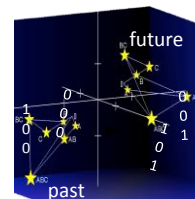


Quantifying Consciousness

Mélanie Boly, MD, PhD



**Neurology & Psychiatry Departments,
University of Wisconsin, Madison**



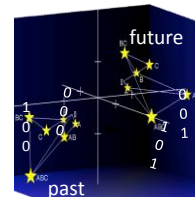
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1

Consciousness ≠ Responsiveness



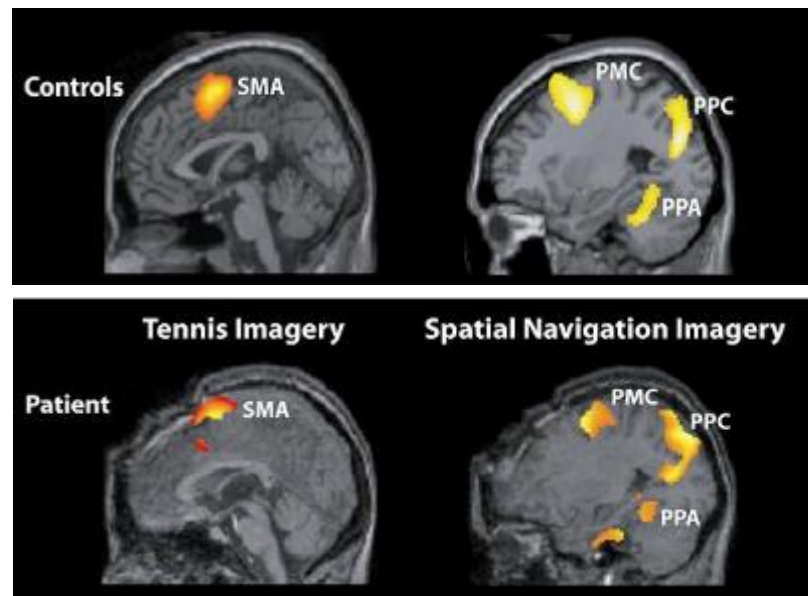
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Common caveat in evaluating NCC: Unresponsiveness \neq Unconsciousness

Example: Imagine playing tennis in the 'vegetative state'



15-20%

Common caveat in evaluating NCC: Unresponsiveness ≠ Unconsciousness

*Consciousness is what disappears during dreamless sleep.
However, subjects awoken from sleep report dreaming 2/3 of time!*

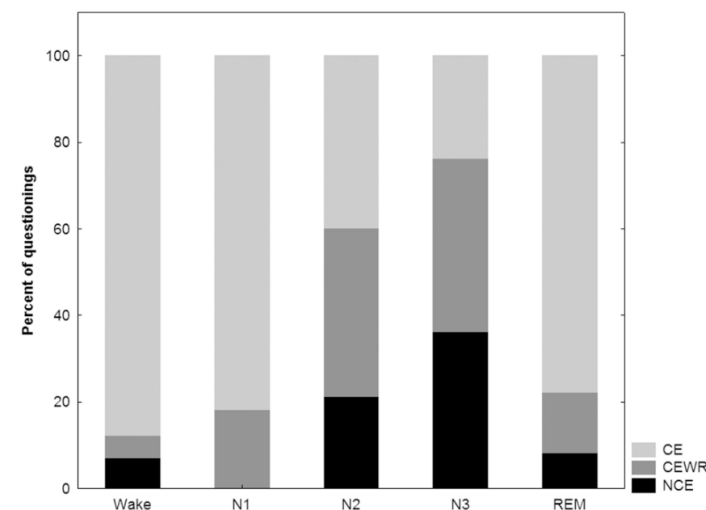
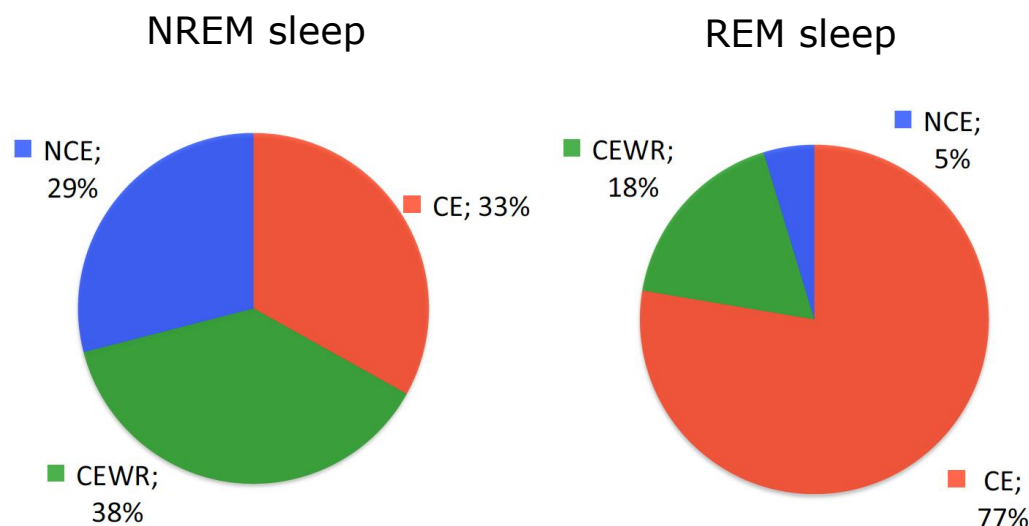
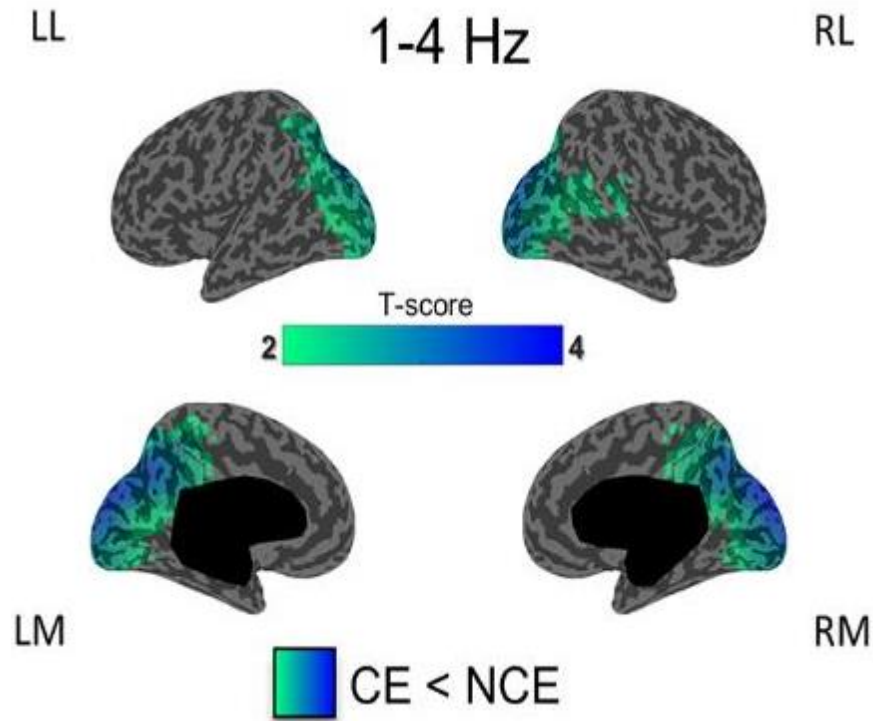


FIGURE 4 | Proportion of conscious experiences (CE), conscious experiences without recall (CEWR) and no conscious experiences (NCE) across stages.

