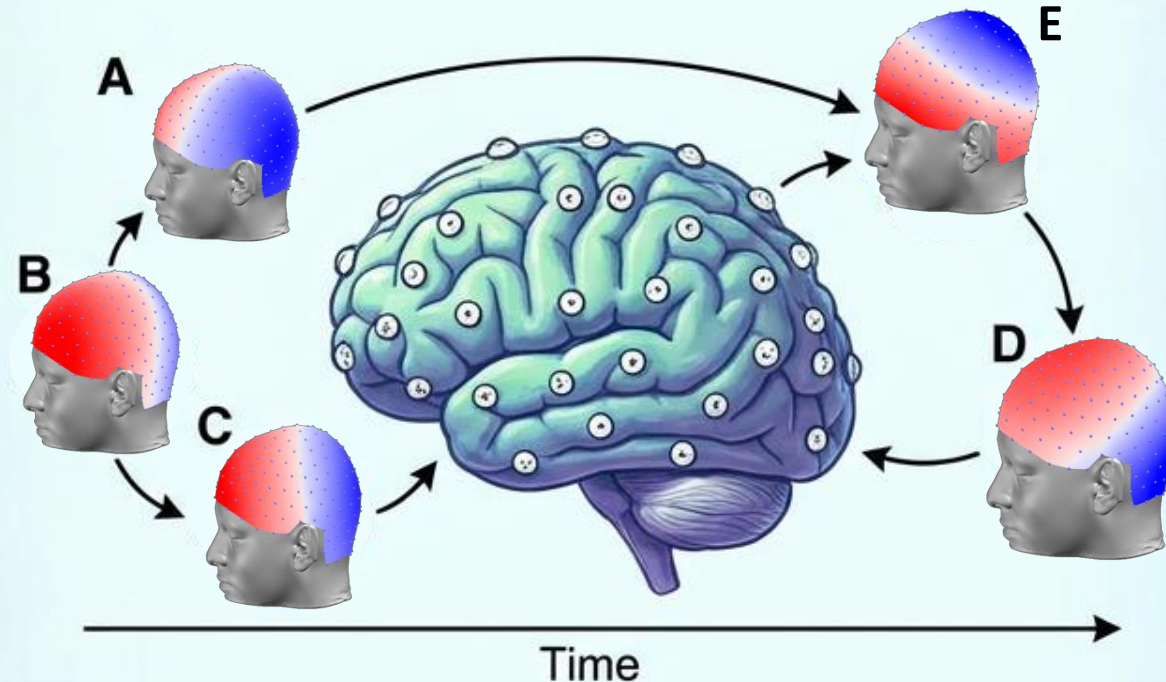


# EEG Microstates: From Methodological Foundation to Clinical Translation



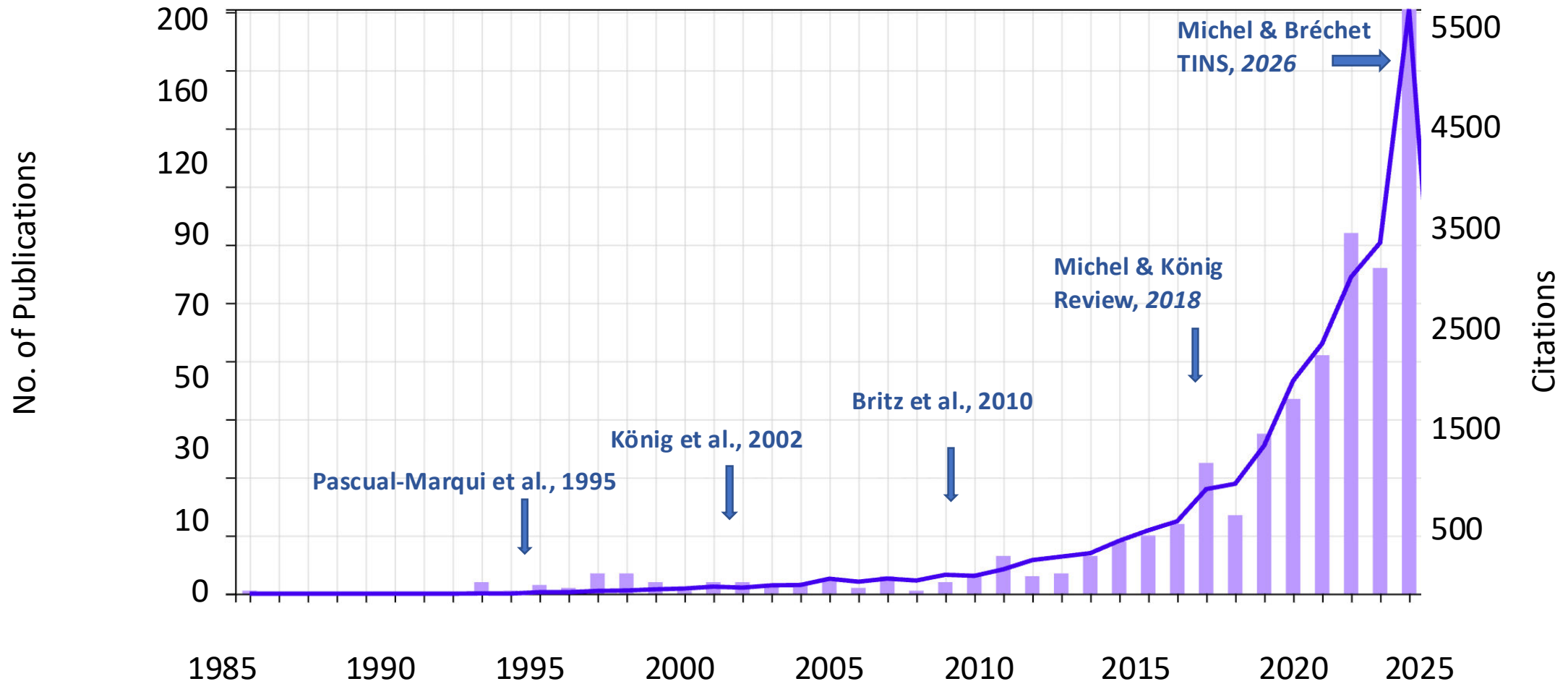
UNIVERSITÉ  
DE GENÈVE

FACULTÉ DE MÉDECINE

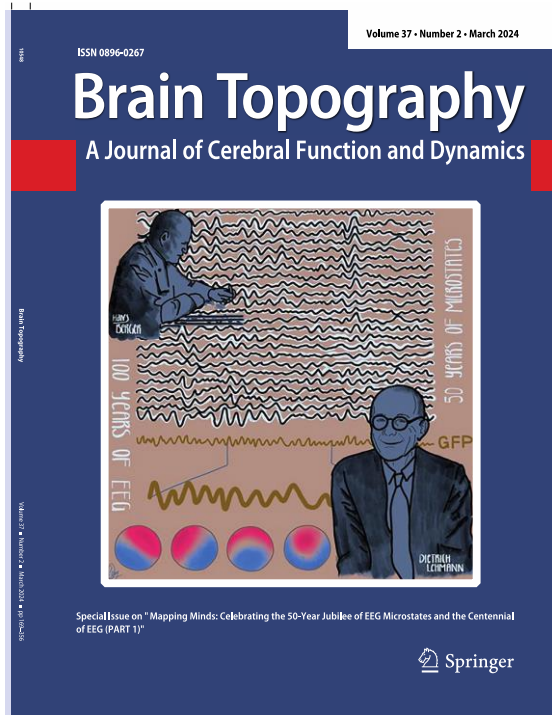
Christoph M. Michel  
University of Geneva, AllHere SA

A L L H E R E  
● ● ● ● ● ● ●

# EEG Microstate Studies



# Special Issue: Mapping Minds: Celebrating the 50-Year Jubilee of EEG Microstates and the Centennial of EEG



Part 1 (March 2024):  
13 papers

48 Submissions

36 Accepted

30 Research papers

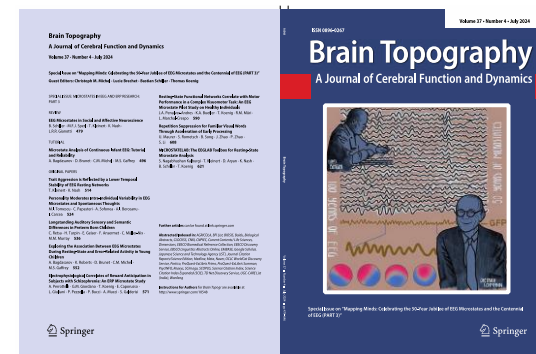
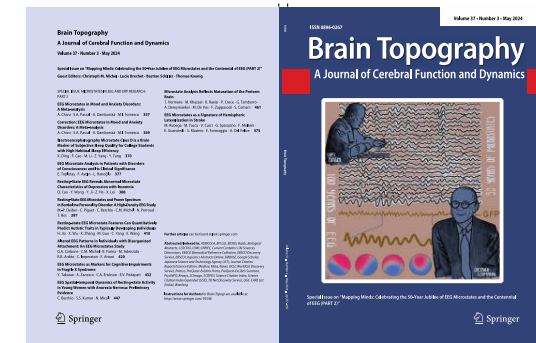
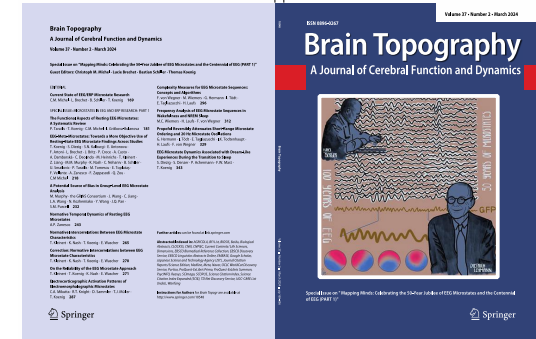
1 Editorial

3 Reviews/Meta-Analysis

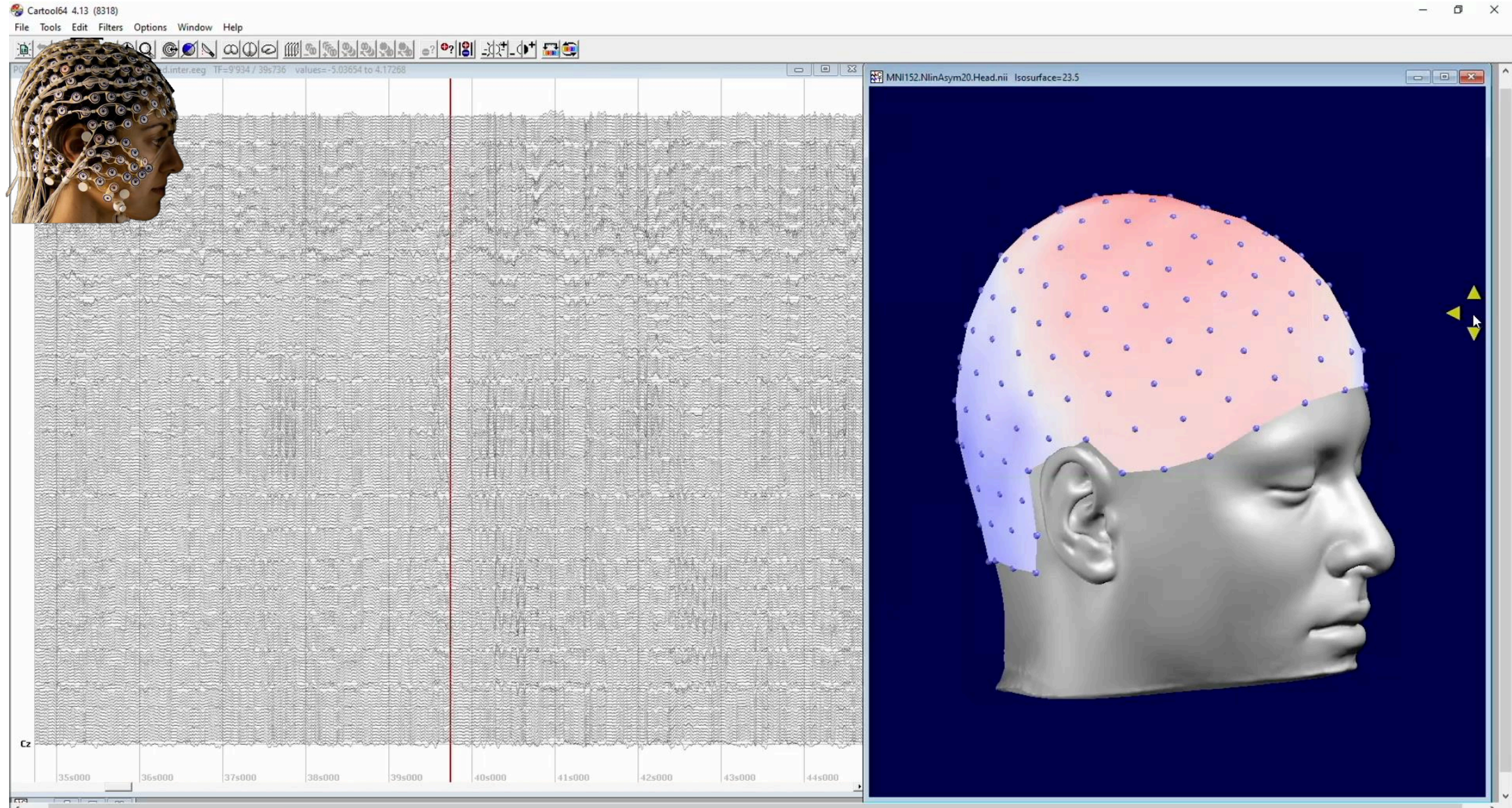
2 Tutorials

Part 2 (May 2024):  
12 papers

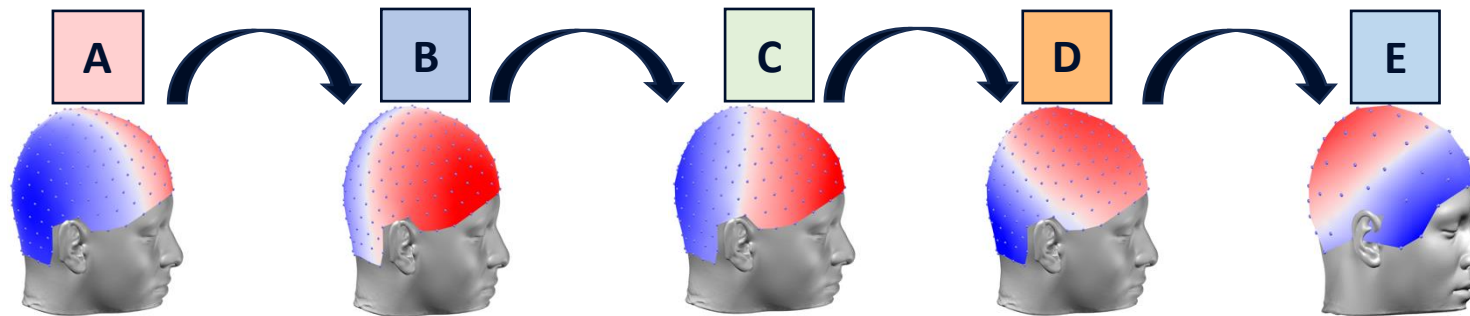
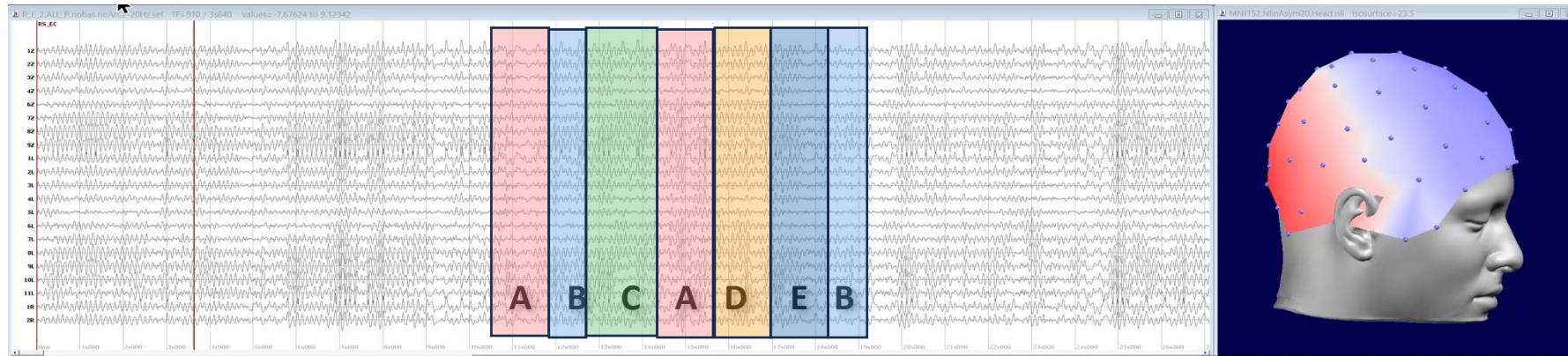
Part 3 (July 2024):  
12 papers



# EEG Topographic Mapping



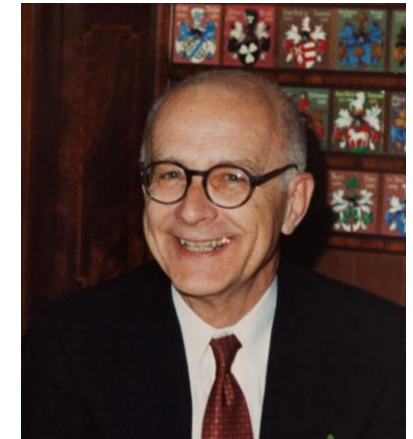
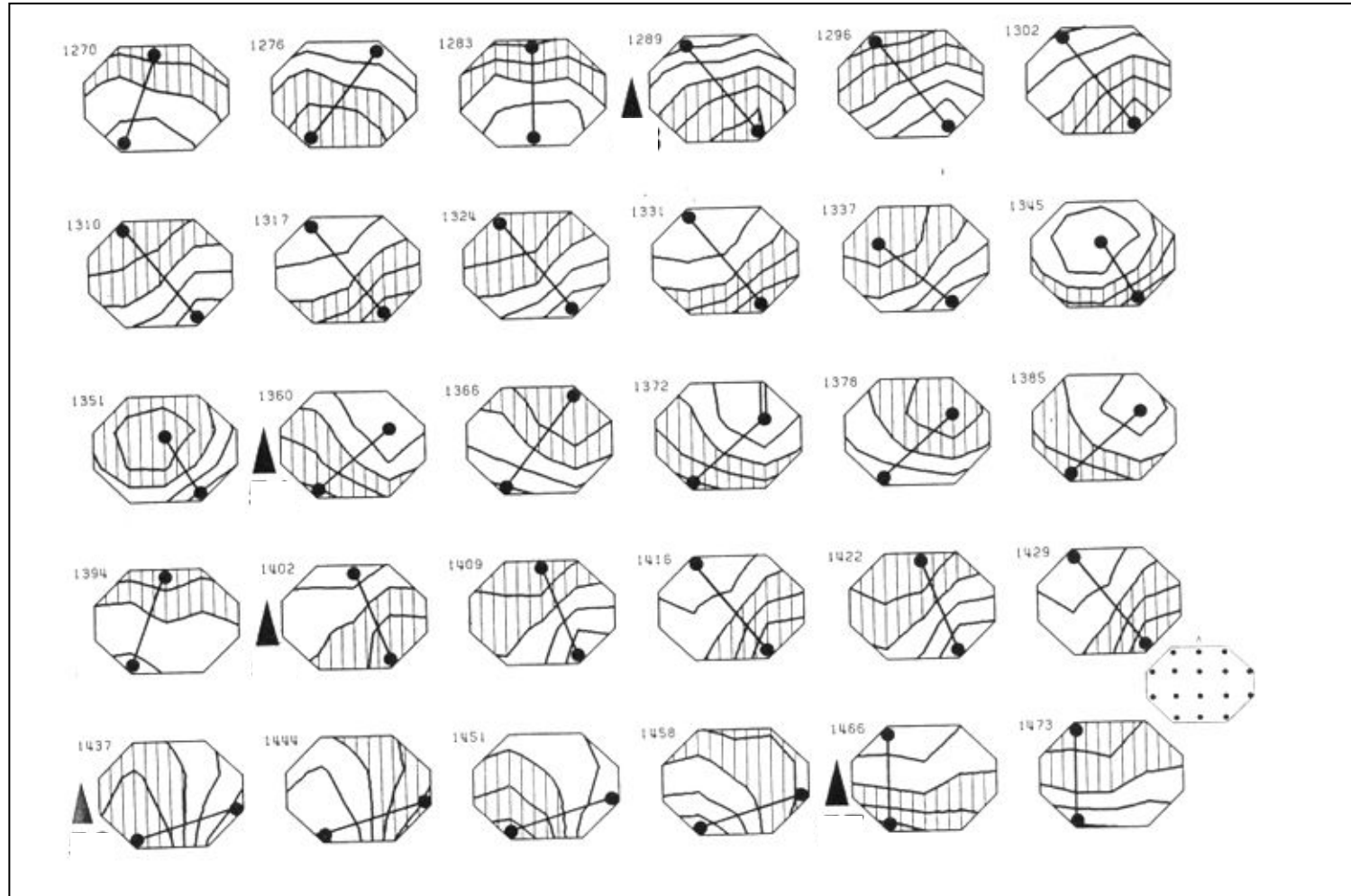
# THE EEG MICROSTATE CLAIM



