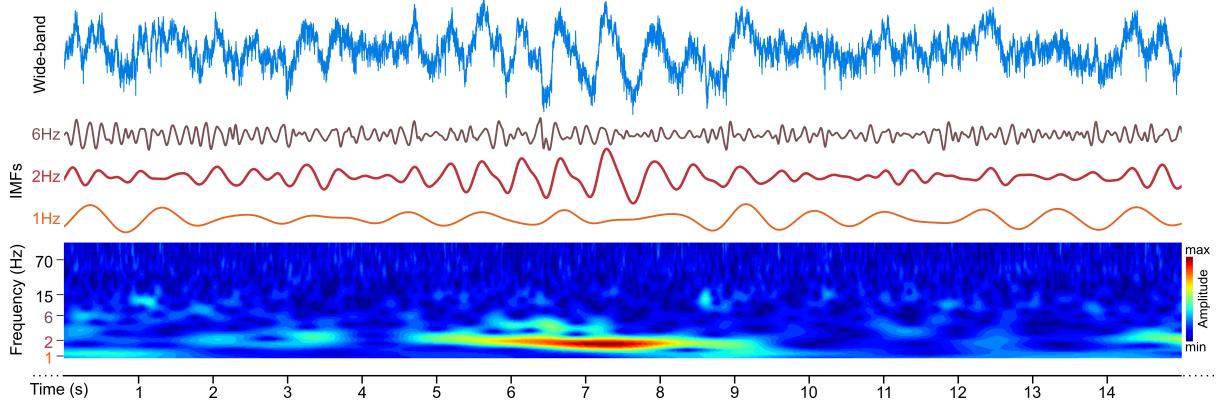


Figure 3.4: **Example hippocampal LFPs showing a 2-Hz burst** Example 15-s hippocampal tetrode recording showing a prominent 2-Hz burst. From top to bottom: wide-band LFPs trace obtained from tetrode recording, IMFs, and the corresponding wavelet spectrogram.

We confirmed this observation by applying spectral parameterization (REF; see Appendix A.III), which separates the periodic components of the power spectral density (PSDs) from the broadband, aperiodic structure of the spectrum. This procedure allowed us to quantify narrow-band oscillatory peaks independently of differences in overall spectral slope across contacts or participants. After removing the aperiodic component, the periodic residuals showed a clear prominence of the 2-Hz component in the hippocampus (Fig. 3.5A). Specifically, the corrected spectra yielded higher power at 2 Hz than at 1 Hz or 6 Hz (Fig. 3.5B), and the computed 2-Hz/6-Hz peak power ratio was consistently positive across hippocampal contacts (mean ratio [95% confidence interval (CI)]: 0.21 [0.15 – 0.27]; Fig. 3.5C). This analysis suggests that hippocampal activity is dominated by a 2-Hz rhythm.

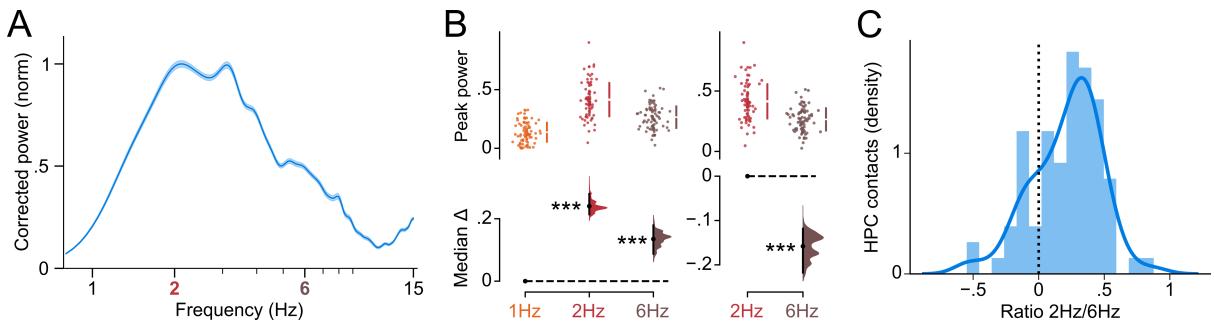


Figure 3.5: **2-Hz oscillations dominate in the hippocampus** (A) PSDs corrected for the power law and averaged across hippocampal macrocontacts free of interictal epileptiform discharges (IEDs). Shaded areas indicate mean \pm SEM. (B) Estimation plots showing median differences between corrected 1-, 2-, and 6-Hz peak power (left), and between 2-Hz and 6-Hz peak power (right). (C) Distribution showing positive 2-Hz/6-Hz peak power ratios in hippocampal contacts.