CE: conscious experience
NCE: no conscious experience
CEWR: conscious experience without recall

NCC: a within-state, no-task paradigm

NREM sleep

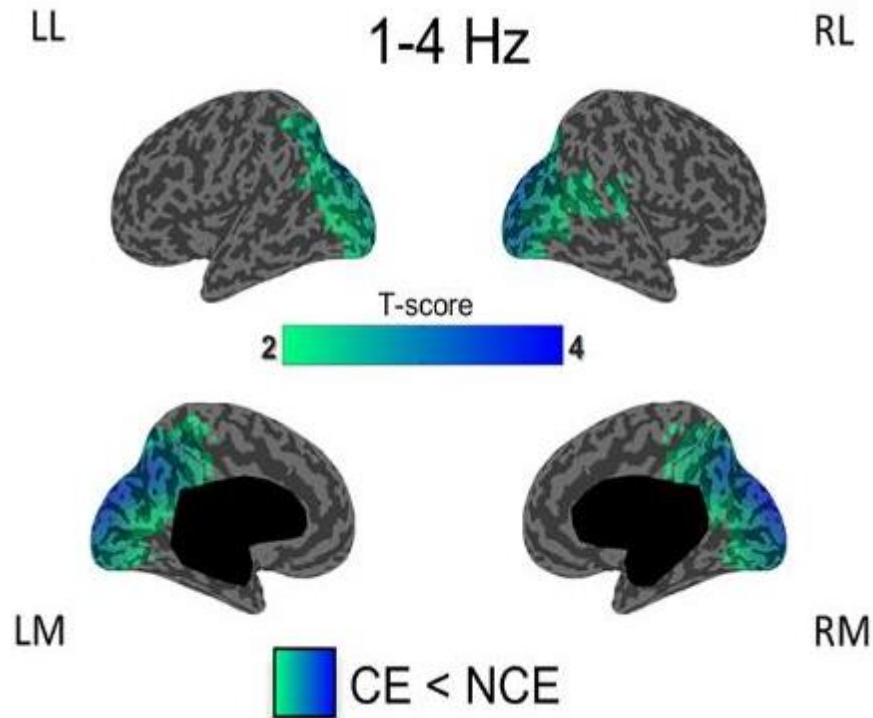


*CE: awakening with report
of Conscious Experience*

*NCE: awakening with
report of No Conscious
Experience*

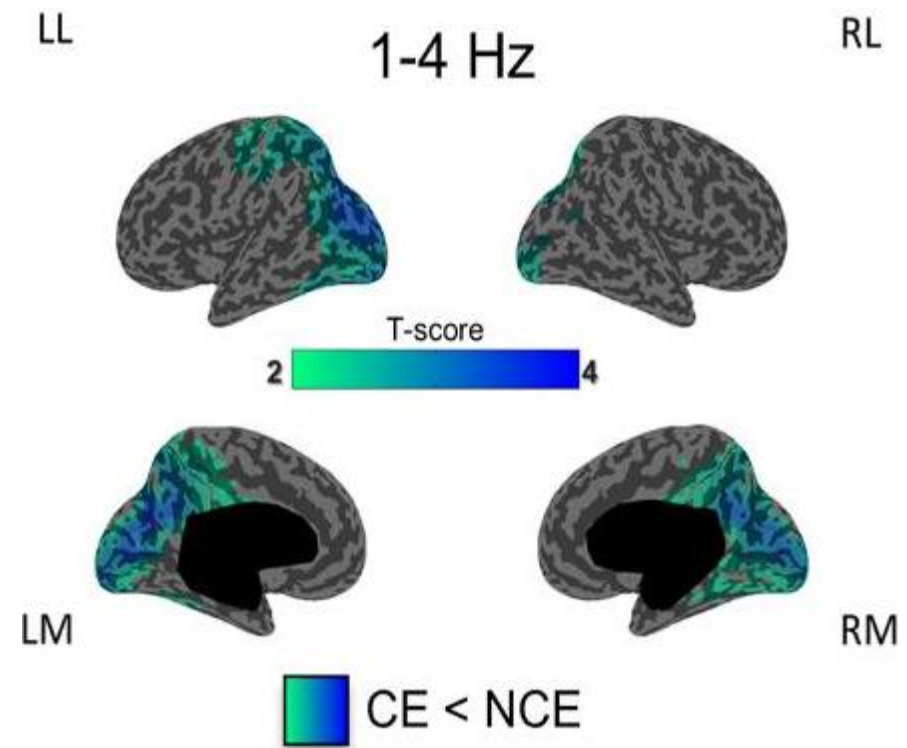
NCC: a within-state, no-task paradigm

NREM sleep



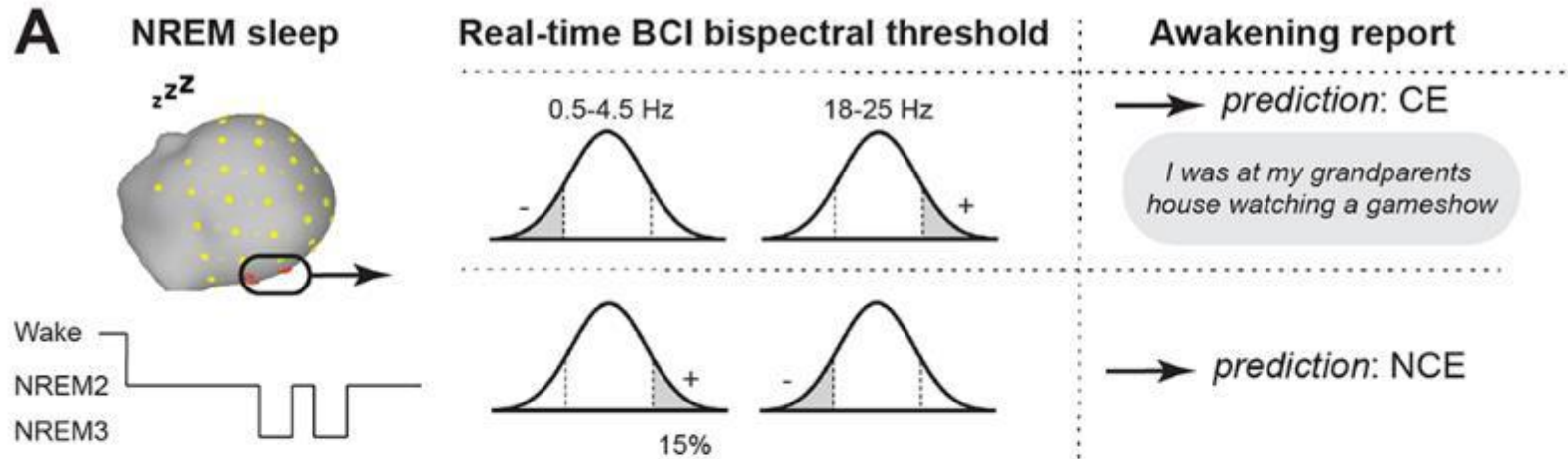
*CE: awakening with report
of Conscious Experience*