Large-scale neural activity proceeds through sequential transitions among a few reproducible spatial patterns rather than continuous fluctuations (Lehmann, 1987)

# The Functional Microstates of the Brain

D. Lehmann et al. Brain micro-states by space-oriented adaptive segmentation. *Electroenceph. Clin. Neurophysiol.*, 1987



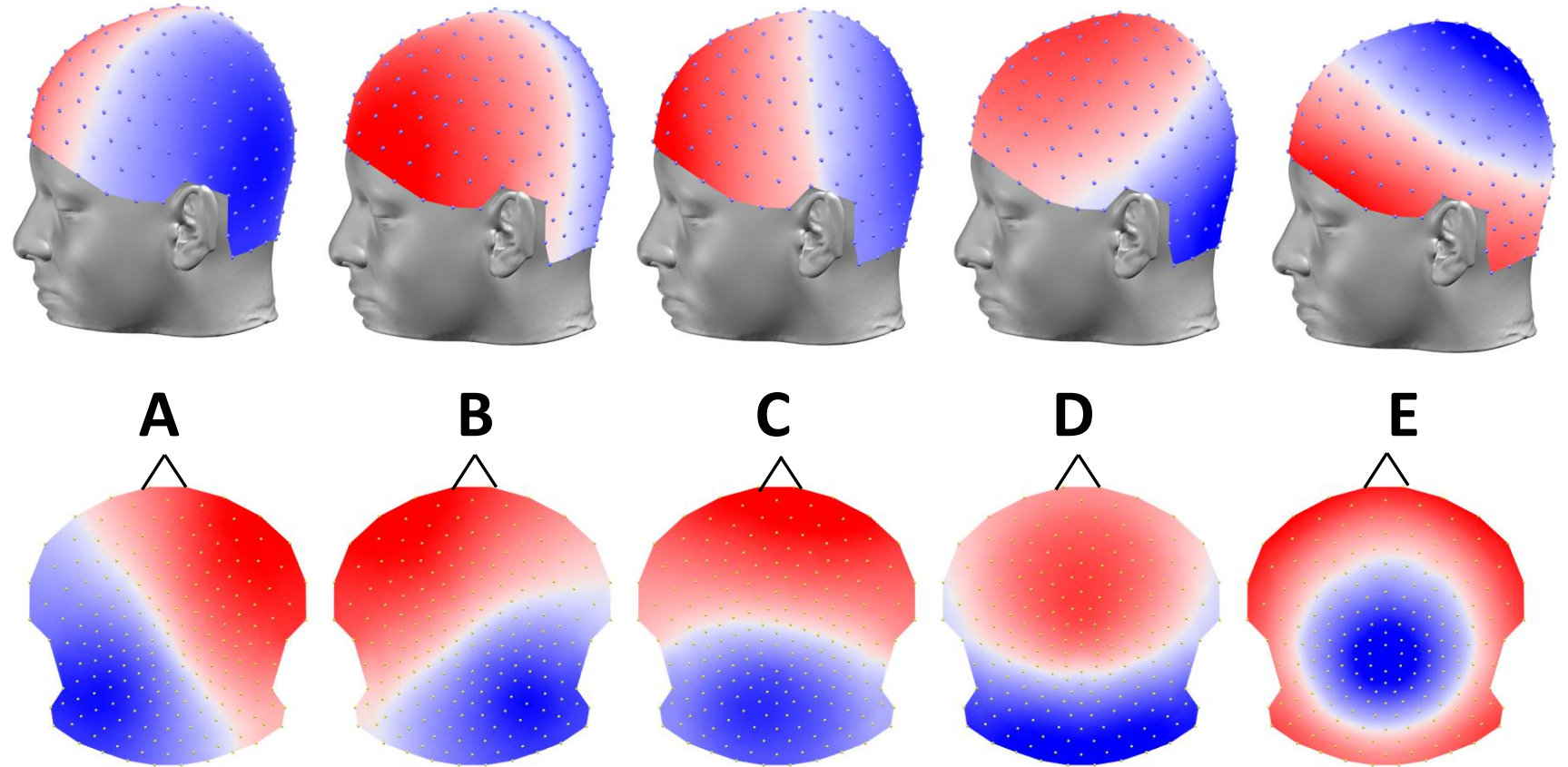
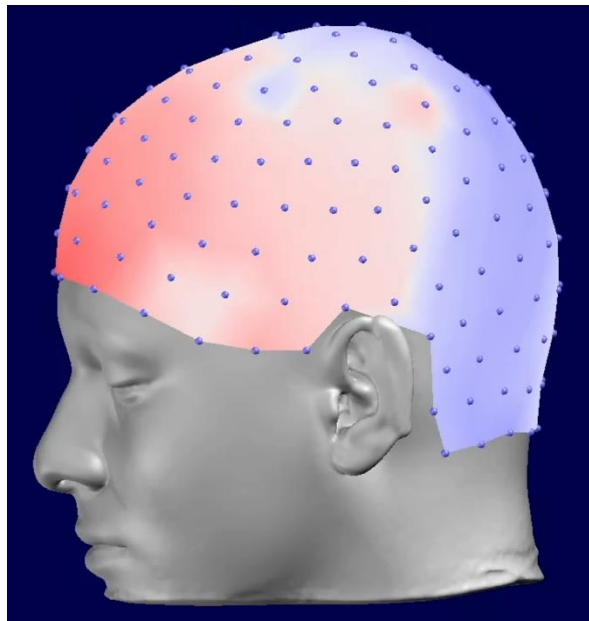
Dietrich Lehmann  
1929 - 2014

« The spatially stationary segments might be basic building blocks of information processing, possibly reflecting the time for consciousness »

# EEG Microstates: from phenomenology to quantification

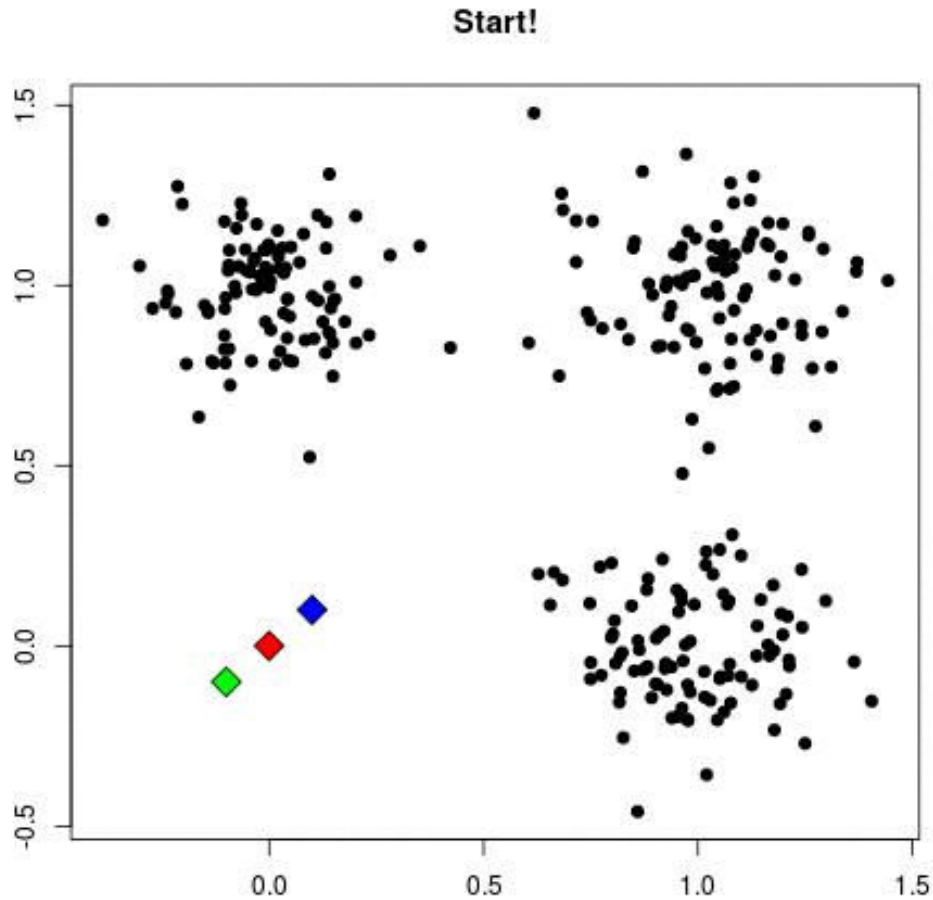
75888

## K-means Cluster Analysis of the Scalp Potential Maps



By ignoring polarity inversions,  
spontaneous EEG can be clustered into a few dominant topographies

# K-means Cluster Analysis of EEG map series



Pascual-Marqui RD, Michel CM, Lehmann D.  
Segmentation of brain electrical activity into microstates  
IEEE Trans Biomed Eng. 1995

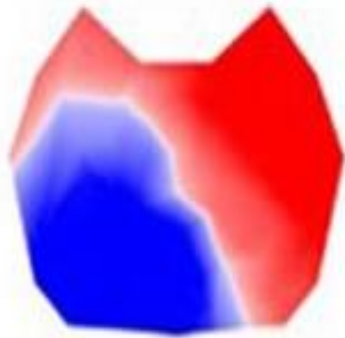
**Foundational assumption 1:** EEG topographies contain meaningful cluster structure

**Criticism:** Any dataset can be clustered, and the output centroids carry no evidence that the data points are actually separated in clusters.

# Empirical support

EEG topographies contain meaningful cluster structure

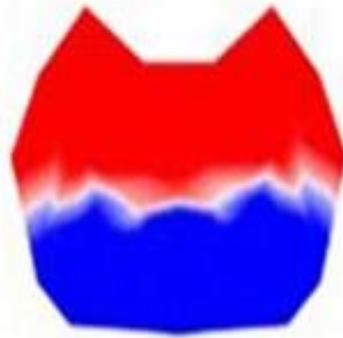
Microstate A



Microstate B



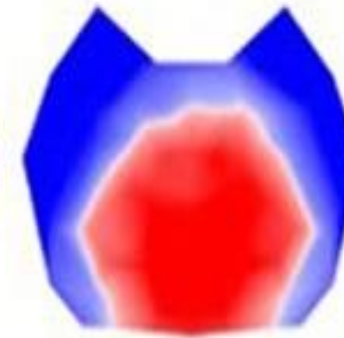
Microstate C



Microstate D



Microstate E



D'Esposito et al., 2012  
D'Esposito et al., 2021

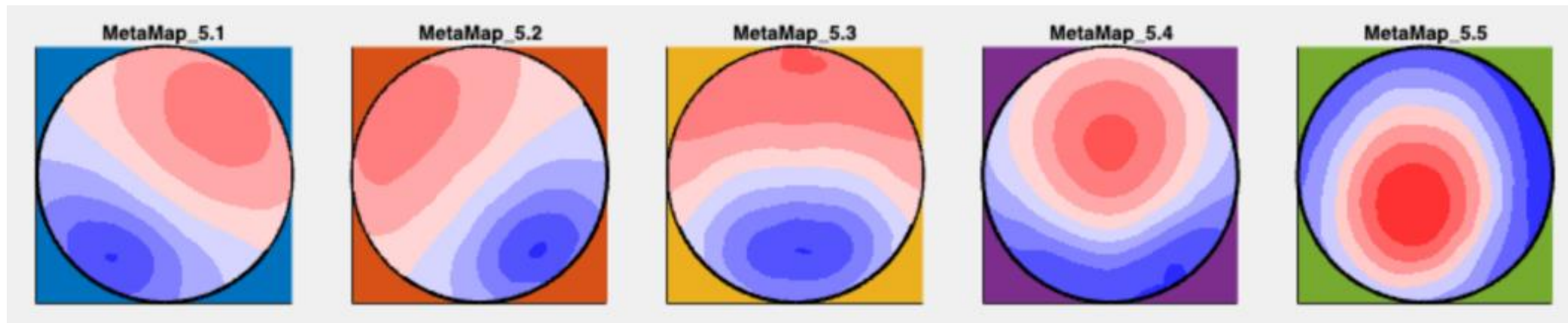
164 subjects  
256-channel EEG

- Same canonical topographies recur across labs, ages, systems, states (Koenig et al. 2023)
- Information-theoretic quantities are invariant across clustering algorithms (von Wegner, 2018)
- microstate temporal parameters show excellent test-retest reliability (Kleinert et al., 2024)

# EEG Microstates

## Meta-microstate template maps

Cluster analysis across 40 different studies

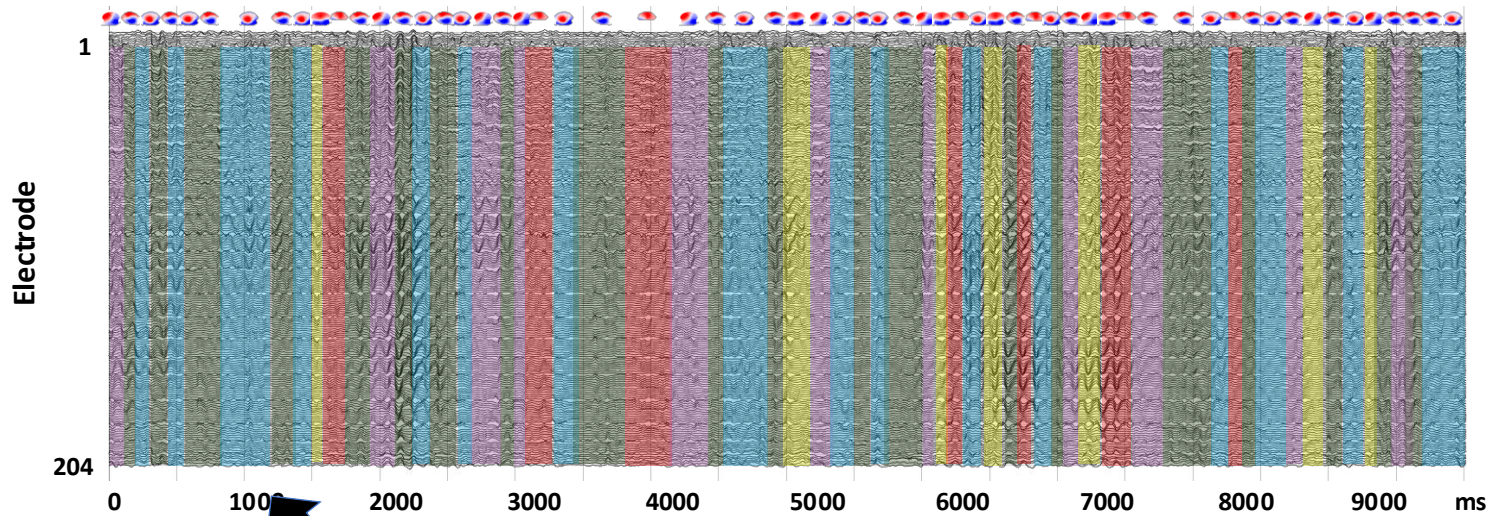


Koenig T, Diezig S, Kalburgi SN, Antonova E, Artoni F, Brechet L, Britz J, Croce P, Custo A, Damborská A, Deolindo C, Heinrichs M, Kleinert T, Liang Z, Murphy MM, Nash K, Nehaniv C, Schiller B, Smailovic U, Tarailis P, Tomescu M, Toplutaş E, Vellante F, Zanesco A, Zappasodi F, Zou Q, Michel CM.

**EEG-Meta-Microstates: Towards a More Objective Use of Resting-State EEG Microstate Findings Across Studies**  
*Brain Topography*, 2023

<https://github.com/ThomasKoenigBern/MS-Template-Explorer>

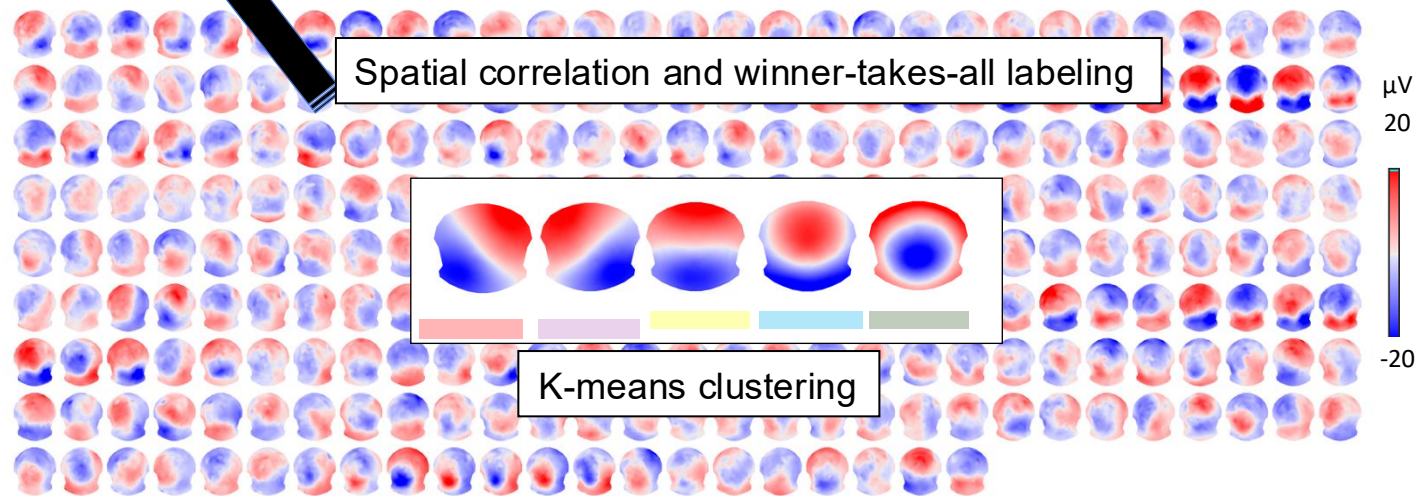
# Segmentation of EEG into Microstate Sequences



Microstate parameters:

- Duration
- Explained Variance
- Occurrence
- Coverage
- Transition Probabilities
- Hurst Exponent
- Complexity

the EEG is parcelled  
into short periods  
of stable states  
lasting around 100 msec