3.II.1.c Hippocampal 2-Hz oscillations are transient

Detection of IMF cycles. Detection of discrete oscillatory bursts. Show multiple examples of 2-Hz bursts across contacts and subjects, particularly in contacts clear from IEDs. Quantification of bursts duration.

3.II.1.d Validation of 2-Hz oscillations

3.II.1.d.i Local referencing reduces detection of slow oscillations

Local referencing on micro and bipolar referencing on macro => This is why we will be using CAR throughout the manuscript

3.II.1.d.ii Slow-oscillation amplitude and IEDs rate

Detection of IEDs (methods). IEDs are transient, non-oscillatory events. IEDs rate increases at rest. 1- and 2-Hz oscillations are more prominent in contacts clear from IEDs.

3.II.1.d.iii Phase reversal of hippocampal 2-Hz oscillations

Echo to the introduction where we will have presented how the dipole is structured between layers, in humans and rodents. Show maybe one laminar recording from rodents. Then show phase reversal with cycle-triggered average of LFPs.

3.II.2 Hippocampal 2-Hz is selectively evoked in the memory task

3.II.2.a Hippocampal 2-Hz power increase with task engagement

Methods: one-over-f fitting. Results: Example contact; estimation plots with various controls; LMEMs. This is all using contacts free of interictal discharges (reader will understand why because we explained in the previous subsection). Burst duration is also higher in learning and recalling.

3.II.2.b Hippocampal 2-Hz bursts are evoked by mnemonic cues

3.II.2.b.i ERPs are modulated by mnemonic engagement

ERPs change throughout the task in the hippocampus.

3.II.2.b.ii Evoked oscillations follow ERPs deflection

Evoked 1-, 2- and 6-Hz amplitudes relate to mnemonic engagement. Correlation between evoked ERPs deflection and 2-Hz amplitude.

3.II.2.c Hippocampal 2-Hz oscillations are not evoked by motor activity

Methods: Stepping sessions. Results: three example contacts (PSDs) with clear 2-Hz in learning but not during stepping. Statistics on these three subjects.

Note to myself: I could as well add a small control here, using viewing and post-viewing sessions when the participants hit the space bar (second image). Paired analysis by

comparing the evoked amplitude after the first (no motor activity) and the second (motor activity) image seen in a row. It may be confounded by the short term memory effect but we don't expect this to elicit a massive 2-Hz.

3.III Hippocampal neuronal activity is preferentially modulated at 2-Hz

3.III.1 Hippocampal neurons are paced at 2-Hz

3.III.1.a Basic firing properties of hippocampal neurons reveal 2-Hz rhythmicity

Methods: spike sorting and quality control. Results : firing rate distributions show that slow firing neurons constituted the biggest part of our dataset. Waveform classification: mainly broad spikes. So this looks more like pyramidal neurons. Autocorrelograms at 2-Hz. Inter-spike intervals at 500 ms.

3.III.1.b Hippocampal neurons prefer 2-Hz oscillations

Methods: PPC and phase randomization. Results: cycle-triggered average of population rate to illustrate co-modulation at 2-Hz. Example spike-phase distribution reveals preference at 2-Hz. Quantification of spike-phase coupling using PPC.

3.III.2 Hippocampal gamma oscillations are preferentially modulated at 2-Hz

3.III.2.a Gamma activity correlates with spiking activity

Methods: Detection of gamma activity (60-160 Hz). Results: Illustration of the correlation (CAR and bipolar referencing). Correlation with local VS distal gamma.

3.III.2.b Hippocampal gamma activity is preferentially coupled to 2-Hz phase

Methods: PAC with the modulation index and phase randomization. Results: cycle-triggered average of gamma activity to illustrate co-modulation at 2-Hz (with spikes). Example gamma-phase distribution reveals preference at 2-Hz. Quantification of phase-amplitude coupling using PAC. Control with leave one recording day out shows that the effect is not driven by one recording day. Gamma from the anterior and posterior hippocampi prefer 2-Hz (no gradient).