REM sleep

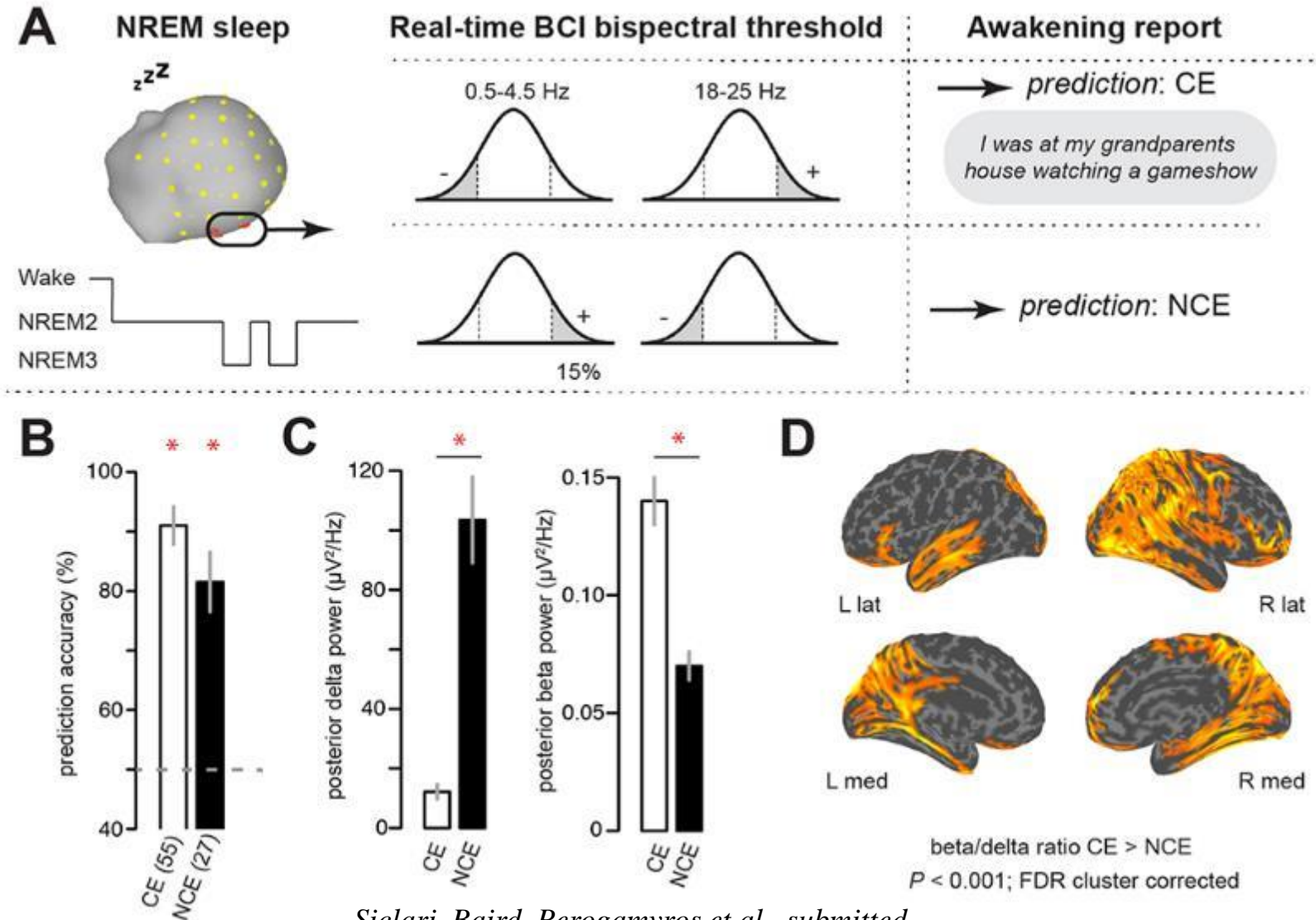


*NCE: awakening with
report of No Conscious
Experience*

NCC: on-line prediction of consciousness/unconsciousness in NREM sleep



NCC: on-line prediction of consciousness/unconsciousness in NREM sleep

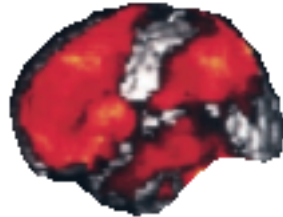


Siclari, Baird, Perogamvros et al., submitted

State-based approaches

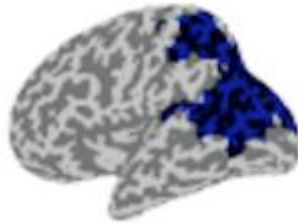
d

PET



but...

EEG



consciousness during
NREM & REM sleep

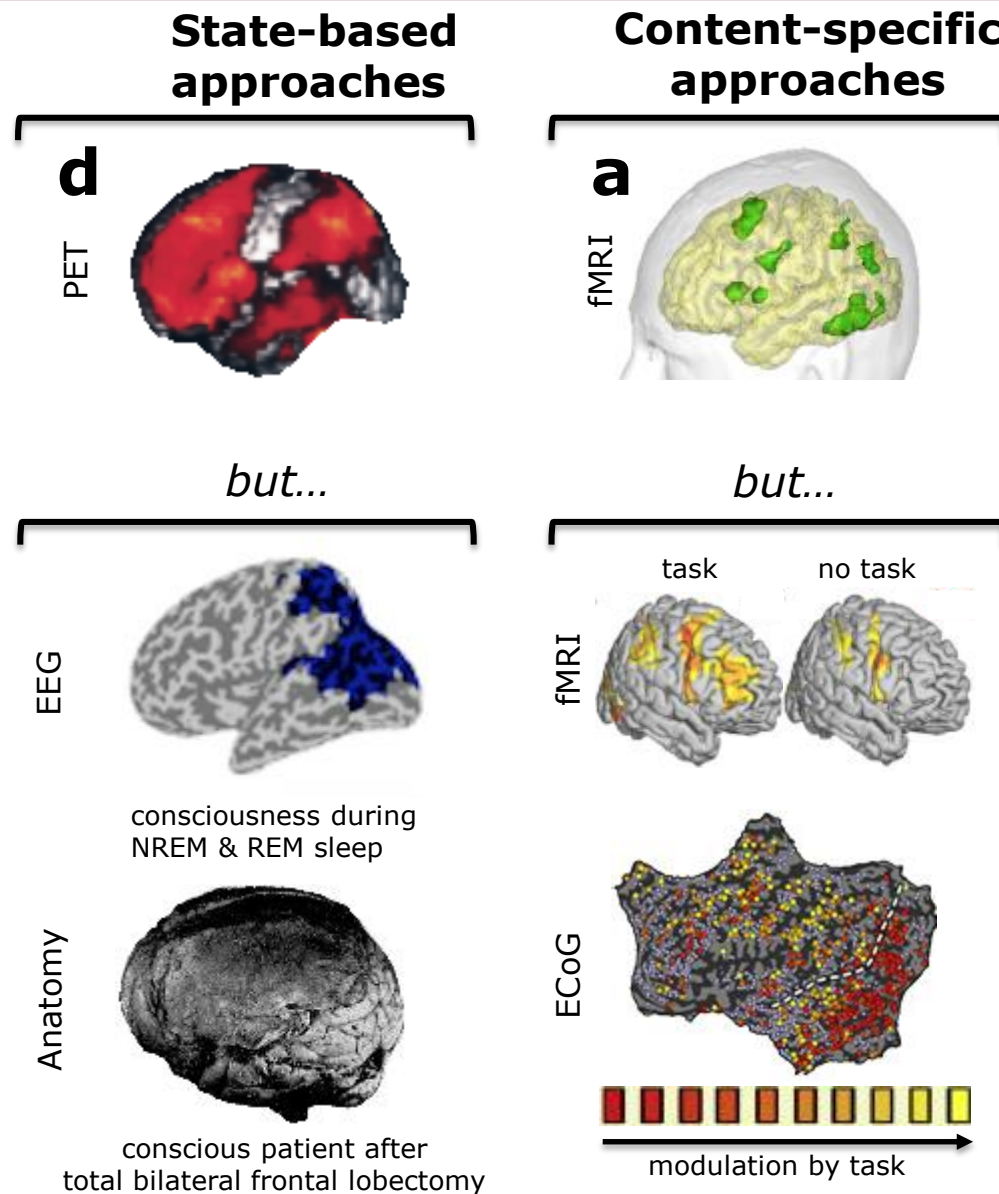
Anatomy



conscious patient after
total bilateral frontal lobectomy

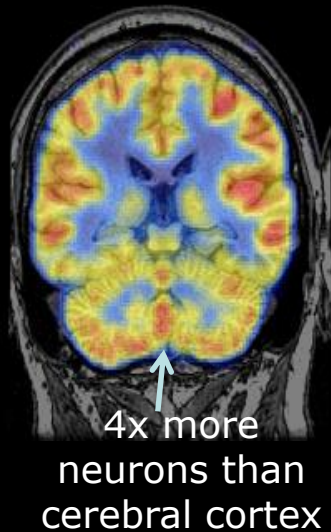
"Patient A., after complete bilateral frontal lobe resection, once 'toured the Neurological Institute in a party of five, two of whom were distinguished neurologists, and none of them noticed anything unusual for more than an hour'."