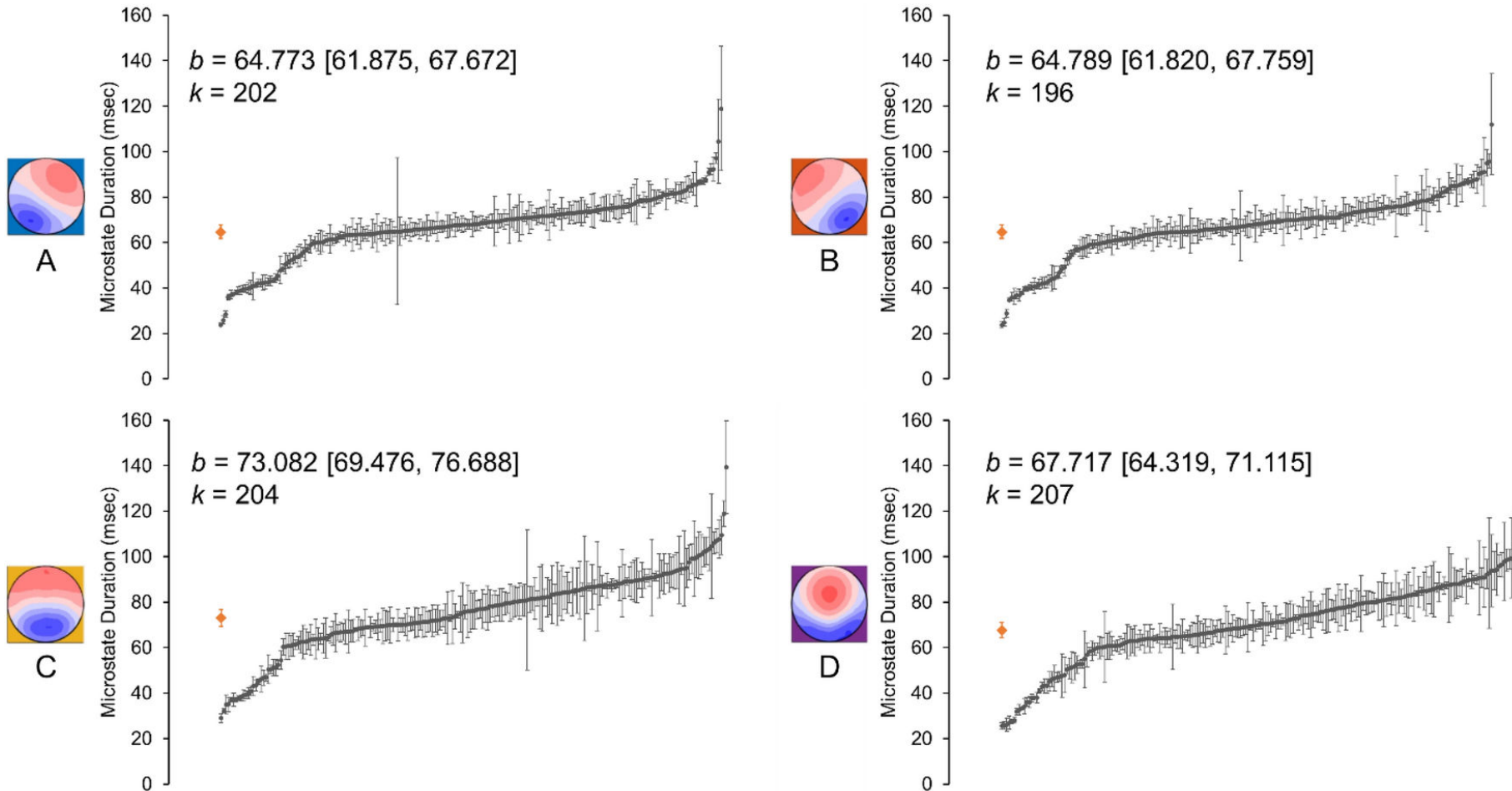


Spatial correlation and winner-takes-all labeling

K-means clustering

# Stability of microstate temporal parameters

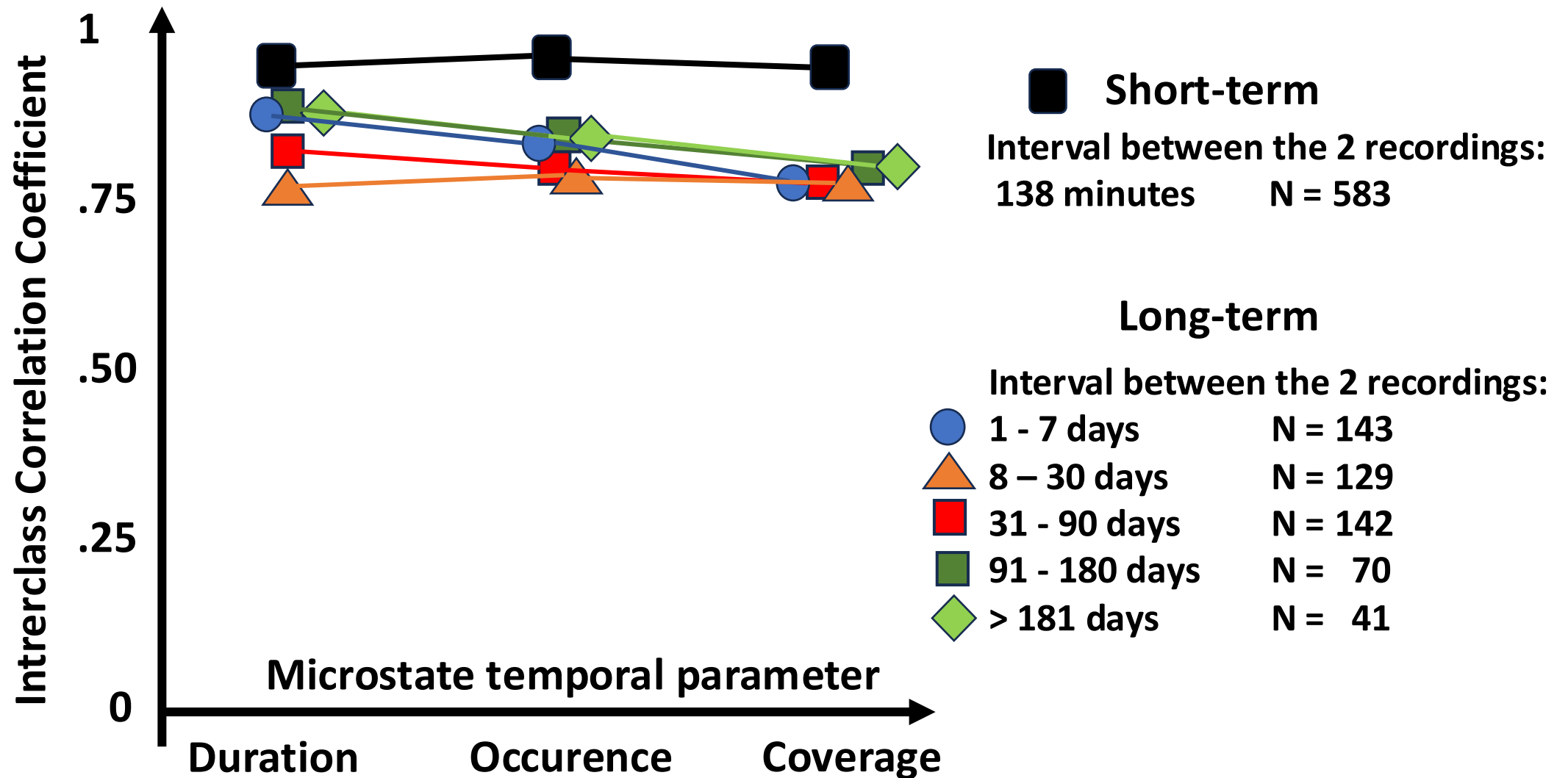
Meta-analysis of 93 articles, representing resting EEG recorded from a total of **6583 individual participants** comprising **228 unique study samples**.



**microstate duration:**  
mean and 95% CIs for all  
study samples

A. Zanesco: Normative Temporal Dynamics of Resting EEG Microstates. Brain Topography, 2023

# Retest-reliability of microstate temporal parameters



# Retest-reliability of microstate sequence patterns

60 healthy young adults two recordings:

short-term: 90 minutes apart

long-term: 30 days apart

## Higher-order microstate sequence analysis

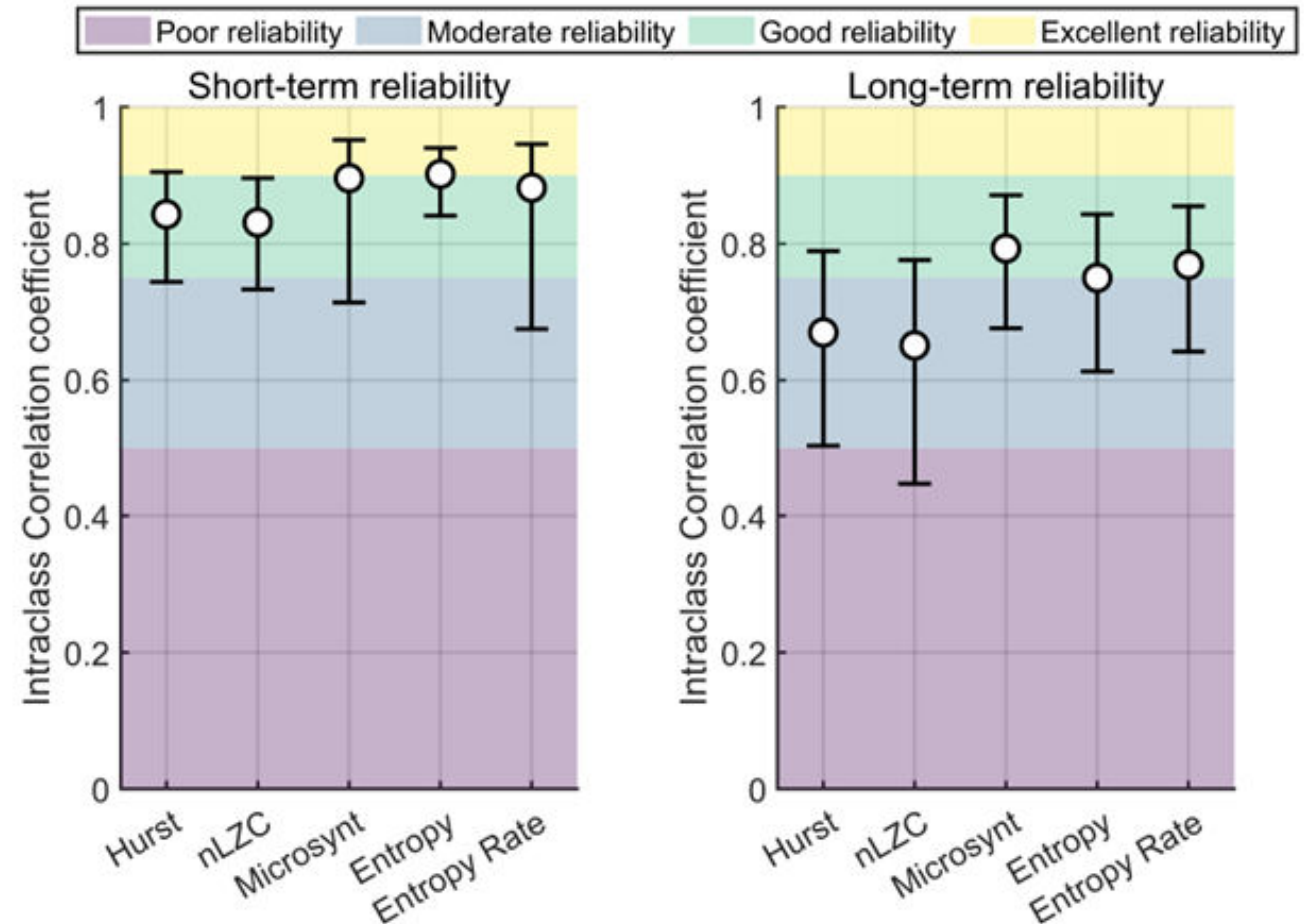
**Hurst exponent:** long-range dependency

**Lempel-Ziv:** sequence compressibility

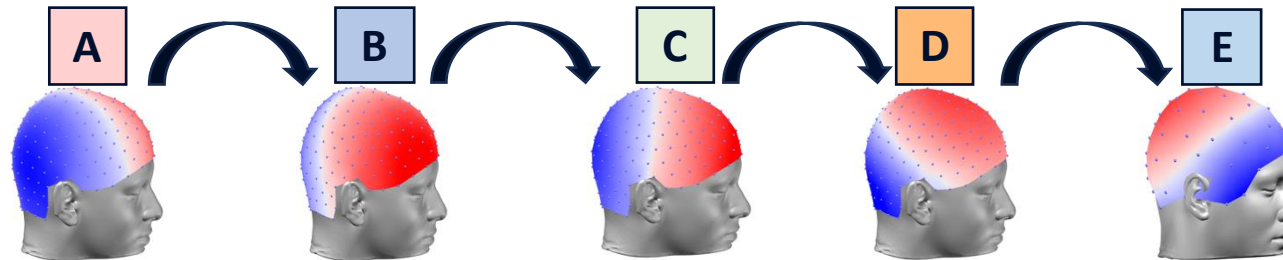
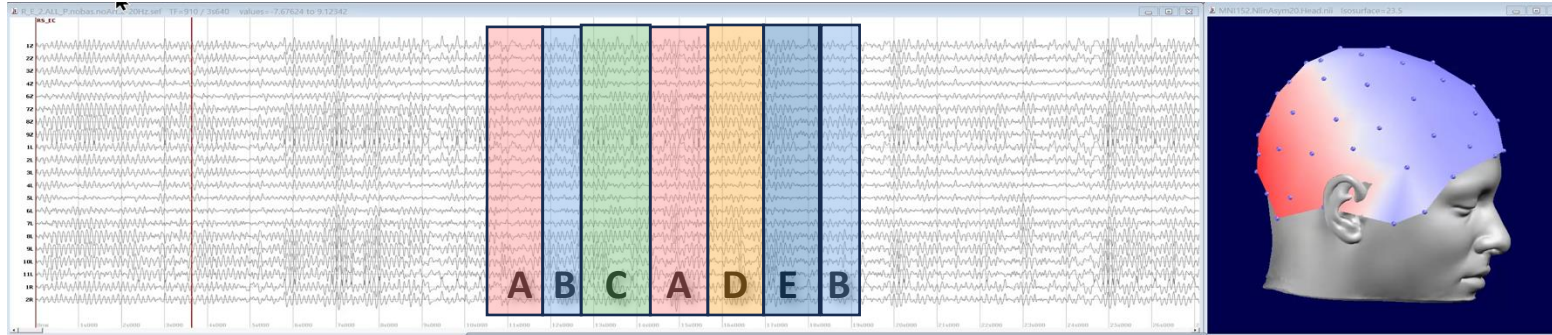
**Microsynt:** sequence complexity

**Entropy:** sequence heterogeneity

**Entropy rate:** randomness of sequences



# Parcellation of EEG into Microstate Sequences



## Foundational assumption 2:

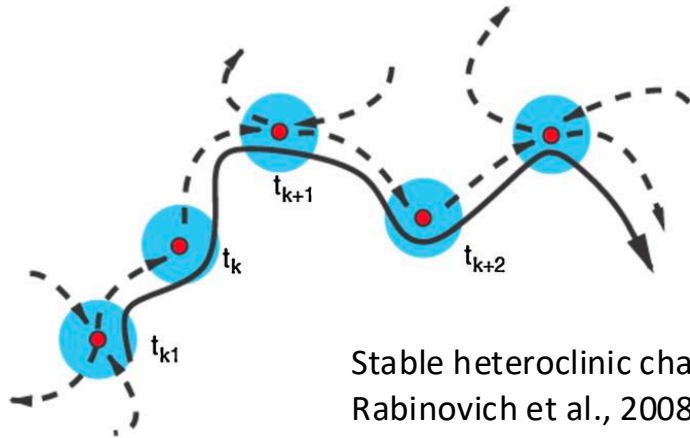
Large-scale neural activity proceeds through sequential transitions among reproducible spatial patterns rather than continuous fluctuations

## Foundational assumption 3:

Only one single dominant network configuration at each moment in time

# Brain dynamics as discrete quasi-stable states

## Theoretical and computational neuroscience



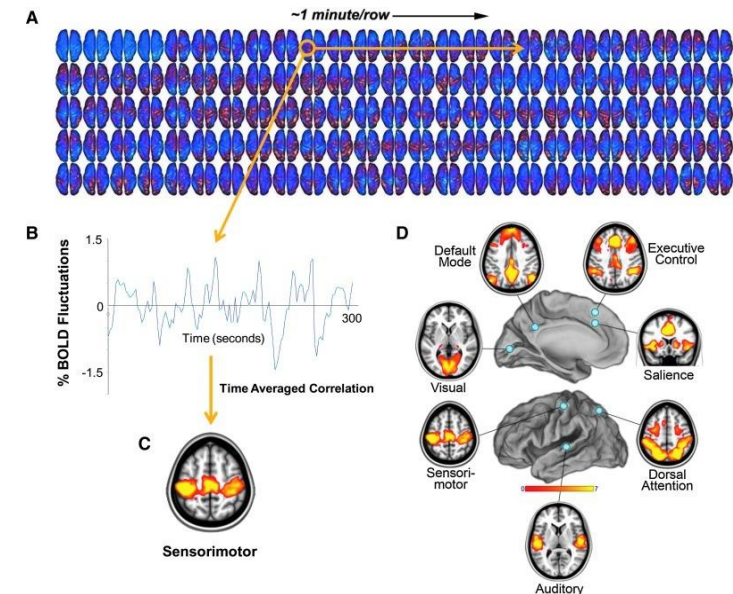
Stable heteroclinic channels  
Rabinovich et al., 2008

The continuous stream of thoughts is  
parcelled into metastable states

*Metastability is a crucial property of  
brain dynamics that allows the  
transitioning between states as part  
of a sequence*

Bressler & Kelso, 2001  
Dehaene & Changeux, 1991  
Baars, 2002  
Rabinovich, 2000, 2008, 2012  
Tognoli & Kelso, 2014  
Meehan & Bressler, 2012  
Deco & Jirsa, 2012  
Changeux & Michel, 2004

## fMRI Resting State Networks



The restless brain, Raichle, 2011

*The intrinsic network dynamics undergo  
momentary stable states with transitions  
between them.*

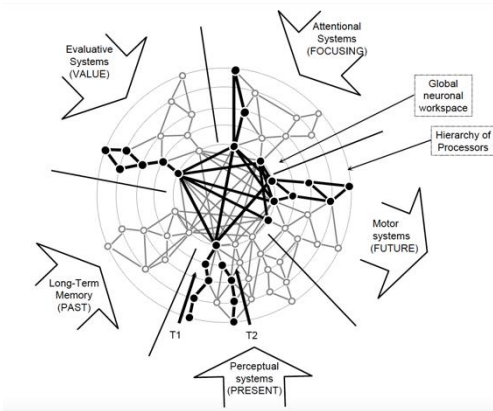
**Intrinsic BOLD networks and EEG microstates  
are signatures of metastable brain state sequences  
on slow and fast timescales.** Meehan & Bressler 2012

# One thought at a time

## Theoretical and computational neuroscience



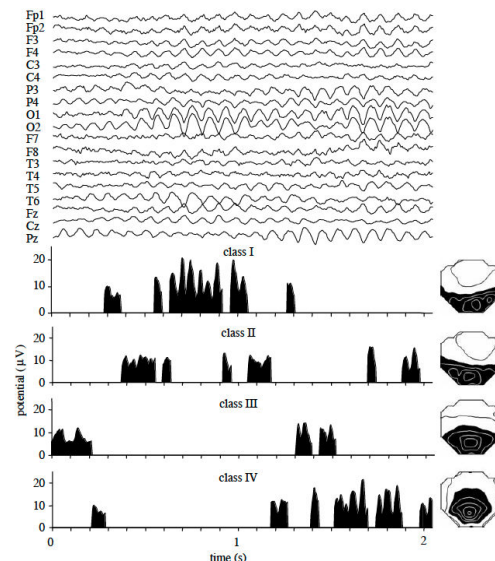
“ Like a bird’s life, the stream of consciousness seems to be made up of an alternation of flights and perchings.”  
“ Each state represents a certain thought with a unitary content, however complex it may be, i.e. during such a state we only have one conscious thought, which will be distinctly different from the thought in the previous or following mind state”. **William James, 1890**



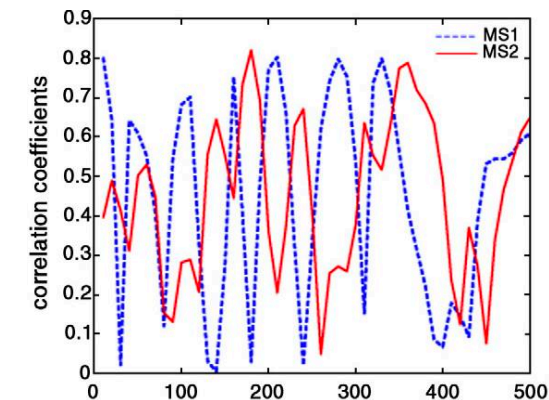
**Global workspace theory** suggests a fleeting memory capacity in which **only one** consistent content can be dominant at any given moment  
**BJ Baars 1997, 2002**  
**Dehaene & Changeux 1998/2005**

## Empirical observation:

the assigned map remains dominant during a coherent time period rather than randomly fluctuating