3.III.2.c Holo-Hilbert amplitude modulation analysis confirms prevailing 2-Hz hippocampal modulation of gamma activity

Methods: HHSA with illustration. Results: 2-Hz modulation prevails in the human hippocampus. 7-Hz oscillations dominated the mouse hippocampus.

3.IV Hippocampal 2-Hz synchronizes neuronal activity across MTL regions

3.IV.1 2-Hz oscillations are preferentially observed in the MTL

3.IV.1.a 2-Hz power dominates in the MTL and particularly in the hippocampus

Cycle-triggered average of LFPs show that 2-Hz oscillations propagate in the MTL. PSDs across the MTL and non-MTL contacts free of IEDs. 2-Hz vs 6-Hz power ratio.

3.IV.1.b Prominent 6-8Hz oscillations in the non-MTL were detected using tmEMD

IMF PSDs in the MTL and non-MTL with example of detected 6-8-Hz bursts in the non-MTL.

3.IV.1.c 2-Hz oscillations are not directly evoked by mnemonic cues outside the hippocampus

3.IV.1.c.i ERPs deflections in MTL and non-MTL regions

ERPs become bigger with familiarity only in the hippocampus.

3.IV.1.c.ii ERPs deflection does not correlate with evoked 2-Hz bursts outside the hippocampus

Measure evoked 1-, 2- and 6-Hz in other MTL and non-MTL regions. The measure of ERP deflections is adjusted to each region to match visual input. Correlation between ERP deflection and evoked 1-, 2- 6-Hz oscillations.

3.IV.2 MTL neurons are paced at 2-Hz

3.IV.2.a Basic firing properties of MTL neurons reveal 2-Hz rhythmicity

Results : Autocorrelograms at 2-Hz. Inter-spike intervals at 500 ms in the MTL. Example neuron in the non-MTL to show we can easily find 6-Hz rhythmicity in the non-MTL.

3.IV.2.b MTL neurons prefer 2-Hz oscillations in the hippocampus

Results: cycle-triggered average of population rate in the EC and HPC to illustrate co-modulation at 2-Hz in these two example structures. Example spike-phase distribution reveals preference at 2-Hz of EC neurons. Quantification of spike-phase coupling using PPC in the MTL. LMEMs showing that MTL gamma is better modulated at 2-Hz than non-MTL gamma.

3.IV.3 Hippocampal 2-Hz synchronizes MTL gamma oscillations

Methods: distal PAC. Results: cycle-triggered average of gamma activity in the MTL. Illustration of phase-amplitude coupling across the MTL. medial temporal lobe (MTL) gamma activity is preferentially coupled to hippocampal 2-Hz phase = quantification of MTL preference for 2-Hz oscillations. Phase synchronization is higher during learning and recalling than viewing sessions.

Transition to Chapter 4: online => offline

4 Neural activity in the offline human hippocampus

4.I Conceptual introduction

4.I.1 The two-stage model of memory

Online (theta) → assembly formation. Offline (ripples) → assembly reactivation.

4.I.2 Hypothesis

Human 2-Hz bursts form the online structure for memory-relevant coactivity patterns. Offline ripples should preferentially reinstate 2-Hz-structured motifs

4.I.3 Analytical overview

Ripple detection and validation, coactivity motif construction. Reactivation analysis

4.II Hippocampal physiology across sleep stages

4.II.1 Hippocampal 2-Hz features REM sleep but not SWS

Methods: describe polysomnography. Example of 2-Hz bursts in REM. 2-Hz power across sleep stages. Maybe: propagation of 2-Hz oscillations in the rest of the MTL (hypothesis of the ponto-geniculocalis oscillations PGO)?

4.II.2 Hippocampal ripples feature SWS and rest sessions

4.II.2.a Detection of hippocampal ripples

Methods: two-step algorithm used to detect ripples. Show the templates, and the quality control used to identify reliable ripples without manual intervention.

4.II.2.b Basic properties of the ripples

Show raw examples as well as ripple-triggered averages of LFPs and spectrograms. Distribution of ripple frequency centers around 70 Hz. Ripples ride on a sharp-wave. Ripples can be detected on the local tetrodes as well.

4.II.2.c Ripples properties across sleep stages

Ripple rate is higher in SWS and N1 than wake and REM. Ripples detected in rest are comparable to N1. Ripples basic properties are stable between pre- and post-learning rests.