Brickner, JAMA 1952

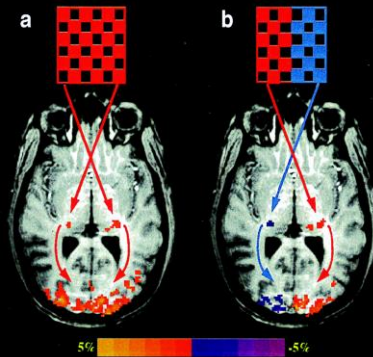


Hard questions

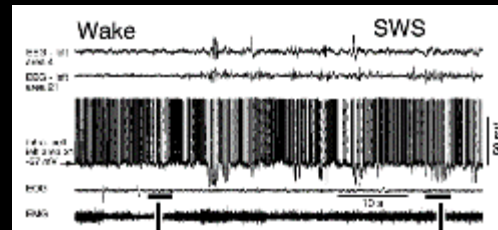
Why not the cerebellum?



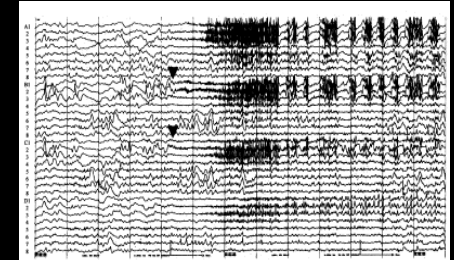
Why not afferent pathways?



Why not the cortex during deep sleep?

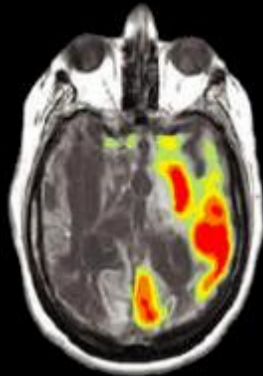


Why not the cortex during a seizure?



Hard calls

Brain “islands” in a ‘vegetative’ subject



Ketamine anesthesia



Sleepwalking

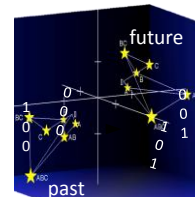


②

Quantifying consciousness From First Principles: Integrated Information Theory



**Neurology & Psychiatry Departments,
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Integrated Information Theory

A principled, systematic approach to a scientific explanation of consciousness should start from consciousness itself.

Fundamental properties of (any) conscious experience:



Information: Experience is specific, being composed of a particular set of phenomenal distinctions (qualia), bound together in various ways, which make it what it is and different from other experiences



Integration: Experience is unitary, meaning that it is composed of a set of phenomenal distinctions, bound together in various ways, that is irreducible to non-interdependent subsets.

AXIOMS => POSTULATES

Integration and Differentiation in neurophysiological terms

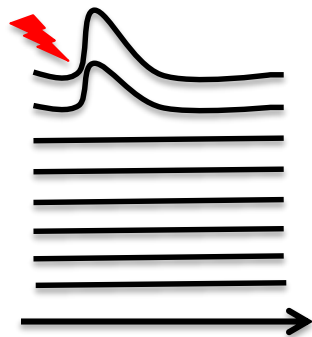
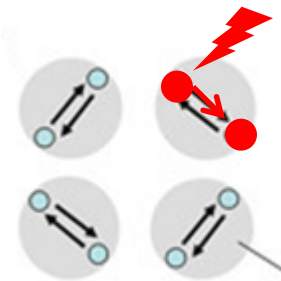
The theory thus predicts that for a system to specify a high level of consciousness (high Φ), it should be both integrated and differentiated.

One can also formally prove mathematically that differentiation provides a bound for Φ (Marshall et al., in press). Thus to have high Φ requires high differentiation.

Theoretical predictions: TMS-EEG

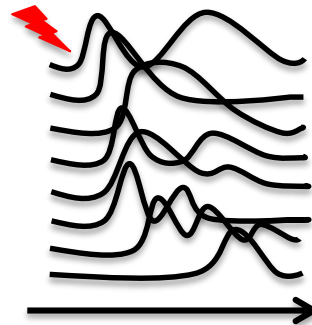
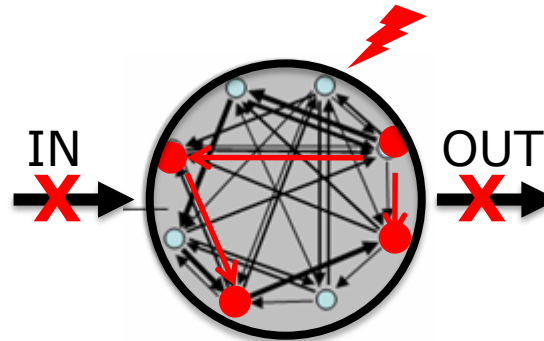
Unconscious:

No Integration



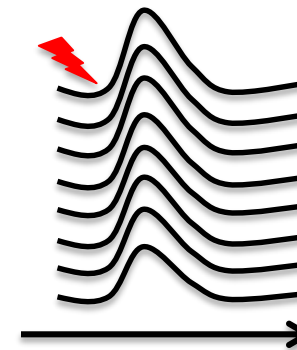
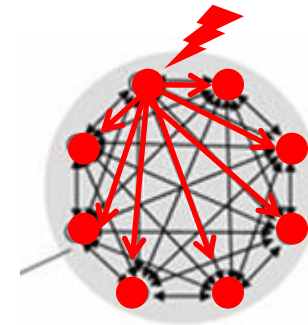
CONSCIOUS:

Integration and Differentiation

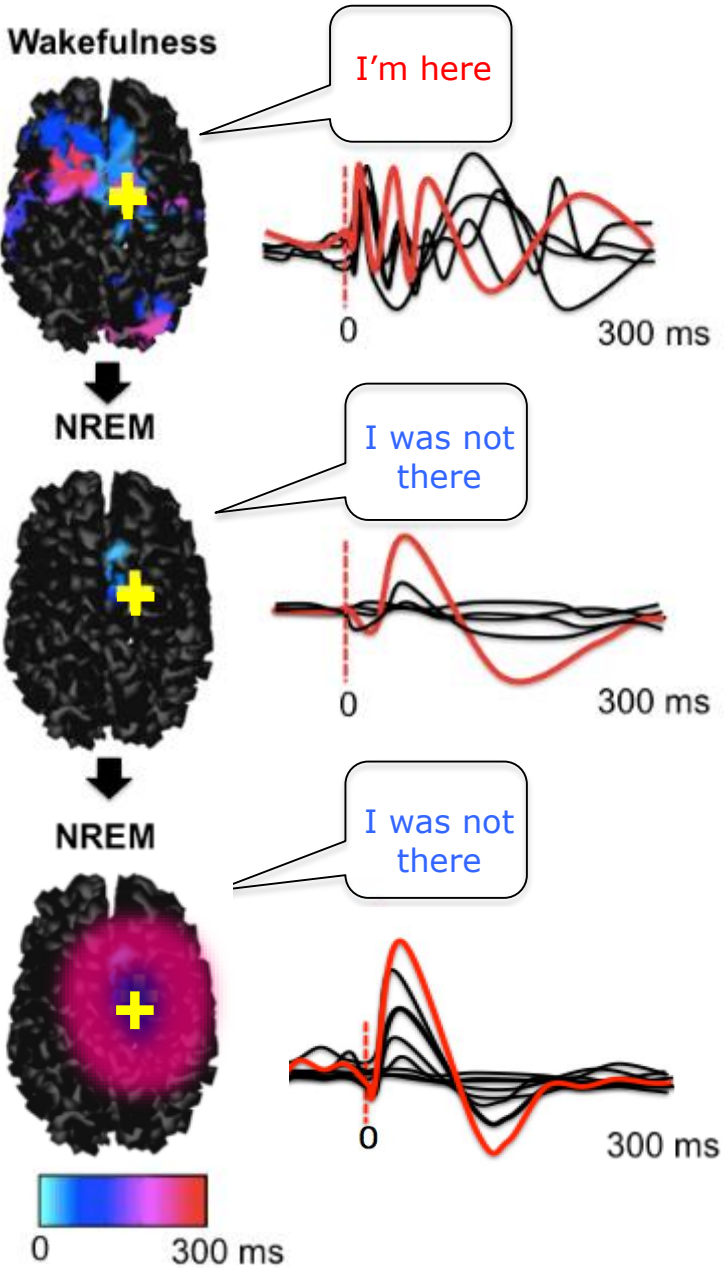


Unconscious:

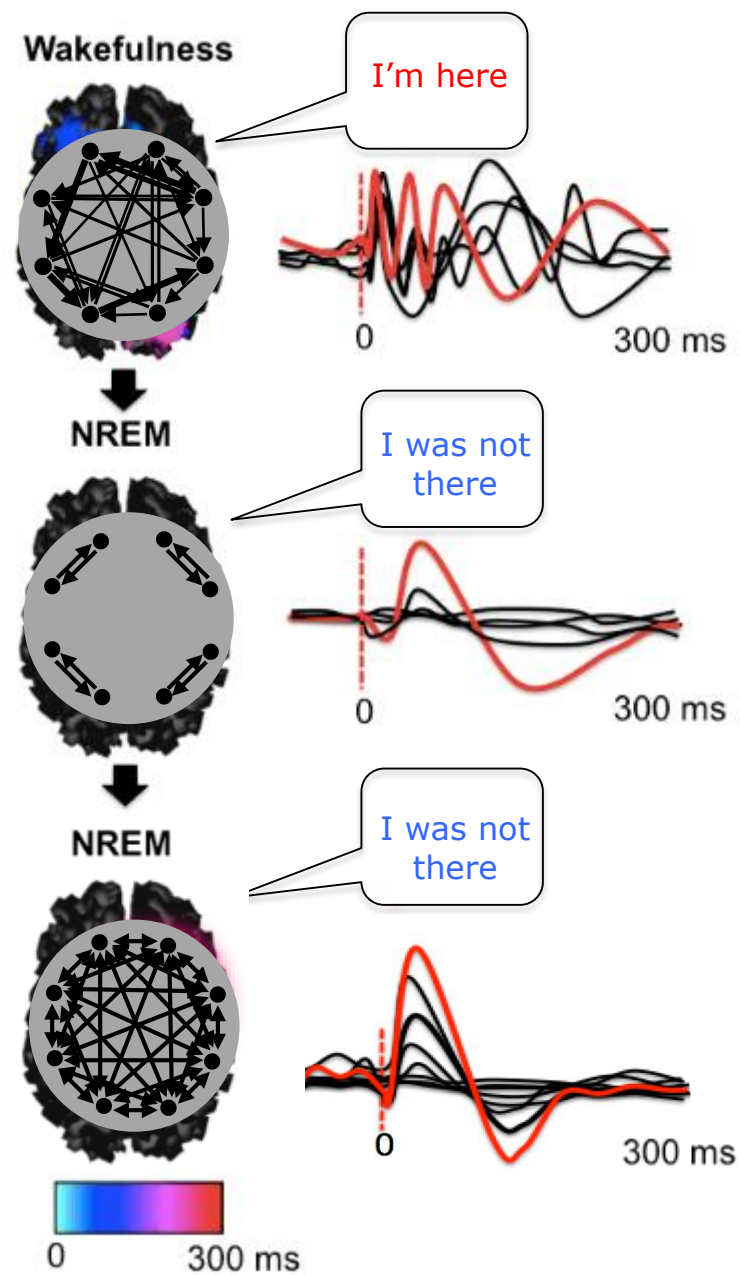
No Differentiation



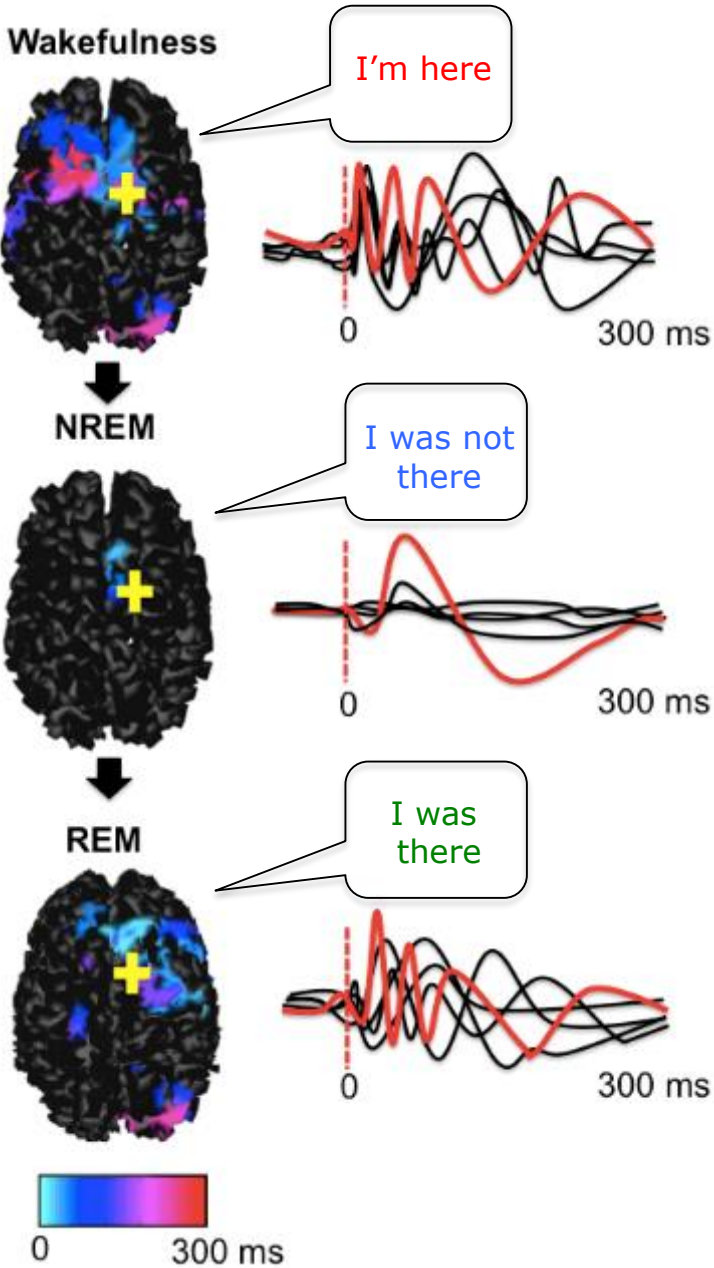
From Wakefulness to Sleep



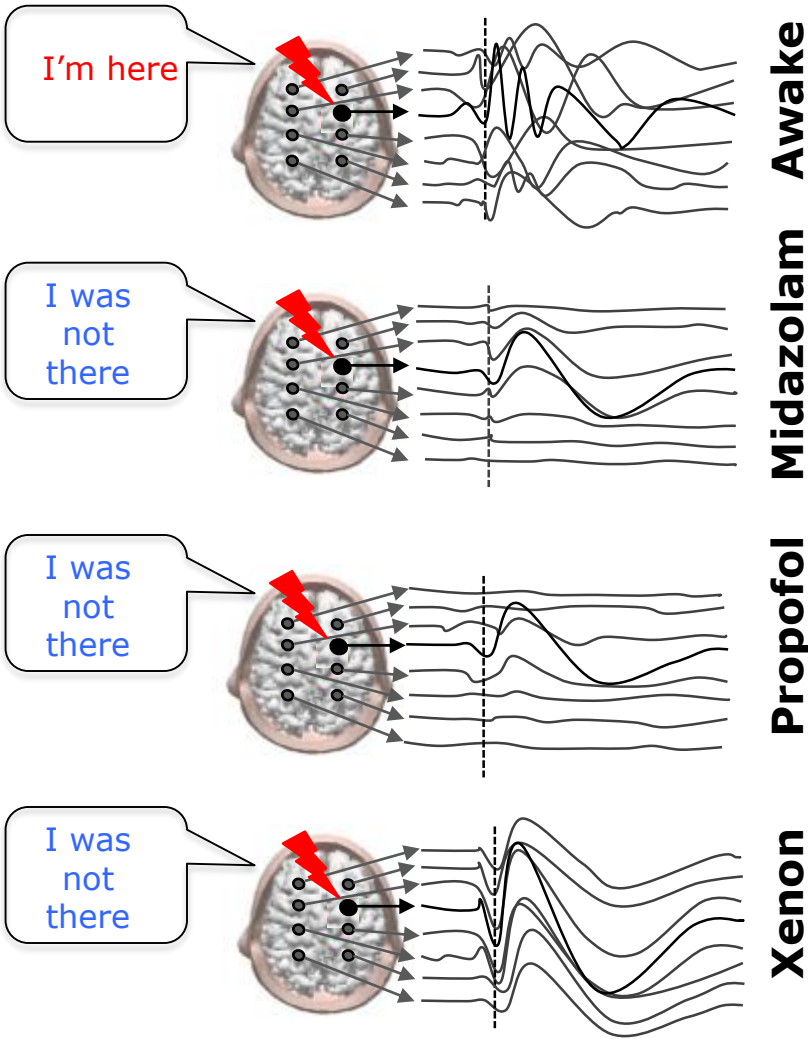
From Wakefulness to Sleep