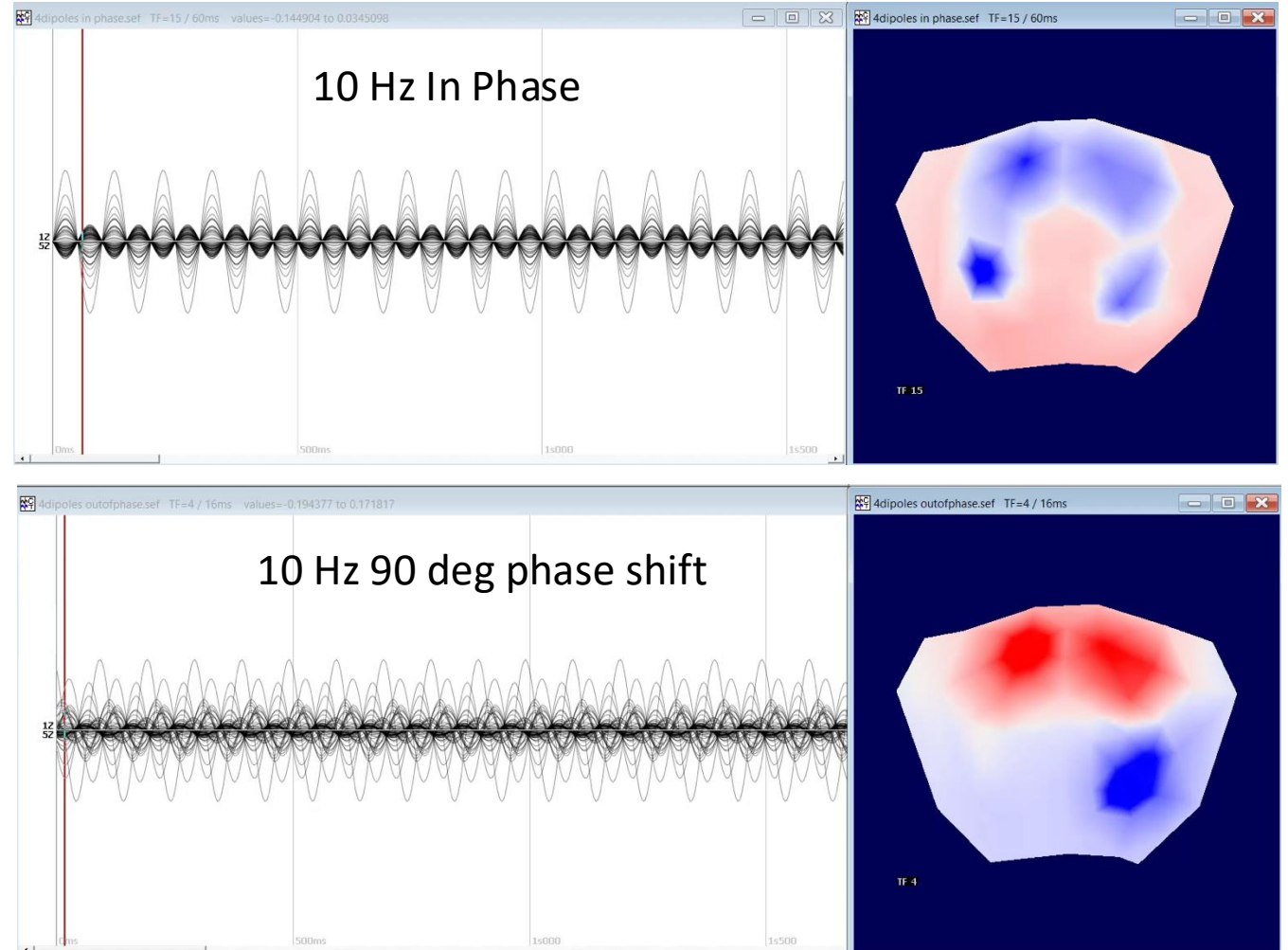
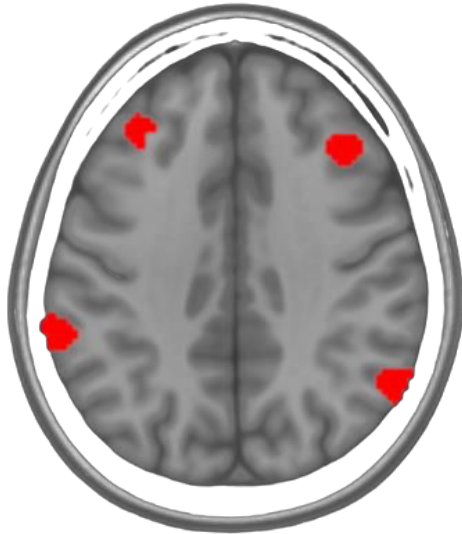


König et al., 2005



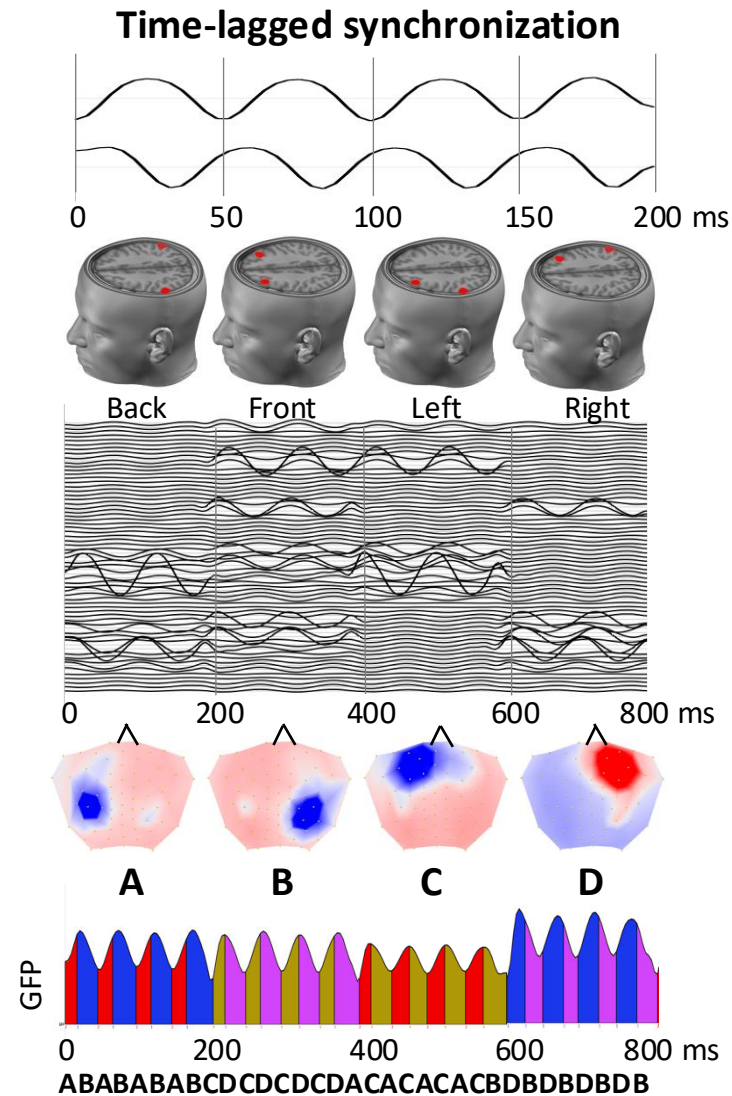
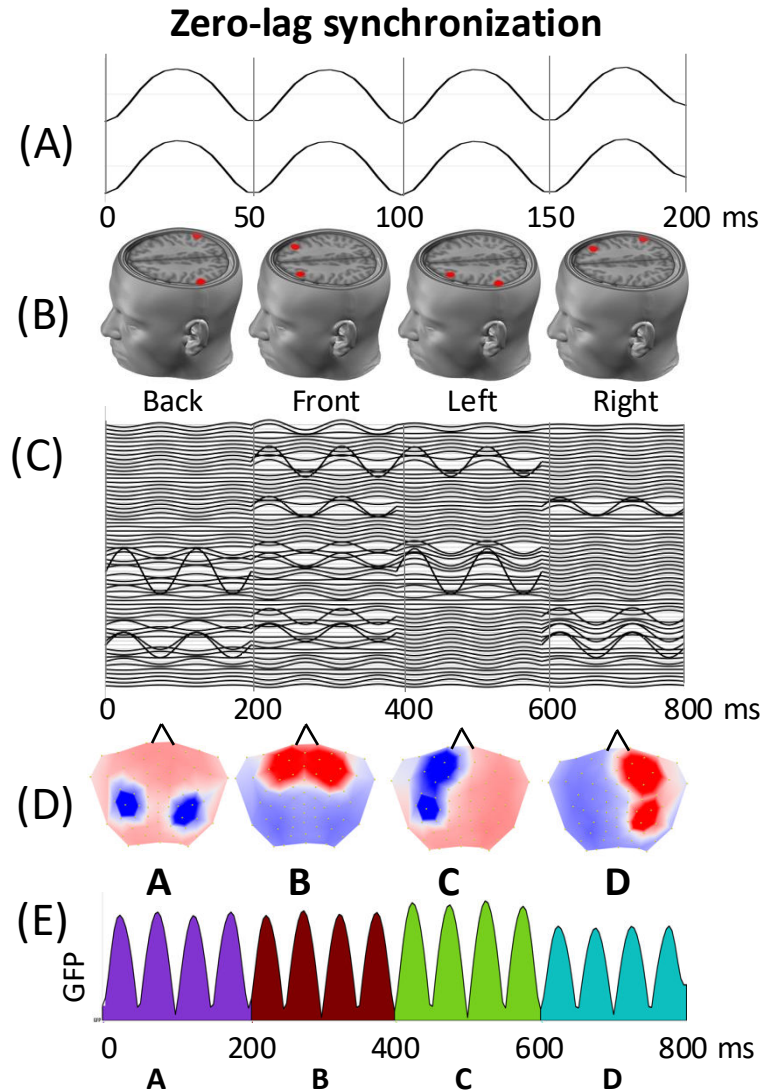
Britz et al., 2010

# Zero-lag synchronization during a Microstate



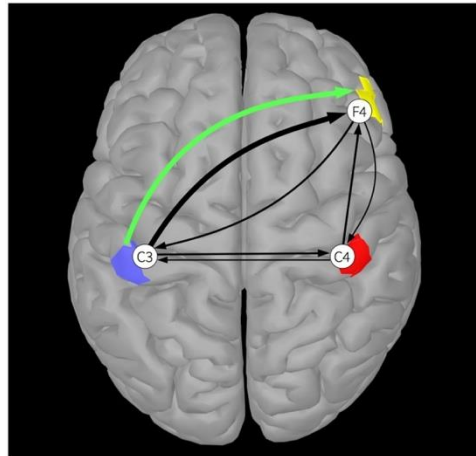
Michel & König, 2018: “ If we assume that spatially distributed activities account for a particular microstate, this implies that the different sources must have had the same temporal dynamics, because differences in the time courses of these sources would result in continuous changes of the scalp field they produce. “

# Zero-lag synchronization of large-scale networks



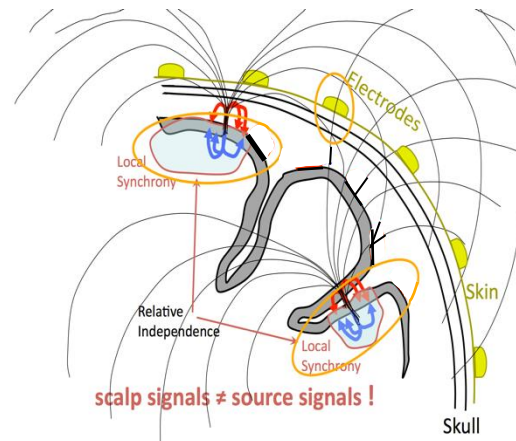
# Connectivity analysis exclude zero-lag synchronization

Brunner et al., 2016



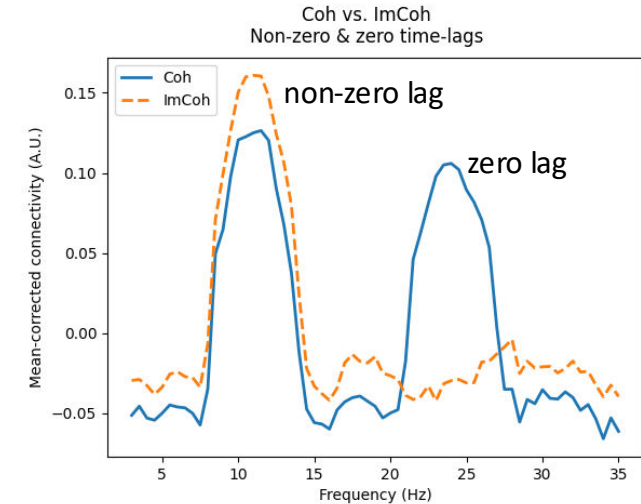
— simulated DTF connection  
— estimated DTF connections between electrode channels

Makeig, 2007



Volume conduction

Nolte et al., 2004



— Coherence  
- - - Imaginary Coherence

MNE Tutorial

- Simultaneous activity, which imposes zero-lag-related signals are generally ignored in EEG/MEG network analyses to avoid spurious phase relations resulting from volume conduction
- the limited spatial resolution of EEG/MEG source reconstruction techniques also leads to spurious temporal relations → orthogonalization of source signals is a standard method which also discards genuine simultaneous dynamics

➔ **Microstate analysis captures genuine neurophysiological synchronization, revealing a network organization fundamentally different from traditional time-lagged connectivity analyses**

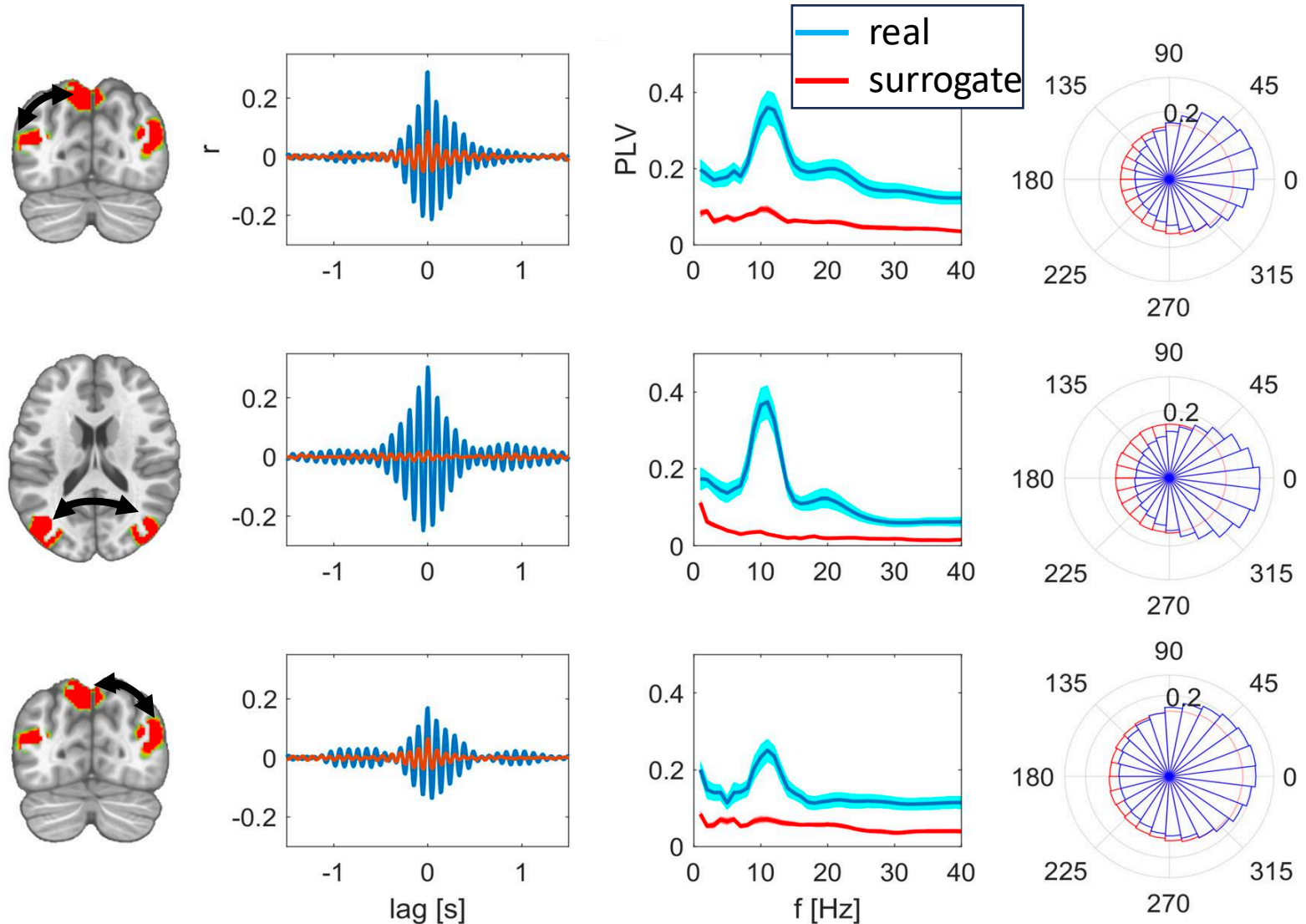
# Brief zero-lag synchronization of distant brain regions

## Real data:

- Resting state EEG
- 18 subjects, 256 channels
- LAURA source estimation
- seed region: PCC
- cross-correlation calculation

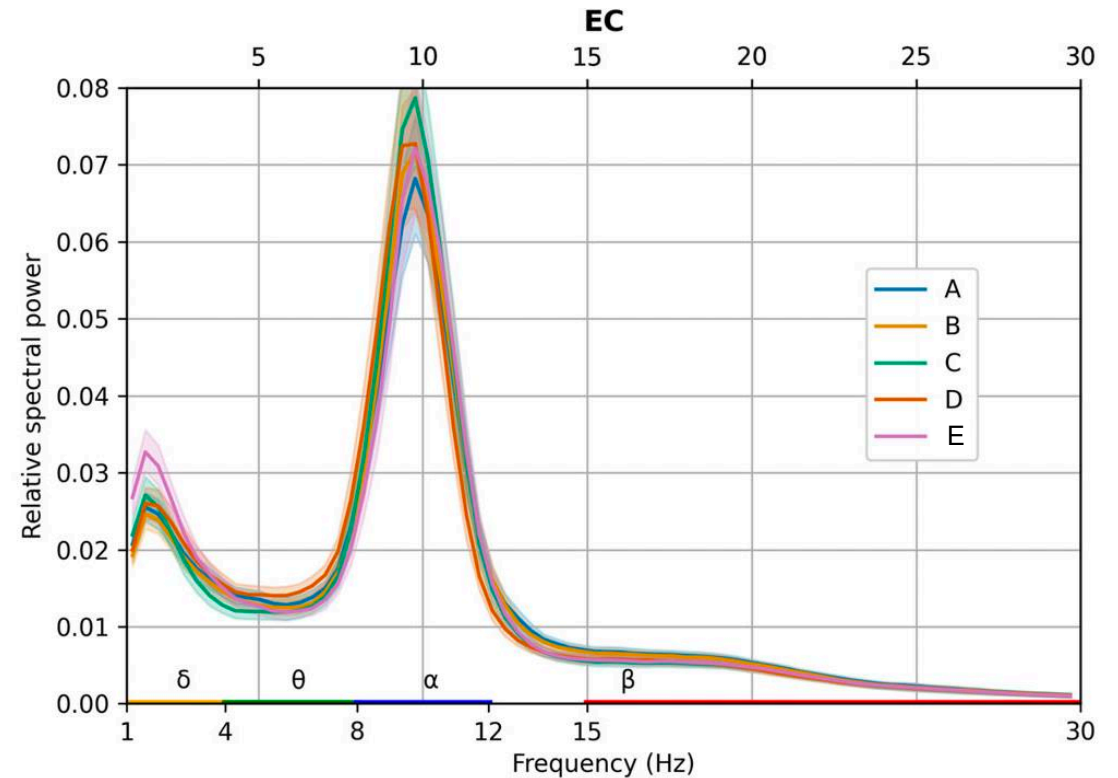
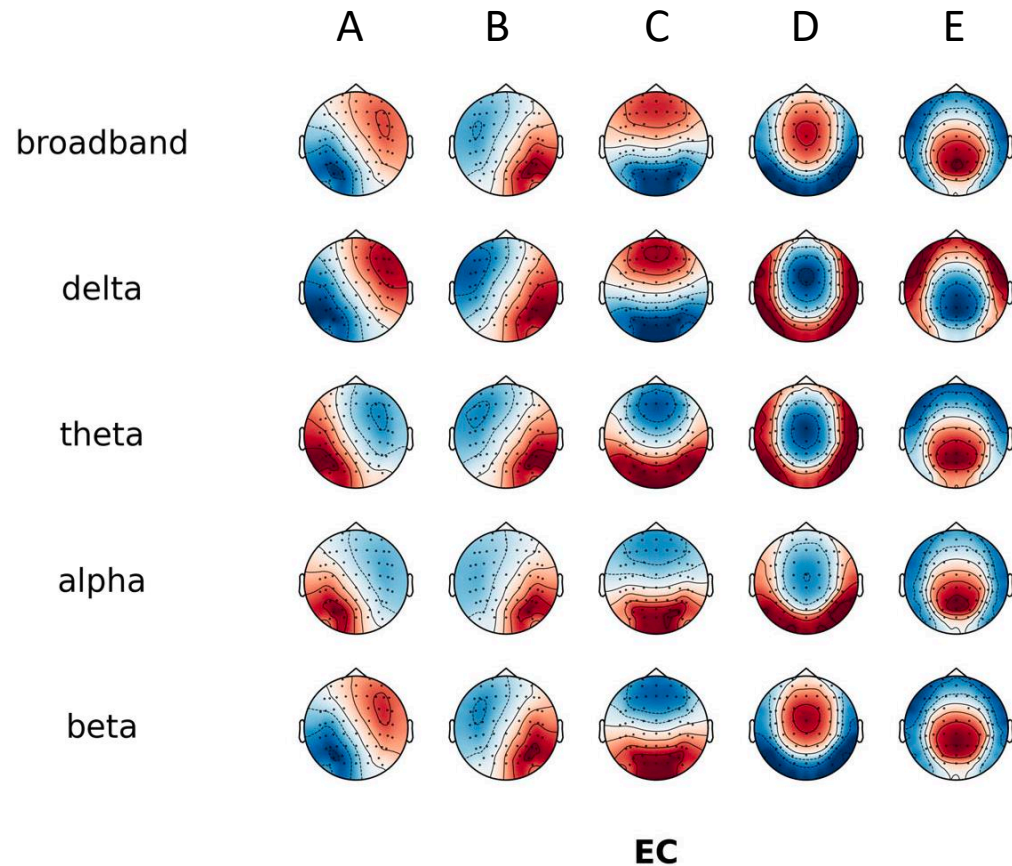
## Surrogate data:

- random temporal shift of real data for each solution point
- EEG reconstruction
- same analysis as for real data



*Genuine simultaneous synchronization between PCC and bilateral IPL that exceeds volume conduction effects*

# EEG Microstates are Broadband activities

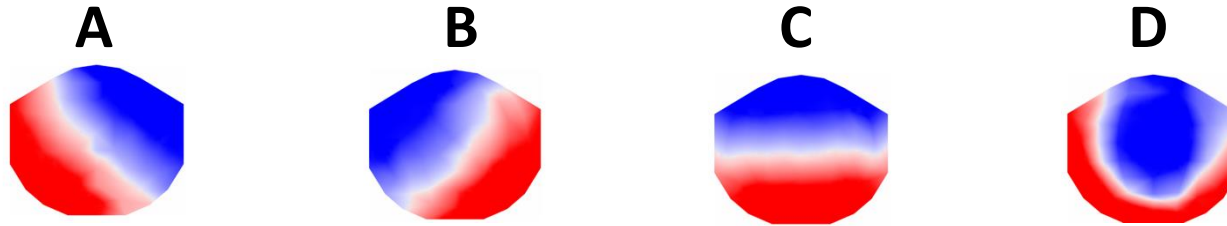


- Same maps in different frequency bands
- Same spectrograms in microstate spatially filtered EEG
- informational independence of MS temporal sequences between spectral bands

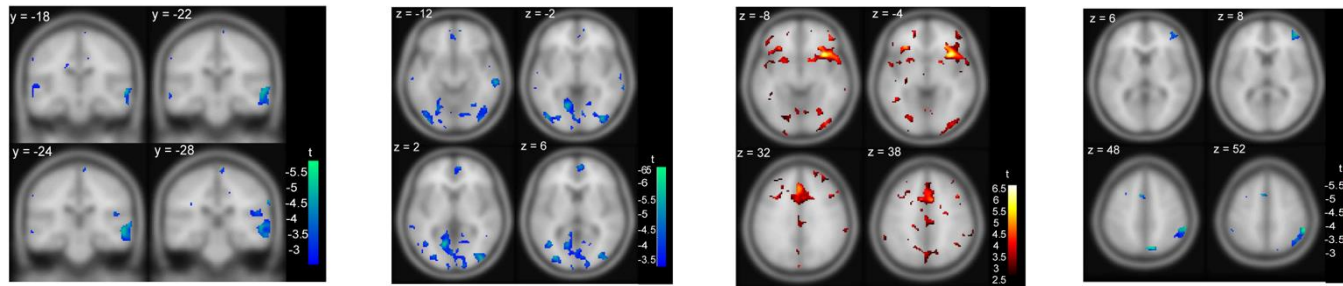
# Brain Networks generating EEG Microstates

## Simultaneous EEG-fMRI

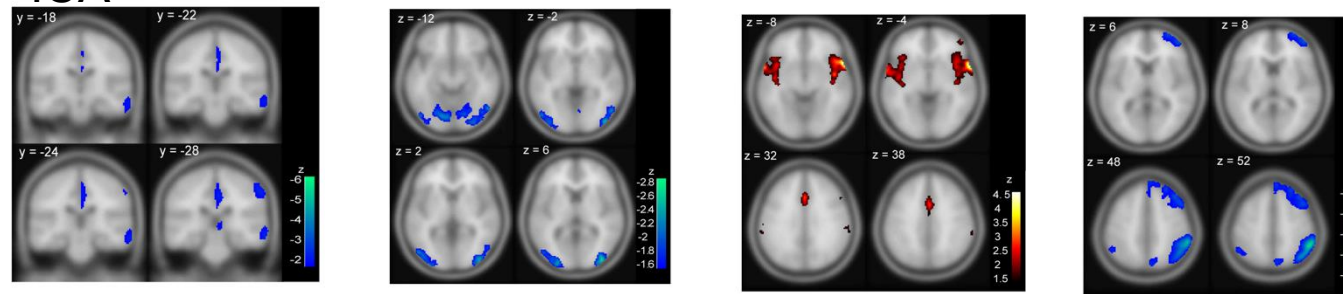
EEG  
Microstates



GLM



ICA



fMRI  
Resting  
States

Auditory

Visual

Salience

Attention  
Executive Control

- 866 citations
- taken as reference for functional interpretation

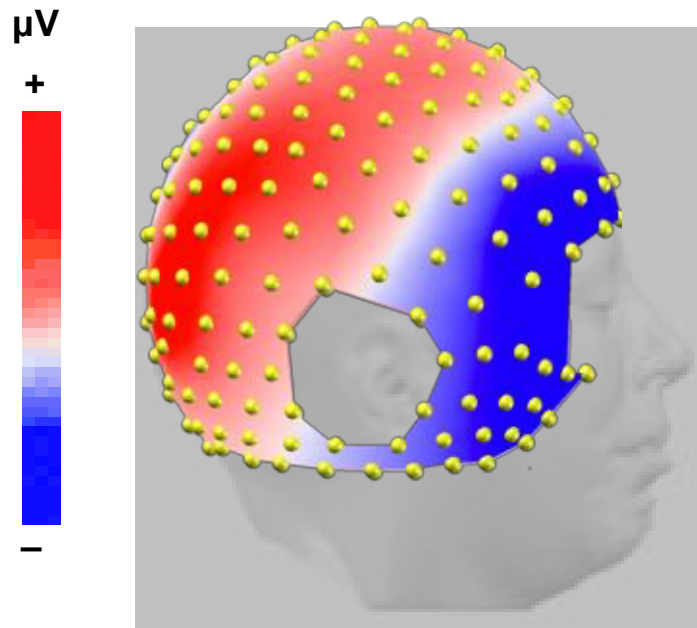
9 subjects  
64-channel EEG  
4 microstates  
artifact corrections  
temporal smoothing

no replication study

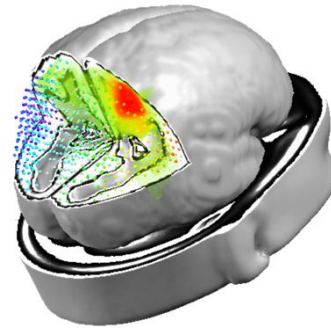
➤ premature functional consensus through citation chains

# The sources of EEG scalp maps

*Scalp potential map*



*Source model*



*Head model*

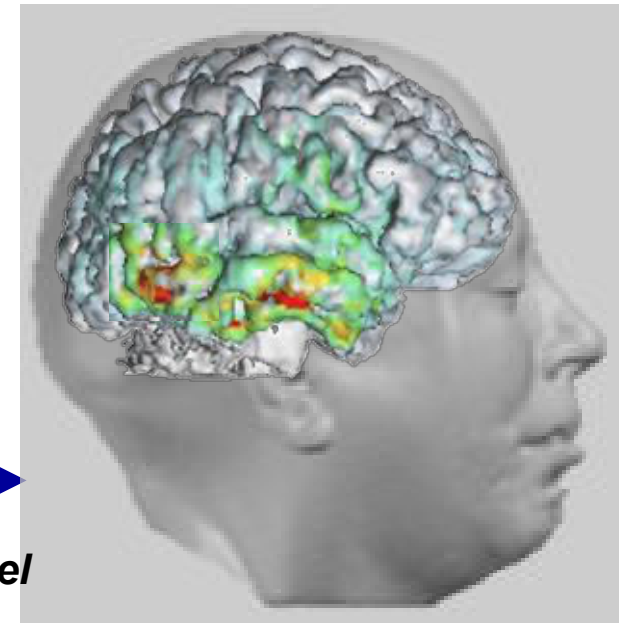


Courtesy:  
F. Babiloni

*distributed linear  
inverse solution  
(LORETA)  
with physiological  
constraints*

*Realistic head model  
with anatomical  
constraints*

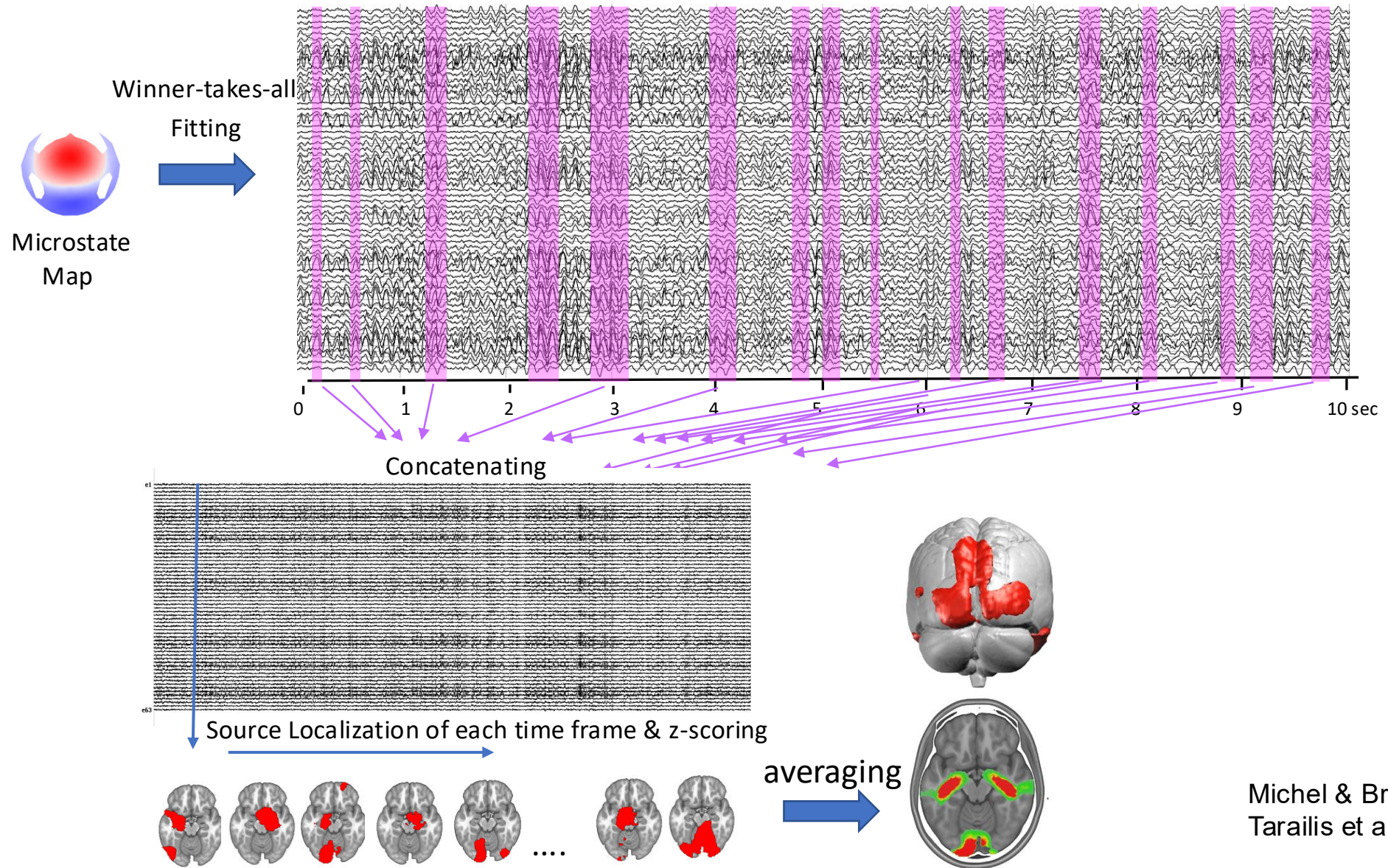
*Current sources  
in the brain*



**Solving the inverse problem**

Michel et al., 2004  
Michel & Brunet, 2019  
Michel & He, 2011, 2018, 2019

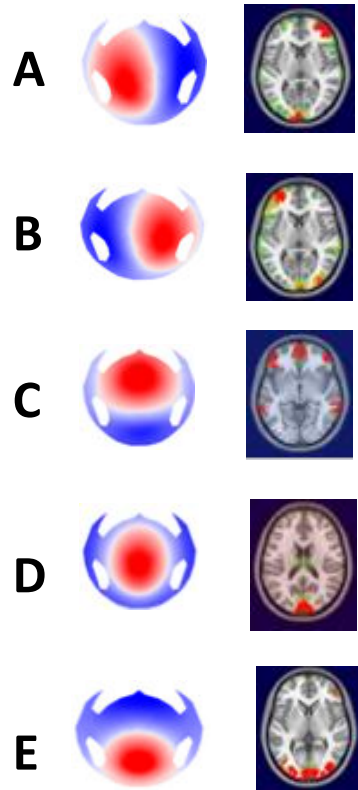
# Source Localization of EEG Microstates



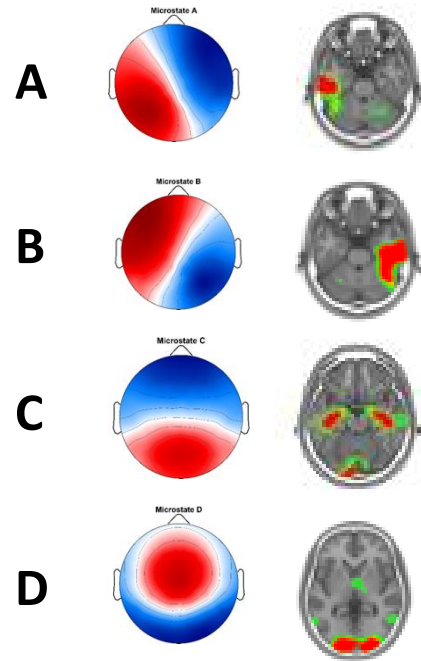
Michel & Bréchet, TINS, 2026  
Tarailis et al., 2025

# Source Localization of EEG Microstates

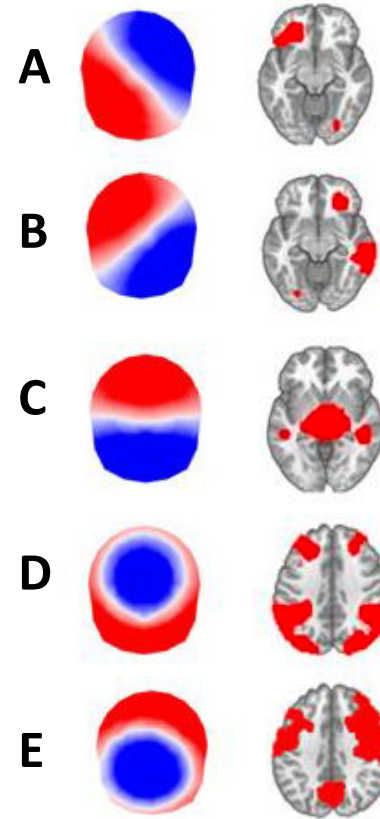
Bréchet et al., 2020  
38 subjects  
256 channel EEG  
SW sleep



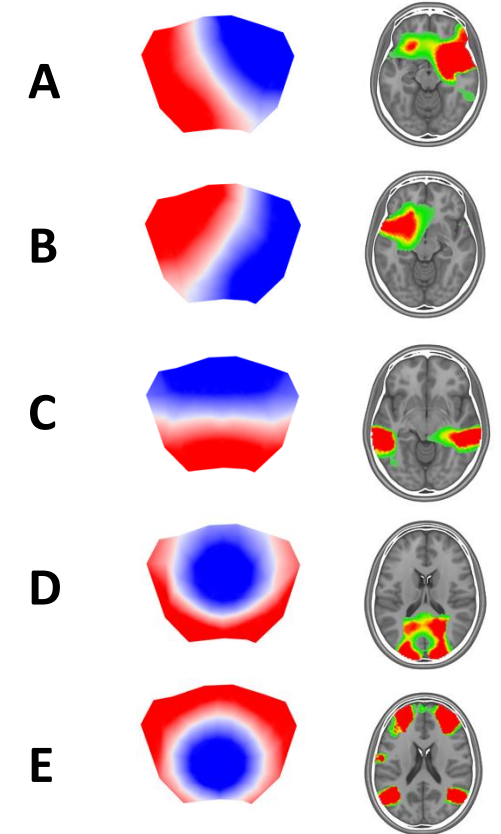
Tarailis et al., 2025  
150 subjects, elderly & MCI  
204 channel EEG  
eyes closed rest



Zanesco et al., in press  
51 young subjects  
128 channel EEG  
eyes open, during task



unpublished  
300 subjects, meditators  
64 channel EEG  
eyes closed meditation



Similar Maps  $\neq$  Similar Sources



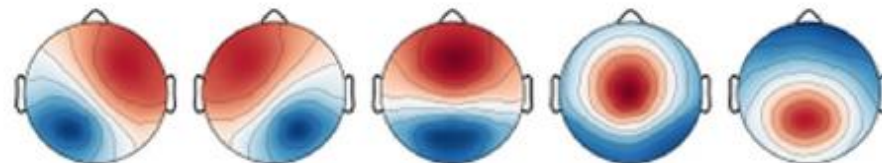
Source localization of the recorded data

# Functional Significance of EEG microstates

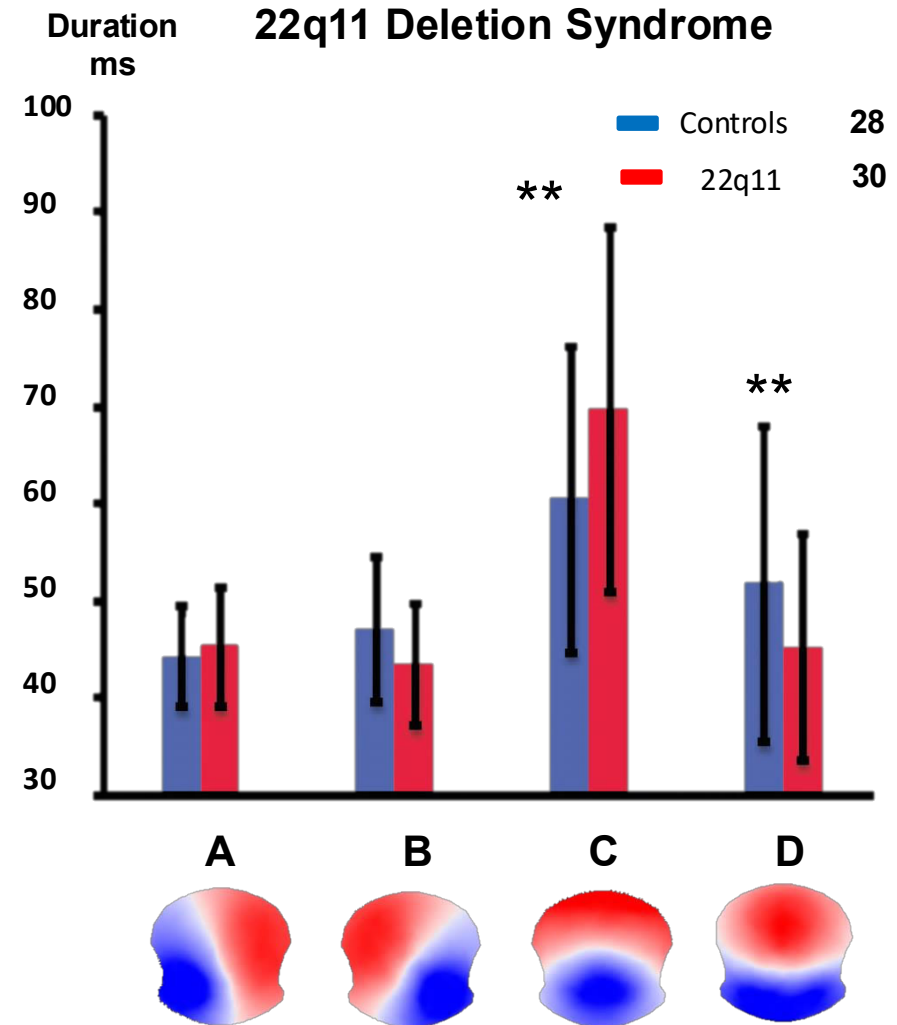
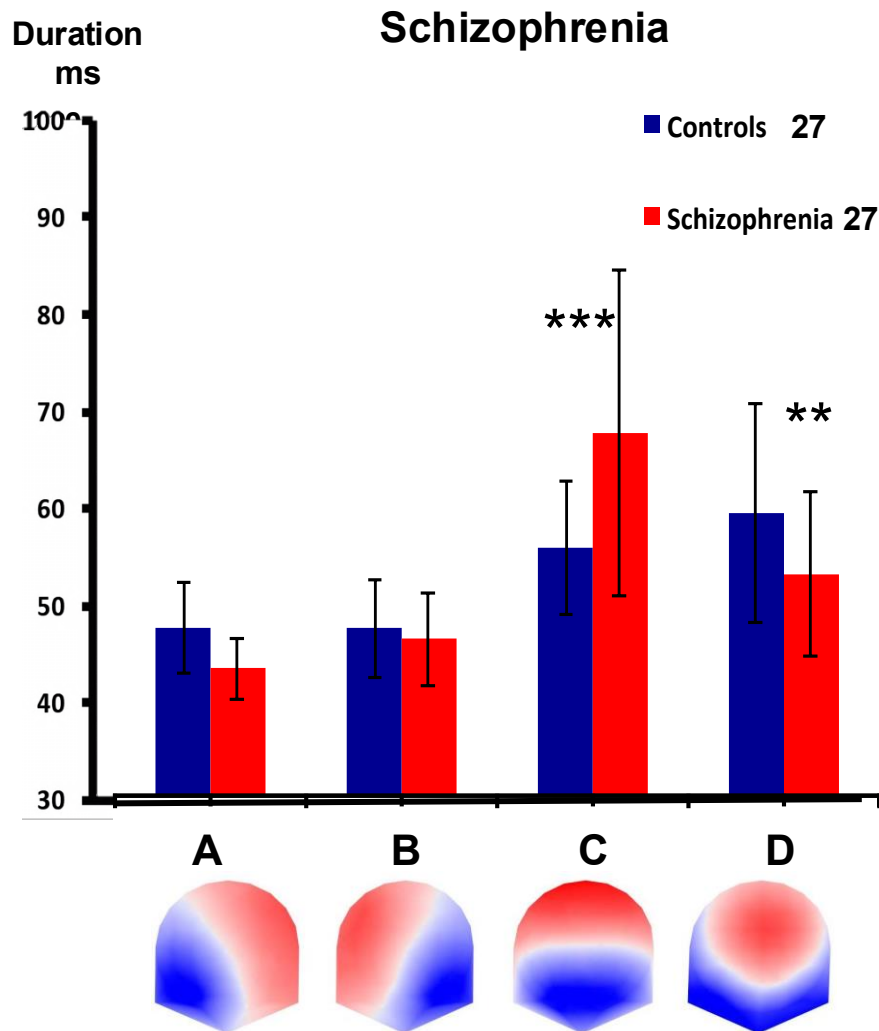
	MS A	MS B	MS C	MS D	MS E
Auditory/Verbal	7	3	1	2	1
Visual	4	15	2	3	1
Memory / Mind-wandering	3	7	9	5	1
Cognition/Attention	4	6	0	15	4
Sensorimotor Self-awareness	1	2	6	7	12