4.II.2.d Hippocampal neurons are modulated by ripples

Trigger average (and quantification!) of the modulation of hippocampal single neurons around sharp wave ripples. Single examples and summary heatmap.

4.II.2.e Ripples propagate to the MTL

Ripple-triggered averages of the LFPs and ripple band in other regions (MTL and non-MTL). The propagation is more consistent in the MTL than the non-MTL.

4.III Neuronal coactivity motifs in 2-Hz bursts reactivate in post-learning hippocampal ripples

4.III.1 Measuring reactivation using neuronal coactivity motifs

4.III.1.a 2-Hz bursts coactivity motifs reactivate in post-learning ripples

Methods: building coactivity matrices and measuring reactivation with MTL single-neurons. In-bursts vs out-of-bursts. 1-, 2- vs 6-Hz bursts (exclusion).

4.III.1.b Reactivation is relevant for behavioural performance

Learning but not viewing coactivity motifs reactivate. All controls related to learning vs viewing (firing rate, shuffled cell ID, out-of-ripples, single subjects). Best better reactivate than worst recalled associations.

4.III.2 Measuring reactivation using gamma coactivity motifs

4.III.2.a Gamma coactivity motifs are physiologically meaningful

Previous figure S18: shuffling contact IDs breaks the matrices. Intra-regional coactivity is higher than inter-regional coactivity. Correlation with 2-Hz phase amplitude coupling matrices (with illustration). Idem with ripple coactivity.

4.III.2.b Gamma coactivity motifs are rigid

All negative results on gamma coactivity, using the exact same analytical framework as with single-neurons. The aim here is to report this negative result, and echo the work done with gamma correlations in the visual field (other lab).

5 Discussion

Limits: what happens out of the oscillatory bursts? Noise does not exist in physiology: what information do these out-of-bursts epochs carry? These would be epochs where the firing rate is higher (aperiodic components), fractal measures are higher, but it remains unclear what is actually happening there for the network. Is it really "not" communicating with other structures? If yes, how does it communicate? What are the alternatives mechanisms to "communication through coherence"? Main challenge to study this is that the rodent hippocampus is virtually always paced by theta. Then maybe that would be the biggest inter-species difference we find: transient oscillations. Note: it could be useful to illustrate this discussion to show 6-8Hz in the temporal cortex as well.

A Appendix: Neurophysiological recordings and analysis of oscillations

A.I Data acquisition and preprocessing

A.I.1 Participants

A.I.2 Electrode models

A.I.3 Co-registration and anatomical verification

A.I.4 Neurophysiological recordings

A.I.5 Detection of IEDs

A.II Decomposing LFPs into oscillatory components

A.II.1 Rationale for IMF-based decomposition

Here we will describe the optimization steps, final parameters of the masks used. Also Exemplify non-linearity of the signal (phase-frequency plots)

A.II.2 Mask optimization and criteria

A.II.3 Cycle detection and quality control

A.II.4 Detection of oscillatory bursts

A.III Other spectral decompositions

A.III.1 PSDs estimation (Welch)

A.III.2 Aperiodic correction using spectral parameterization

A.III.3 Morlet wavelet spectrogram parameters

A.III.4 Stimulus-locked spectral amplitude estimation

A.III.5 Detection of gamma activity

A.IV Cross-frequency analyses

A.IV.1 PAC and phase randomization

A.IV.2 HHSAs

B Appendix: Analysis of single-neuron activity

B.I Spike sorting and single-unit validation

B.I.1 Automated pipeline

B.I.2 Manual curation quality criteria

B.I.3 Waveform classification

B.II Spike-field relationship

B.II.1 PPC and phase randomization

B.II.2 Spike-gamma relationship

C Appendix: Hippocampal ripples and reactivation

C.I Ripple detection and validation

C.I.1 Initial ripple detection

C.I.2 Template matching

C.I.3 Final detection and quality controls

C.I.4 Ripple-triggered averages

C.I.5 Characterization of ripple central frequency

C.II Detection of cross-regional coactivity motifs

C.II.1 Epochs selection

C.II.2 Using single-neurons

C.II.3 Using gamma activity

C.III Reactivation of coactivity motifs in hippocampal ripples

C.III.1 GLMs

C.III.2 Controls

D Appendix: Statistical analyses

D.I Bootstrap and permutation tests

D.II GLMs and LMEMs

D.III Cluster-based permutation