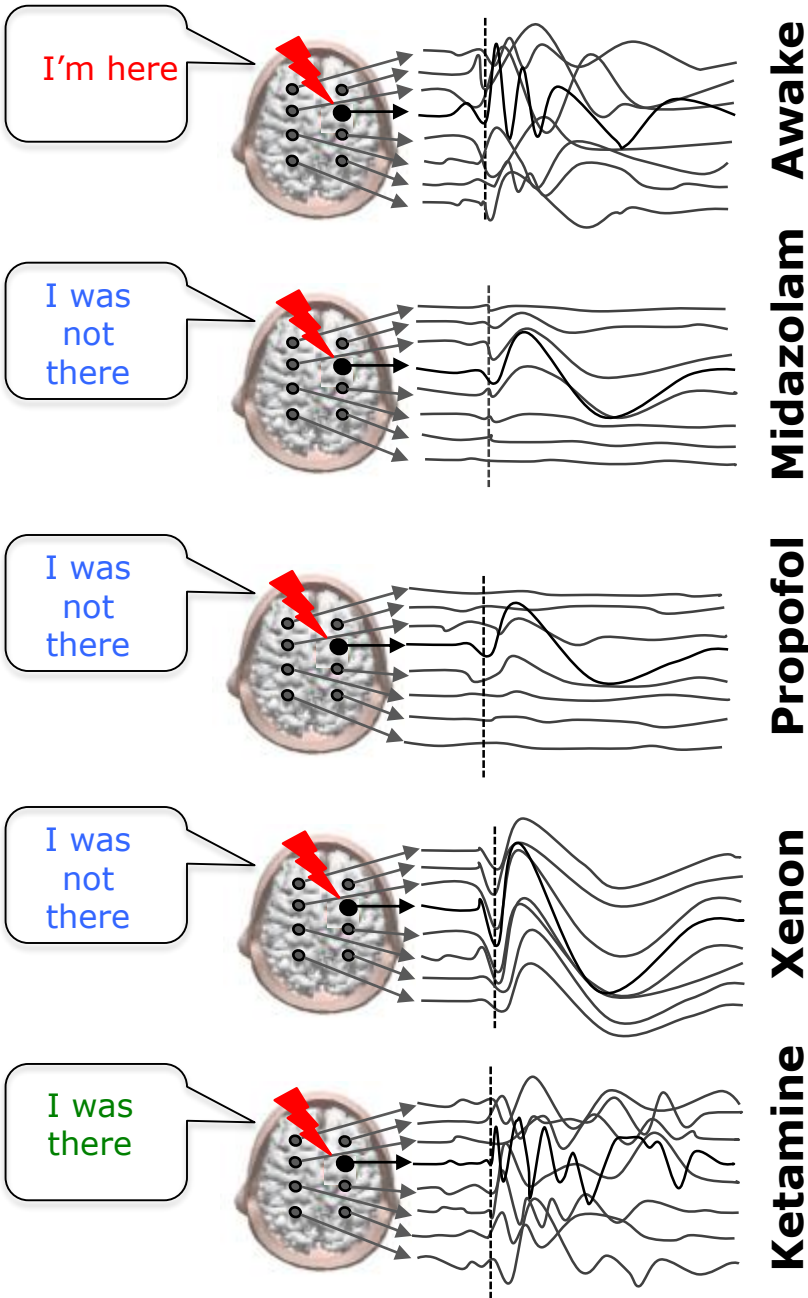
Dreaming



Anesthesia

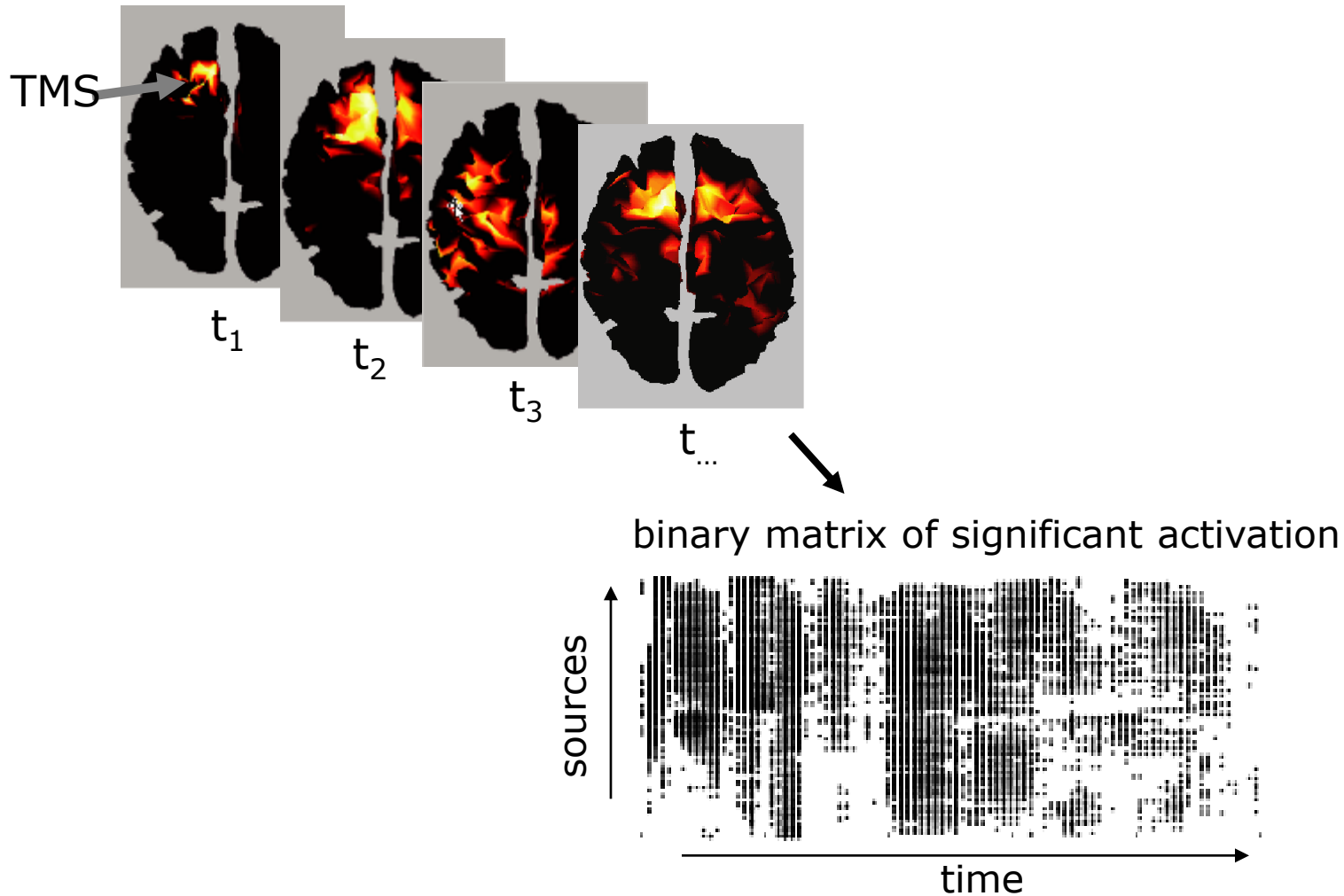


Anesthesia



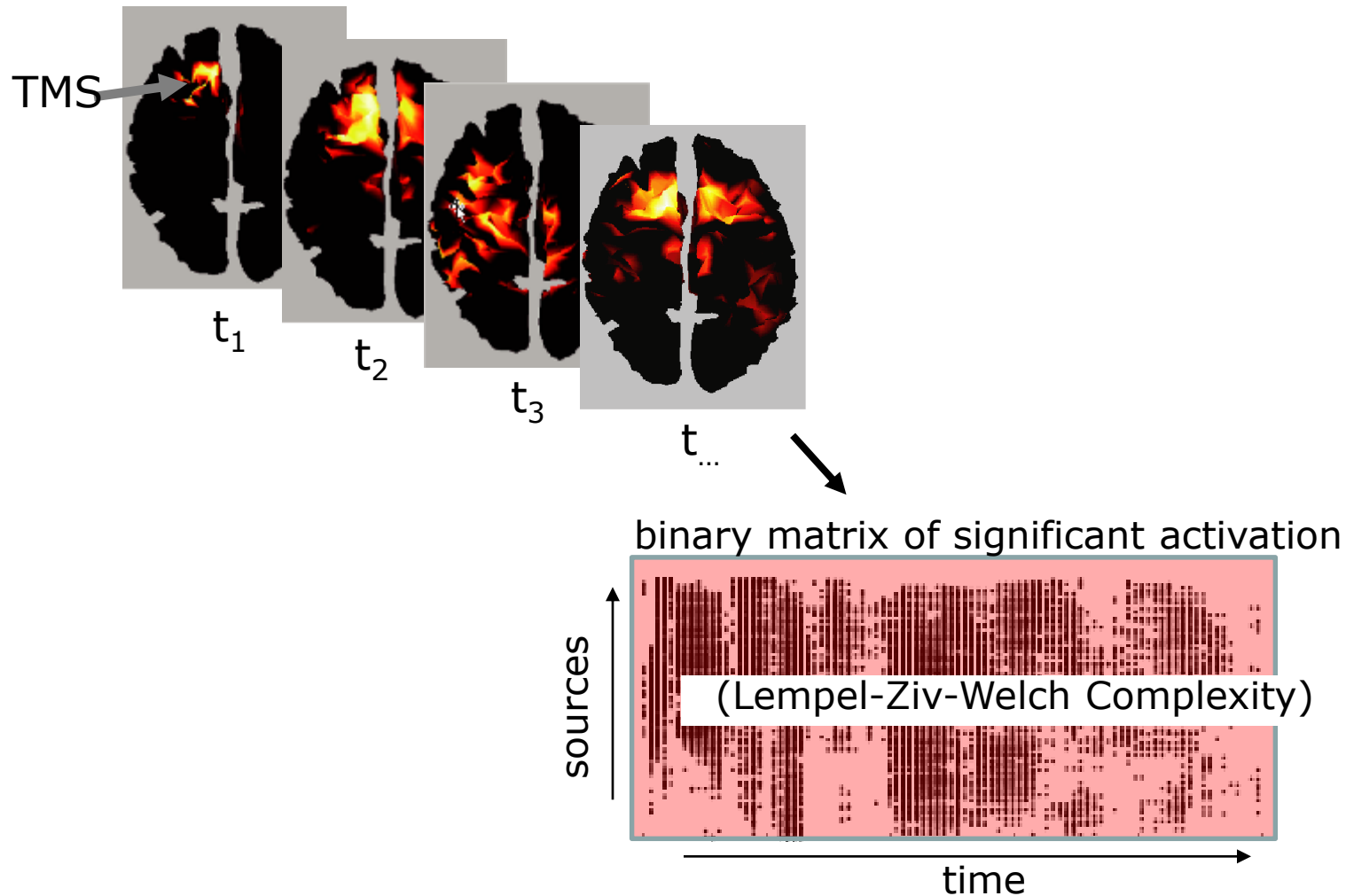