## Review of 50 studies

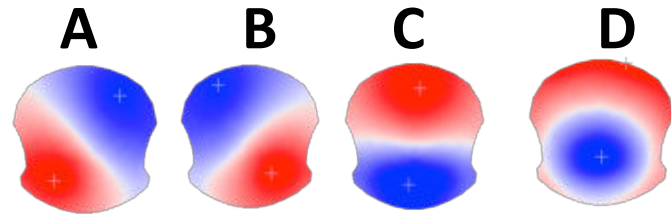
Number of studies attributing a microstate to a functional category



# EEG microstates in Schizophrenia



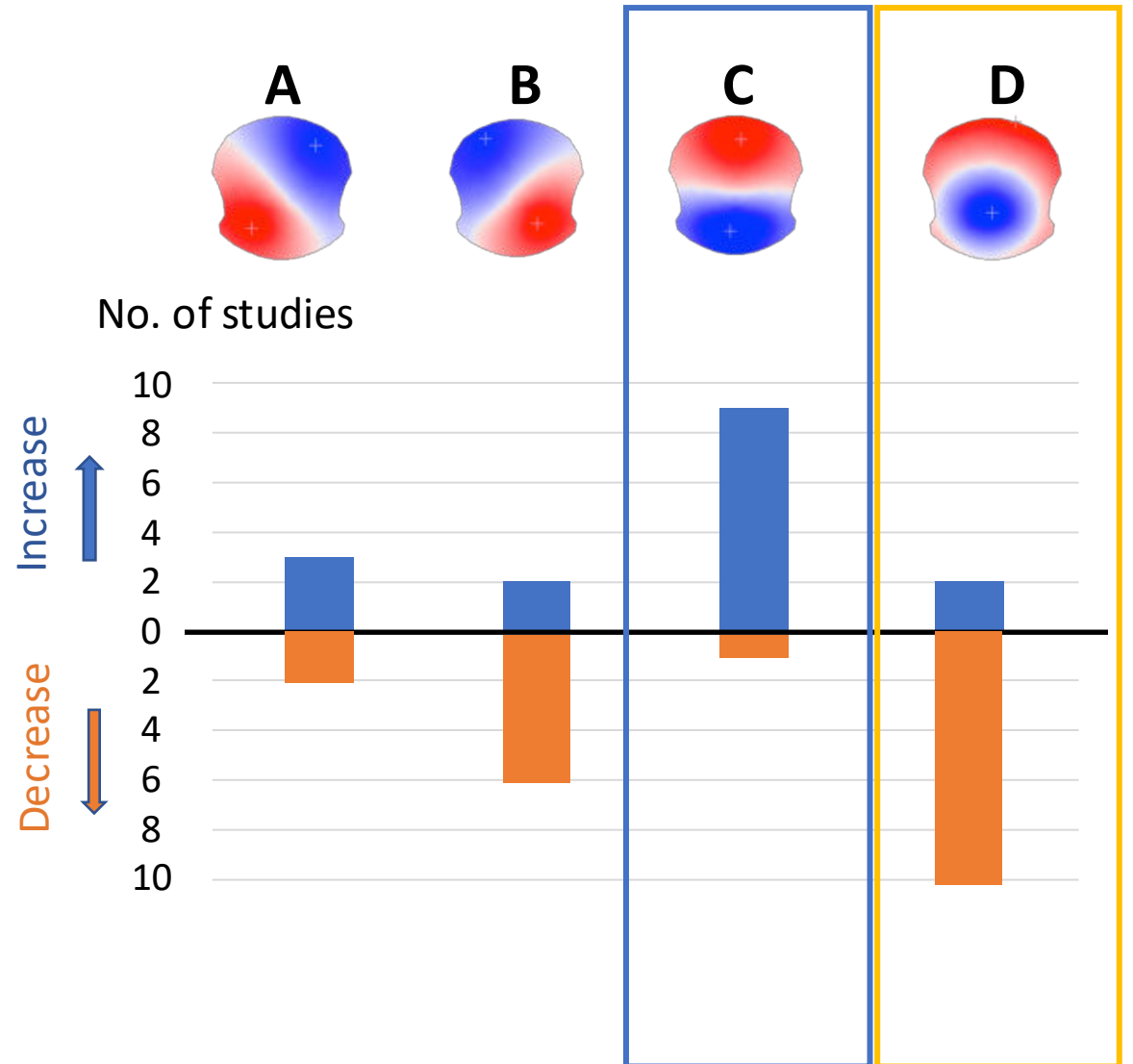
# EEG microstates in Schizophrenia



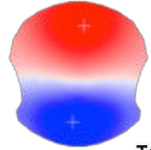
Author	Year	Number	A	B	C	D
König	1999	9				<
Lehmann	2005	27	>	<	>	<
Kikuchi	2007	21			>	<
Nishida	2013	20				<
Andreou	2014	18		>		
Tomescu	2014	30			>	
Tomescu	2015	57			>	<
Giordano	2018	142			>	
Soni	2018	34	<			
Murphy	2020	22	<			
Baraditz	2020	70	>	<		>
da Cruz	2020	101		<	>	<
Wang	2021	20	<	<	>	<
Kim	2021	14				<
Sun	2021	46		<	>	
Sun	2022	23			>	<
Chen	2022	40	<			
Lin	2022	39	<			>
Bissonnette	2022	12	>	>	<	<

**19 Studies**

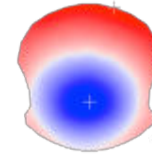
**745 Patients**



# EEG microstates in Schizophrenia: Meta-Analysis



Microstate C Coverage

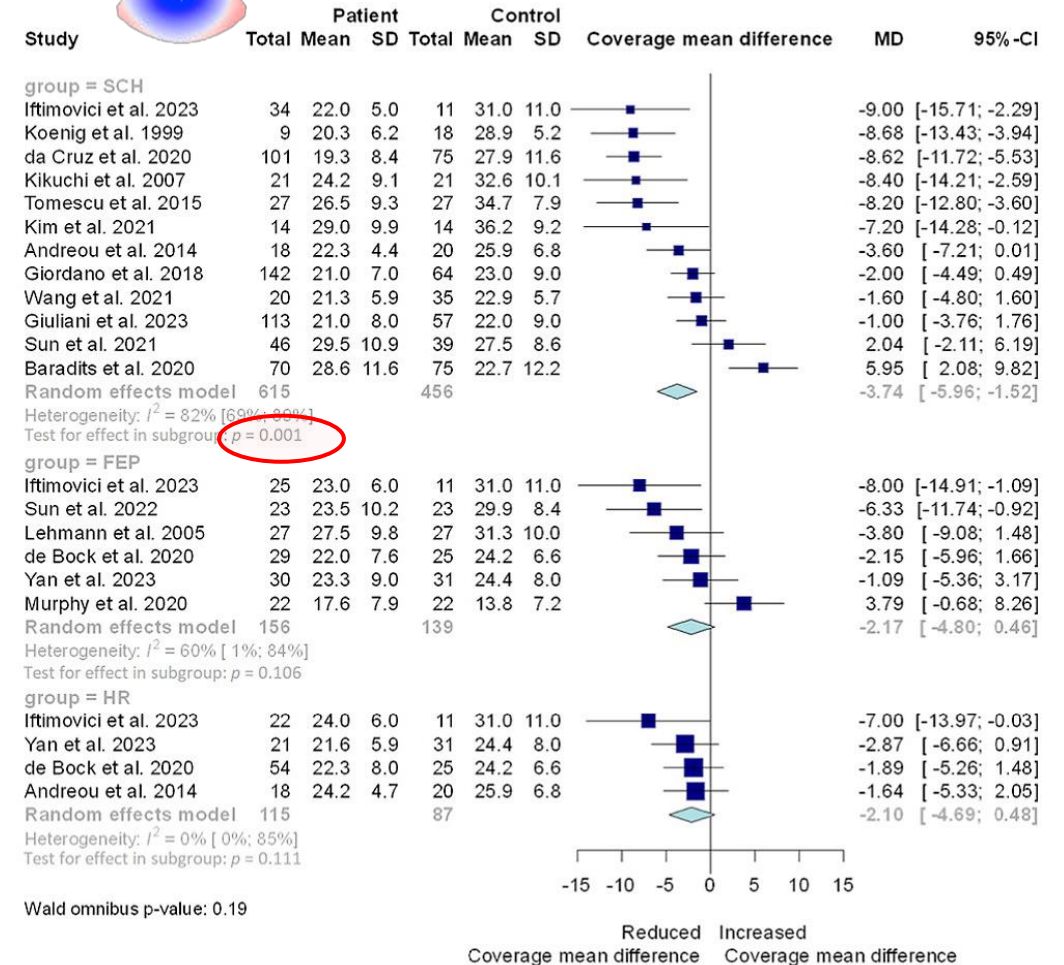
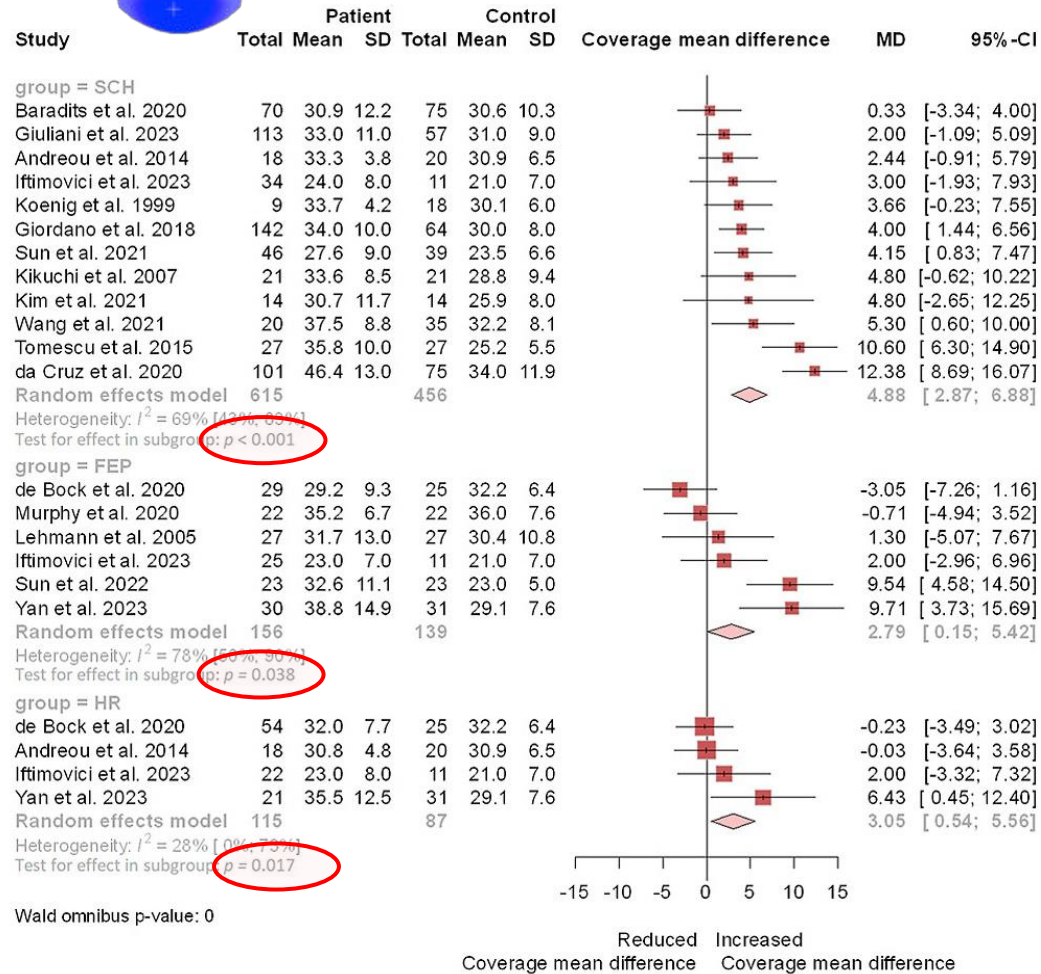


Microstate D Coverage

Schizophrenia

first-episode psychosis

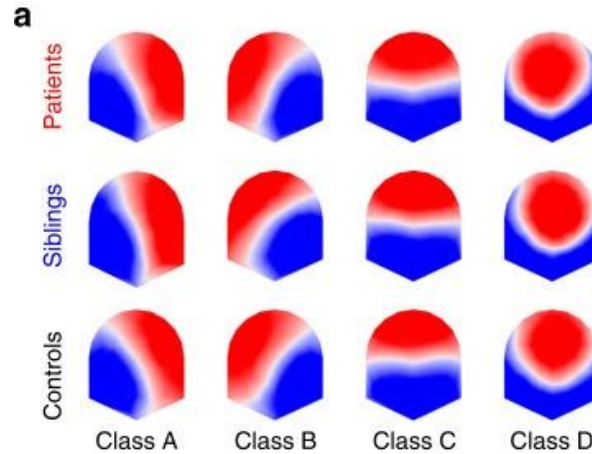
high risk of psychosis



# EEG microstates in Schizophrenia

Da Cruz, Herzog et al.: EEG microstates are a **candidate endophenotype** for schizophrenia.

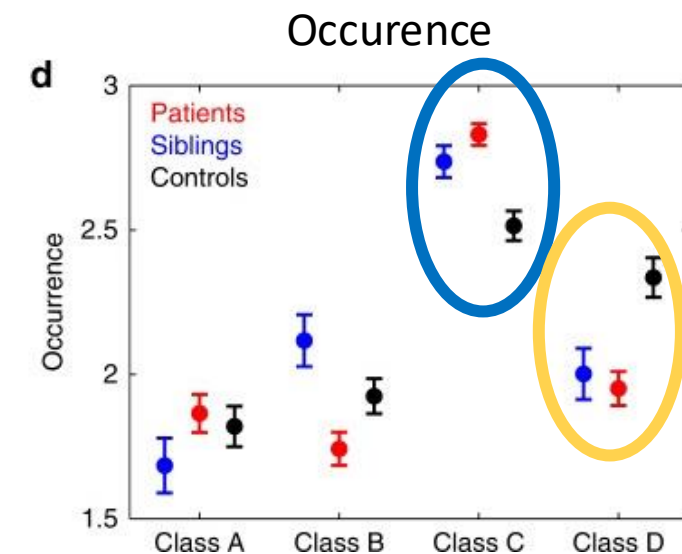
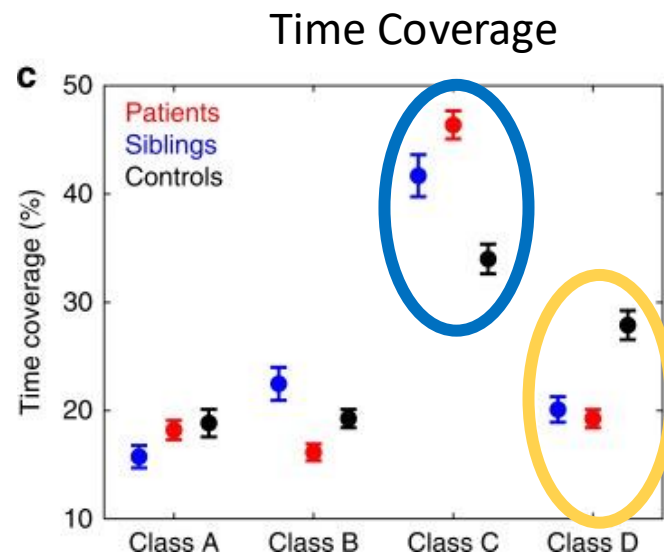
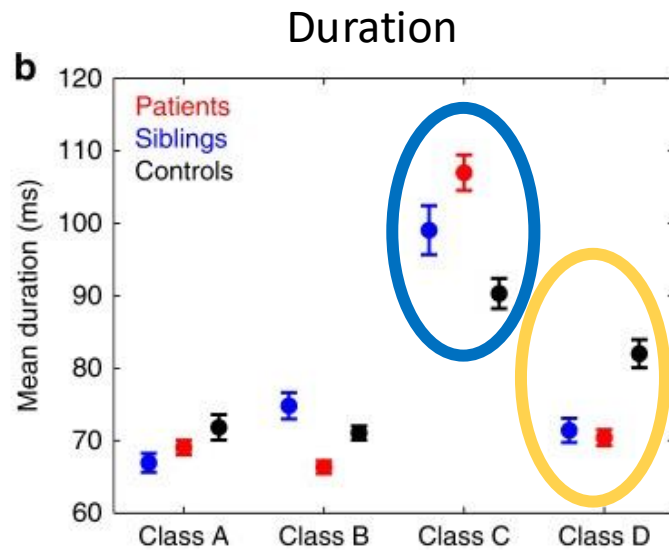
*Nature Communication 2020*



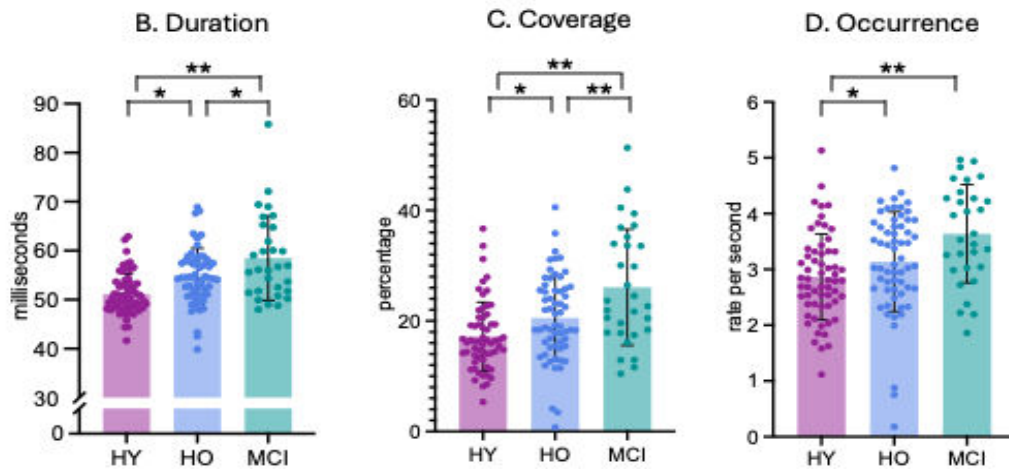
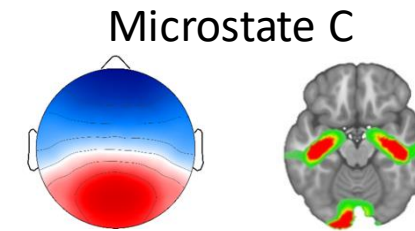
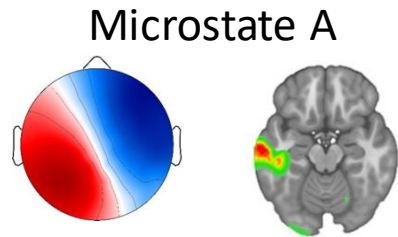
101 Patients

43 Siblings

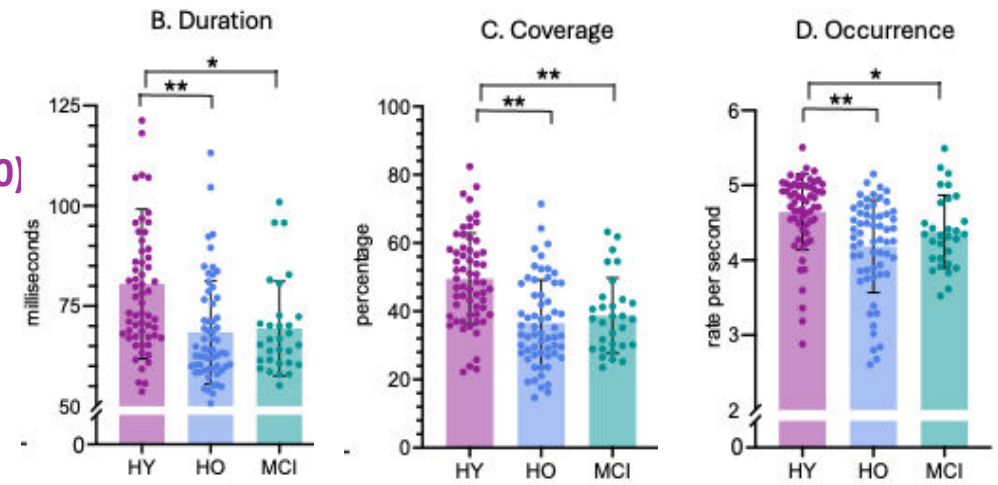
75 Controls



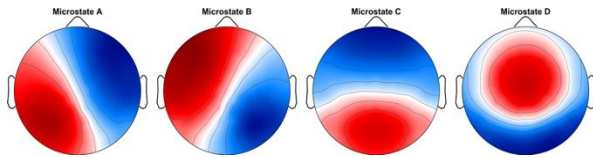
# EEG microstates in Dementia



Healthy Young (N=60)  
Healthy Old (N=60)  
MCI (N=30)



# EEG microstates in Dementia: Meta-Analysis



N = 346 AD patients; 71.2 ± 4.8 years  
 N = 523 MCI patients; 70.5 ± 2.2 years  
 N = 434 healthy controls; 67.4 ± 3.7 years

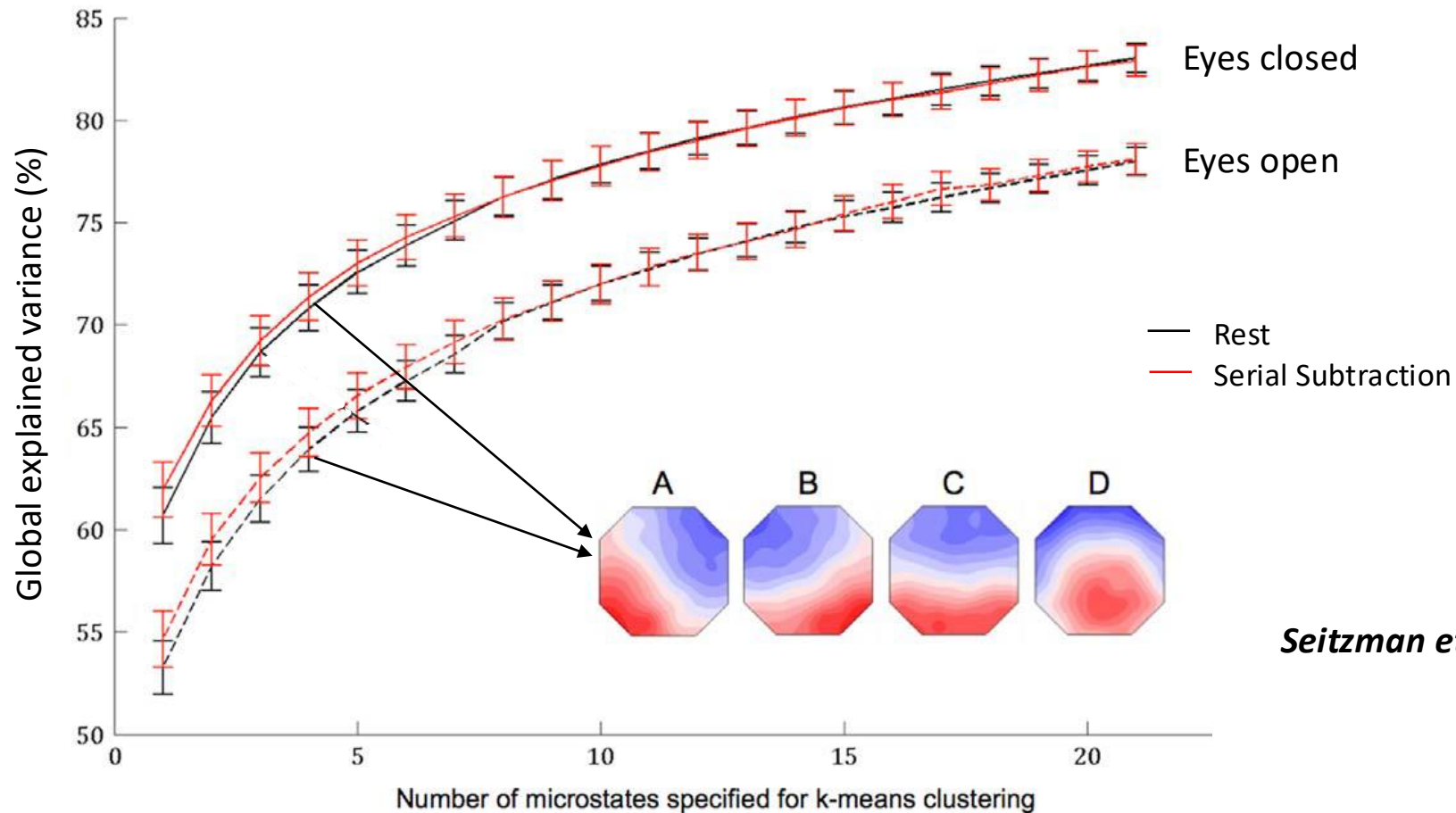
## MILD COGNITIVE IMPAIRMENT

MCI vs. HC	A	B	C	D
Duration	↑ $g = 0.398$	-	-	↓ $g = -0.306$
Occurrence	↑ $g = 0.462$	-	-	↓ $g = -0.190$
Coverage	↑ $g = 0.462$	-	-	↓ $g = -0.319$

## ALZHEIMER'S DISEASE

AD vs. HC	A	B	C	D
Duration	↑ $g = 0.440$	↑ $g = 0.328$	-	-
Occurrence	-	-	↓ $g = -0.213$	↓ $g = -0.304$
Coverage	↑ $g = 0.468$	-	-	-

# How many microstate maps?

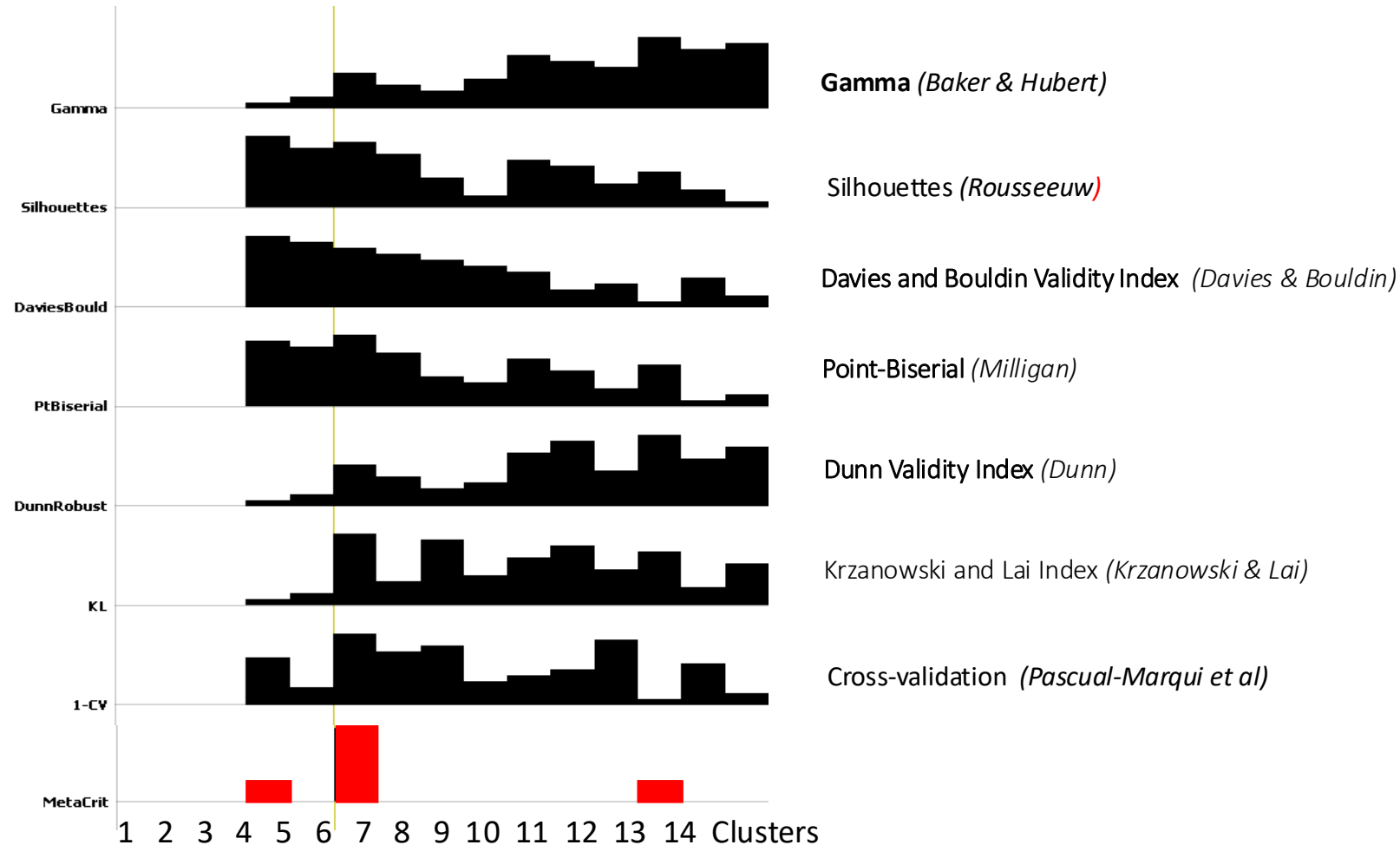


*Seitzman et al., Neuroimage 2017*

The widespread practice of fixing cluster numbers to four for "comparability" goes against data-driven principles

*Michel & Bréchet, TINS, 2026*

# Data-driven Cluster Optimization

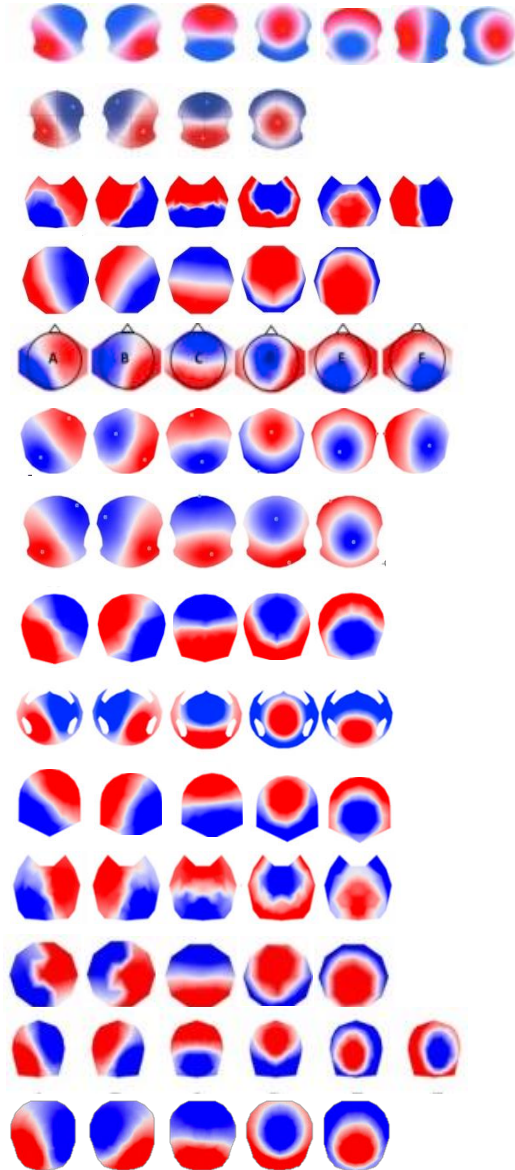


**Meta-Criterion = Median ( Arg Max (criterion))**

Custo et al., 2017  
Bréchet et al., 2019, 2020

# Number of microstate maps

27 studies (2017-2022) using optimization criteria



Custo, 2017

Tomescu, 2018

D’Croz-Baron, 2019

Sverak, 2019

Brechet, 2019

Damborska, 2019

Damborska, 2020

Zanesco, 2020

Brechet, 2020

Zanesco, 2021

D’Croz-Baron, 2021

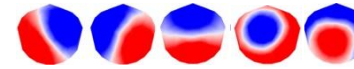
Zanesco, 2021

Zanesco, 2021

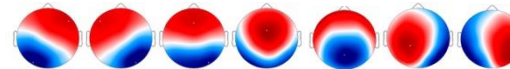
Jabes, 2021



Deolindo, 2021



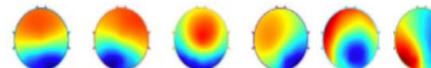
Bochet, 2021



Tarailis, 2021



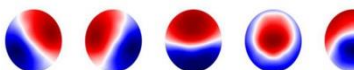
May, 2021



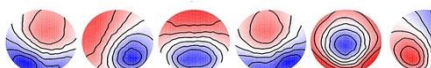
Gold, 2021



Tomescu, 2022



Hao, 2022



Thiriaux, 2022



Qin, 2022



Bagdasarov, 2022



Ferat, 2022



Artoni, 2022



Linton, 2022

# All Here- An Organisation dedicated to Meditation Research and Applications

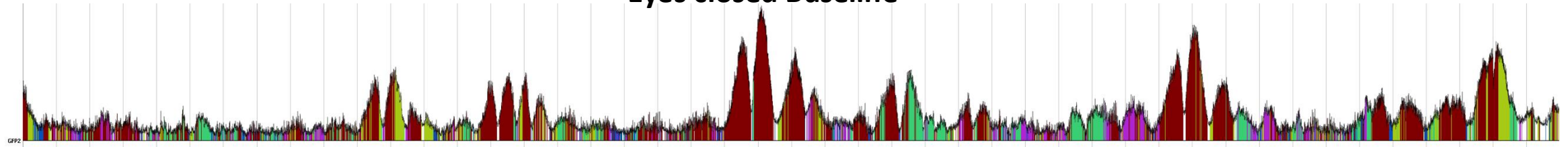


All Here Meditation Institute in  
Geneva, Switzerland  
[www.allhere.org](http://www.allhere.org)

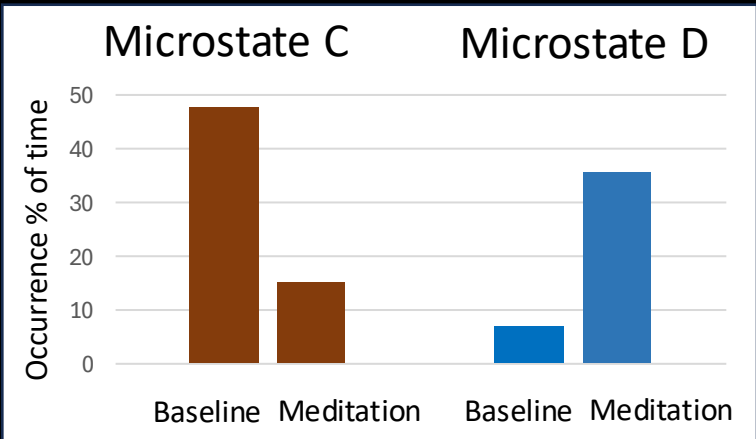
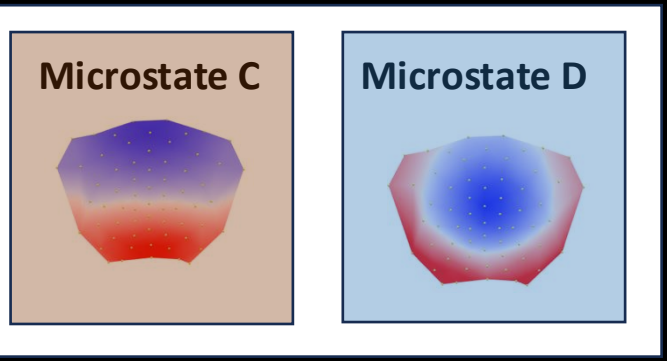
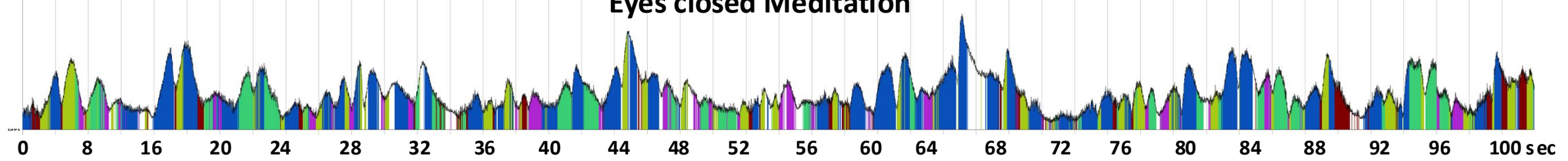