A quantification: Perturbational Complexity Index (PCI)

non-parametric statistics at the source level



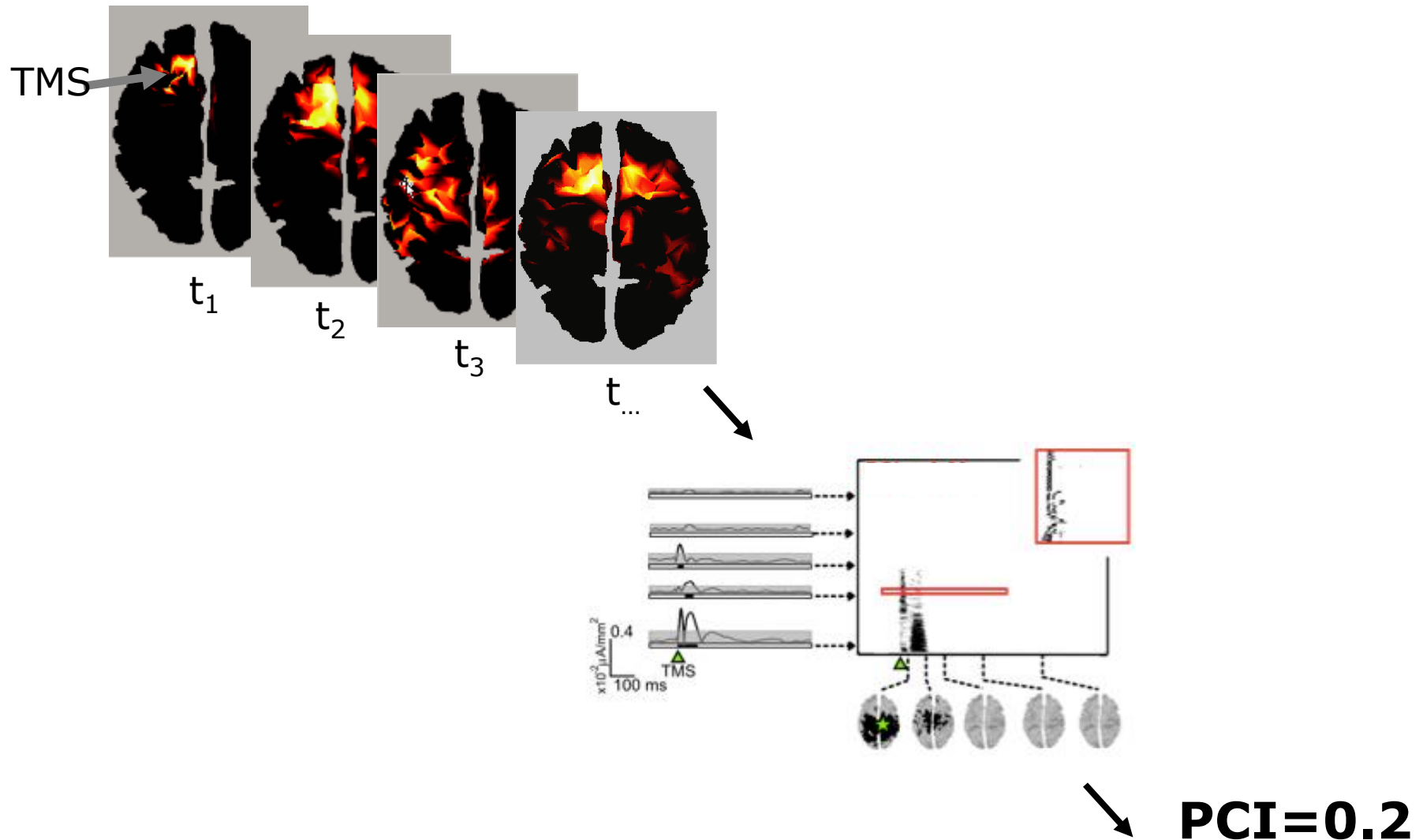
A quantification: Perturbational Complexity Index (PCI)