# Yogic Samadhi practitioner (>20 years of experience)

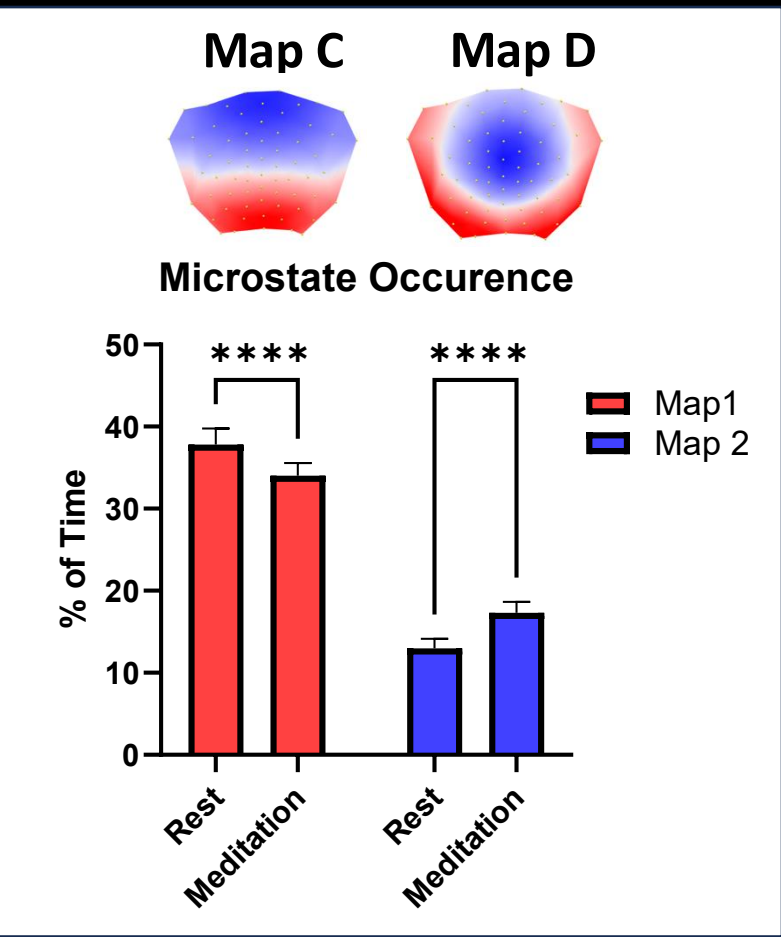
Eyes closed Baseline



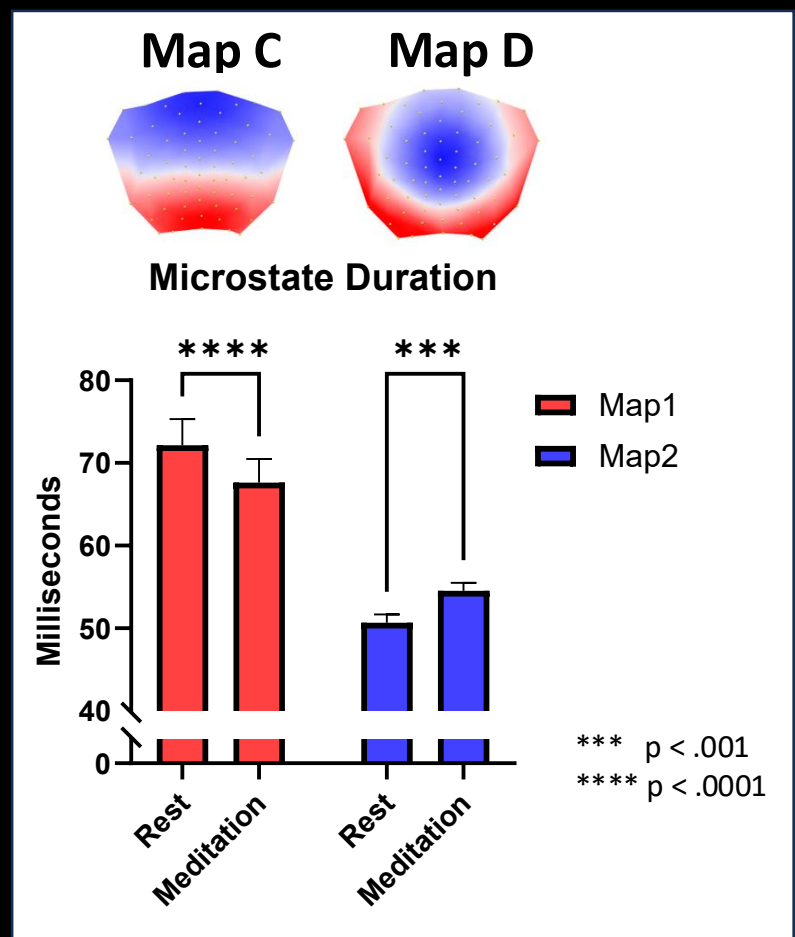
Eyes closed Meditation



# N = 32 beginners following guided focused attention meditation (observing the air)



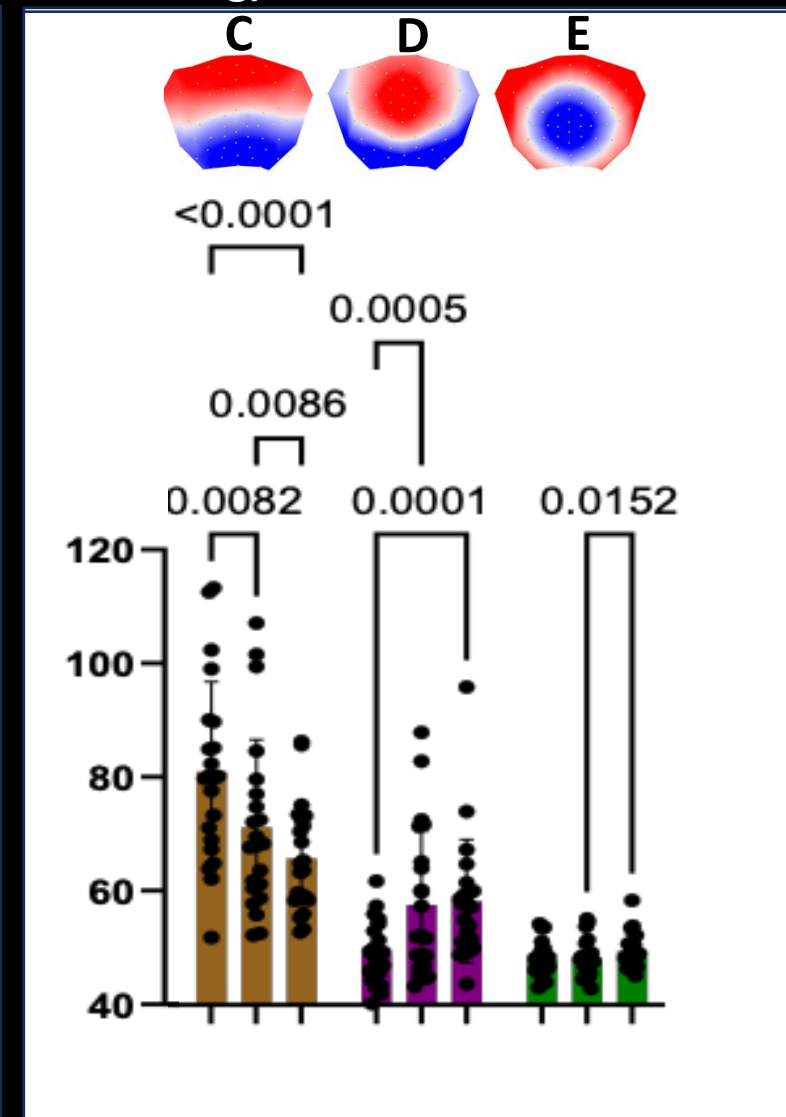
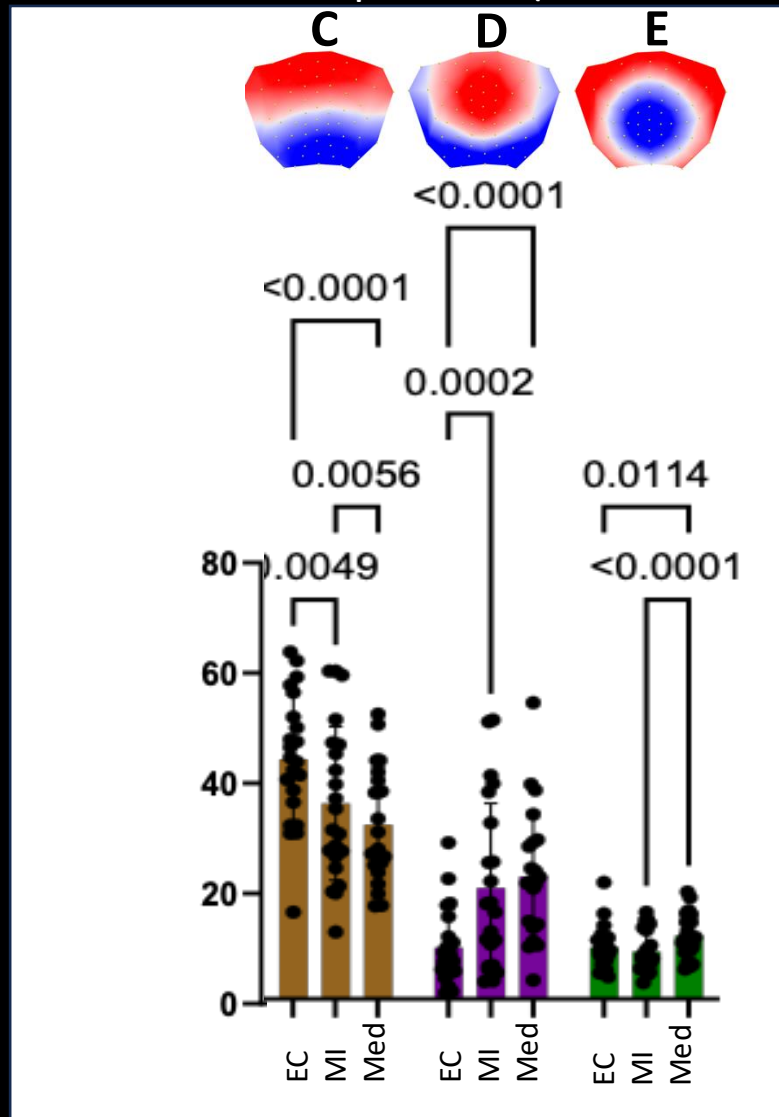
ANOVA  
Interaction Condition \* Map:  
F (1, 33) = 45.93; p<0.0001



ANOVA  
Interaction Condition \* Map:  
F (1, 33) = 36.93; p<0.0001

# N = 22 expert meditators

## Ānāpānasati (mindfulness of breathing) meditation



ANOVA

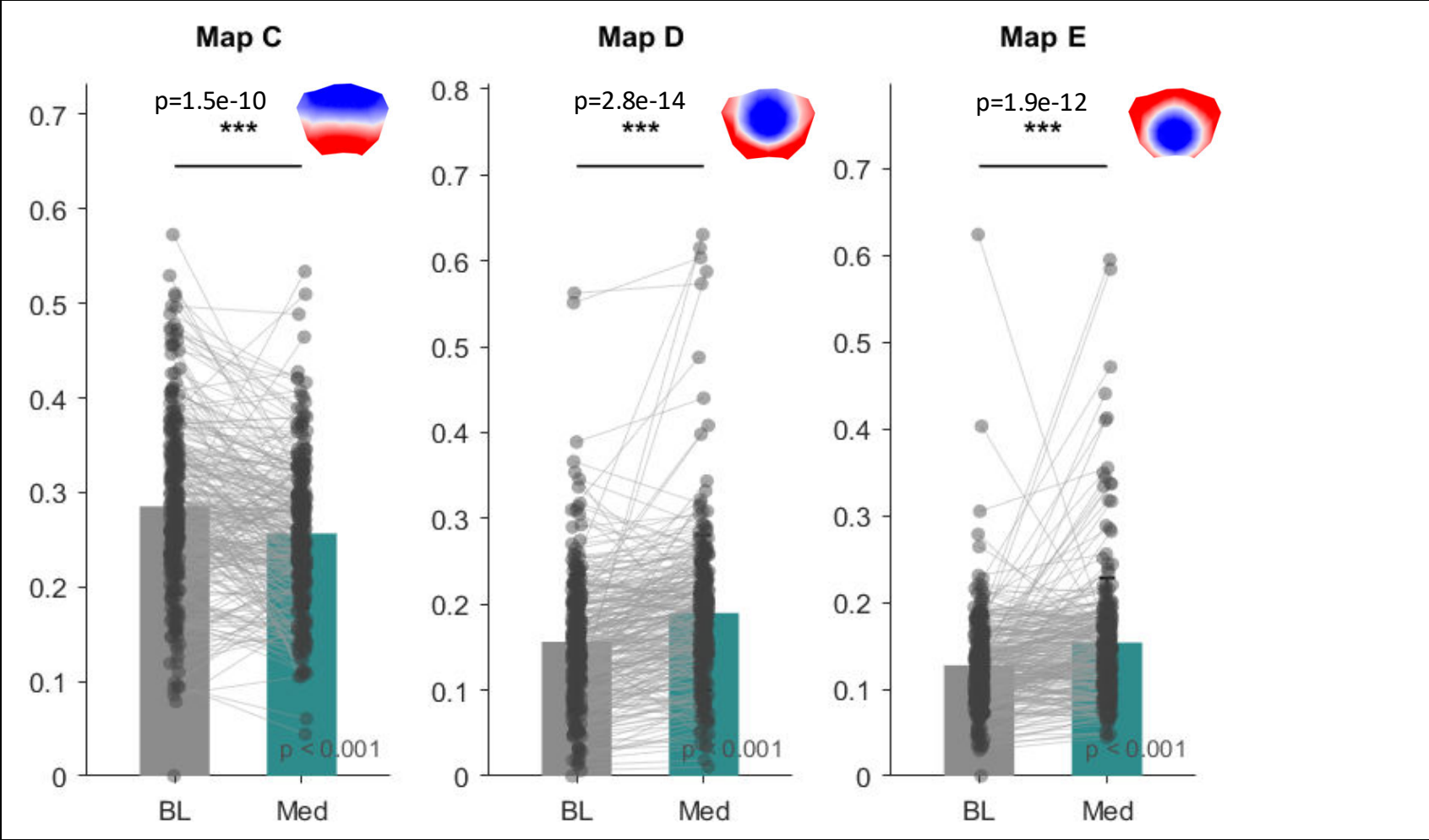
Interaction Condition \* Map:  
F (2.5,53) = 17.46; p<0.0001

ANOVA

Interaction Condition \* Map:  
F (1.7, 36) = 31.21 p<0.0001

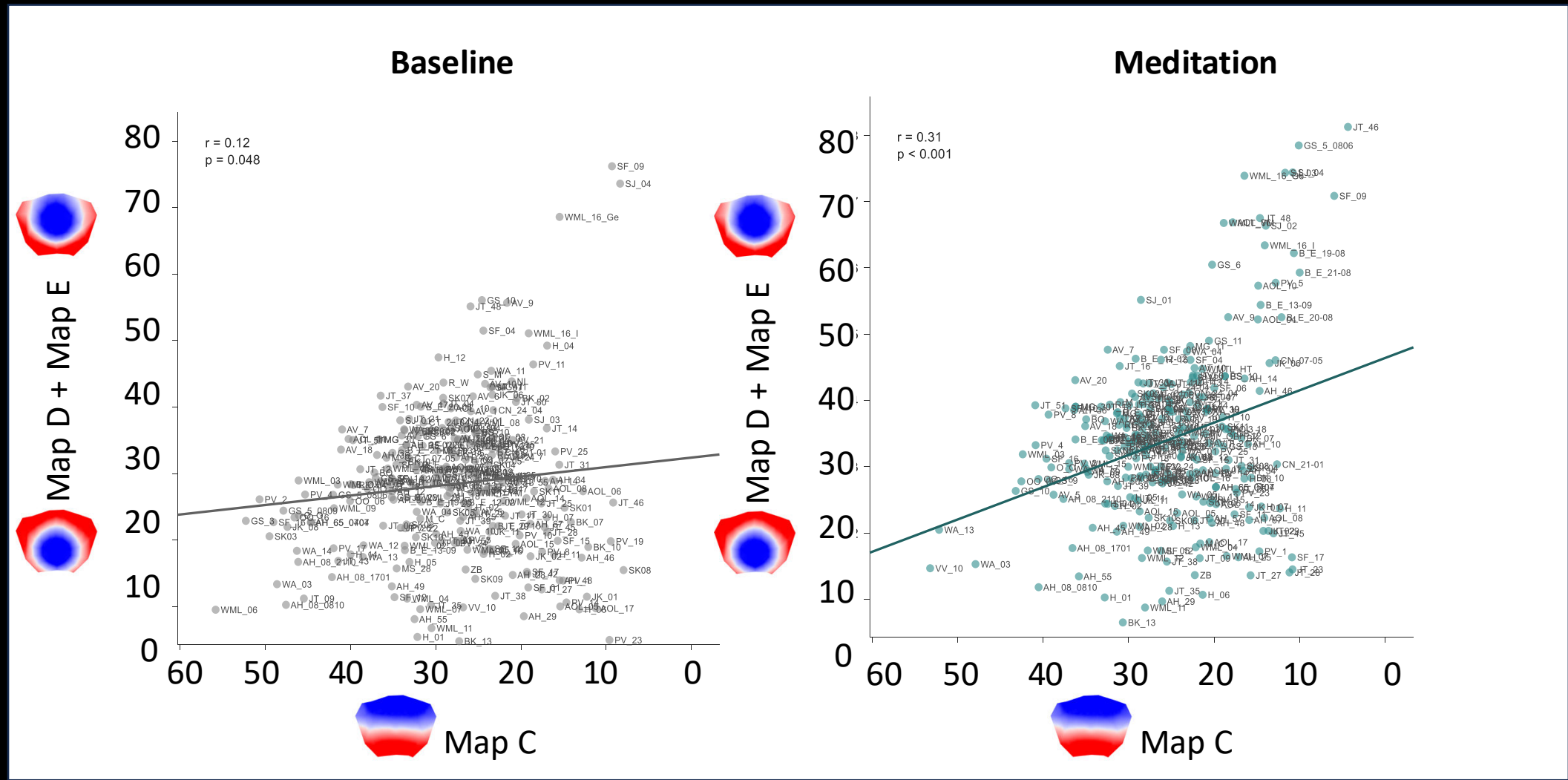


**N = 300 participants**  
**different cultures, different meditation techniques**  
**different expertise (beginners to highly experienced monks)**





**N = 300 participants**  
**different cultures, different meditation techniques**  
**different expertise (beginners to highly experienced monks)**



# The time course of EEG Microstates

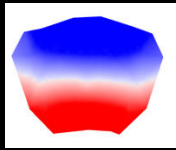


N = 300 participants

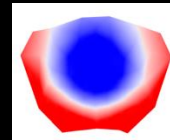
different cultures, different meditation techniques

different expertise (beginners to highly experienced monks)

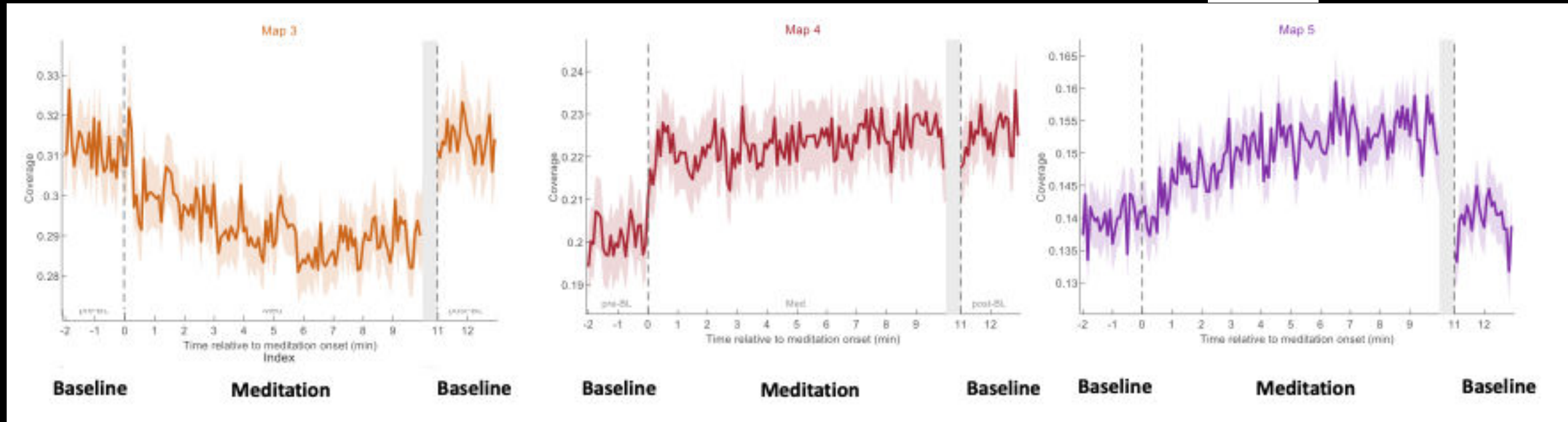
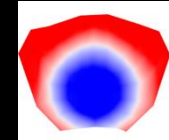
Map C



Map D



Map E

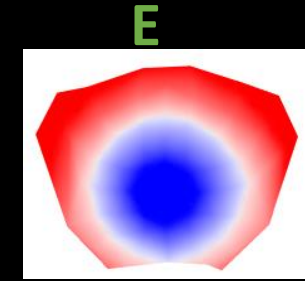
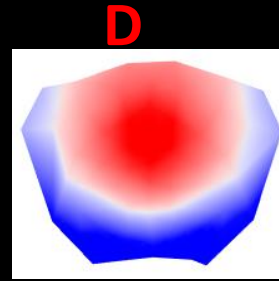
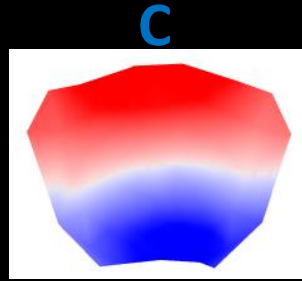


# EEG Microstates during Meditation

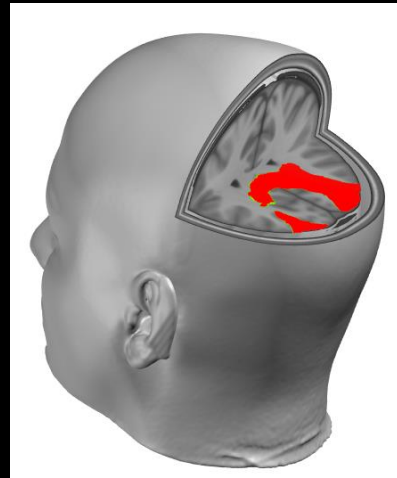
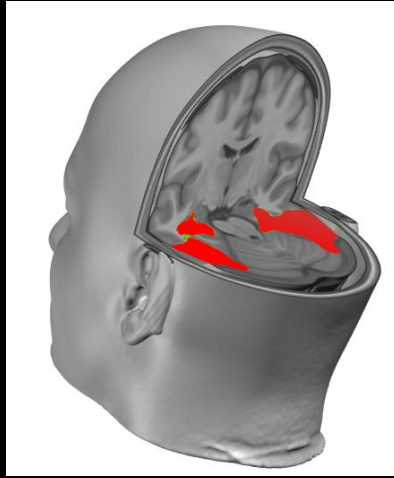
A L L H E R E



Microstate Map



Source Localization



Medial/lateral temporal cortex  
(hippocampus,  
parahippocampal gyrus)

Posterior medial cortex  
(PCC/precuneus)

Left Temporoparietal Junction (TPJ)  
Dorsolateral Prefrontal Cortex (DLPFC)  
Left ventromedial temporal lobe

Function

**Mind Wandering**  
Memory retrieval  
Self-referential  
thought

**Attention**  
Internally  
directed  
cognition

**Self-awareness**  
Interoception  
Self-monitoring

# The Functional Brain Mapping Lab



UNIVERSITÉ  
DE GENÈVE

FACULTÉ DE MÉDECINE

A L L H E R E