non-parametric statistics at the source level



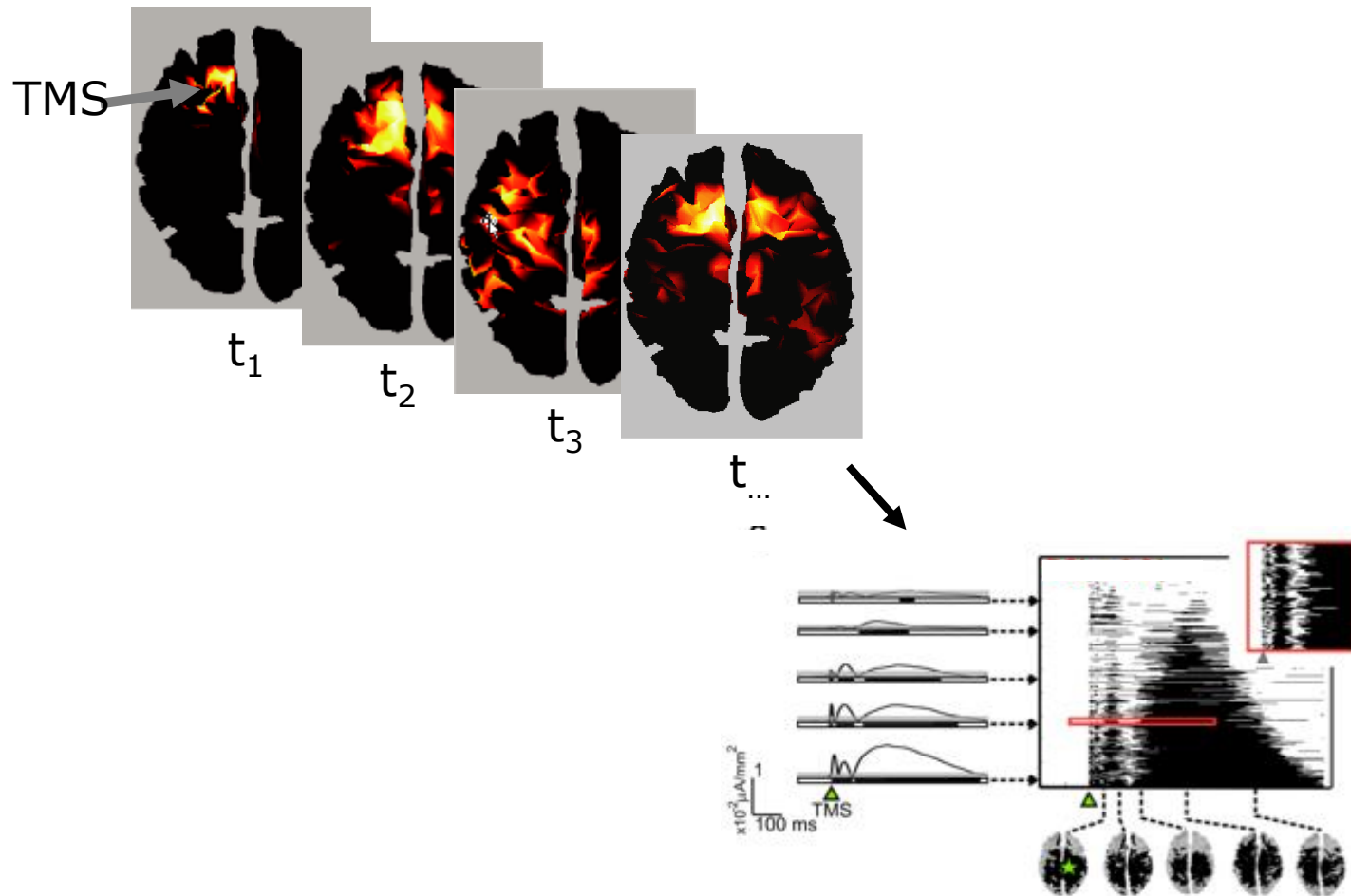
A quantification: Perturbational Complexity Index (PCI)

non-parametric statistics at the source level



A quantification: Perturbational Complexity Index (PCI)

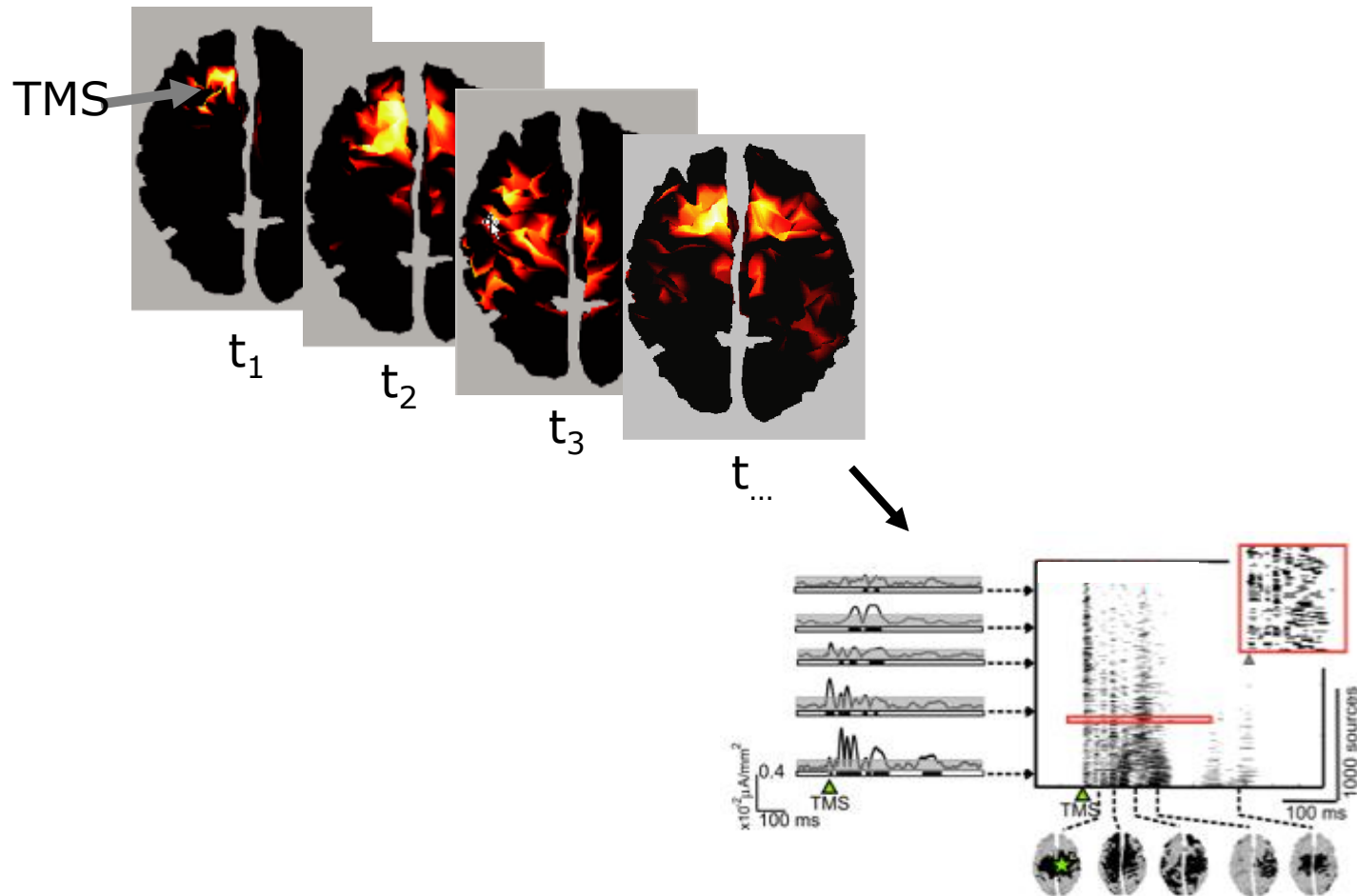
non-parametric statistics at the source level



PCI=0.21

A quantification: Perturbational Complexity Index (PCI)

non-parametric statistics at the source level



↓ **PCI=0.6**

Disorders of Consciousness

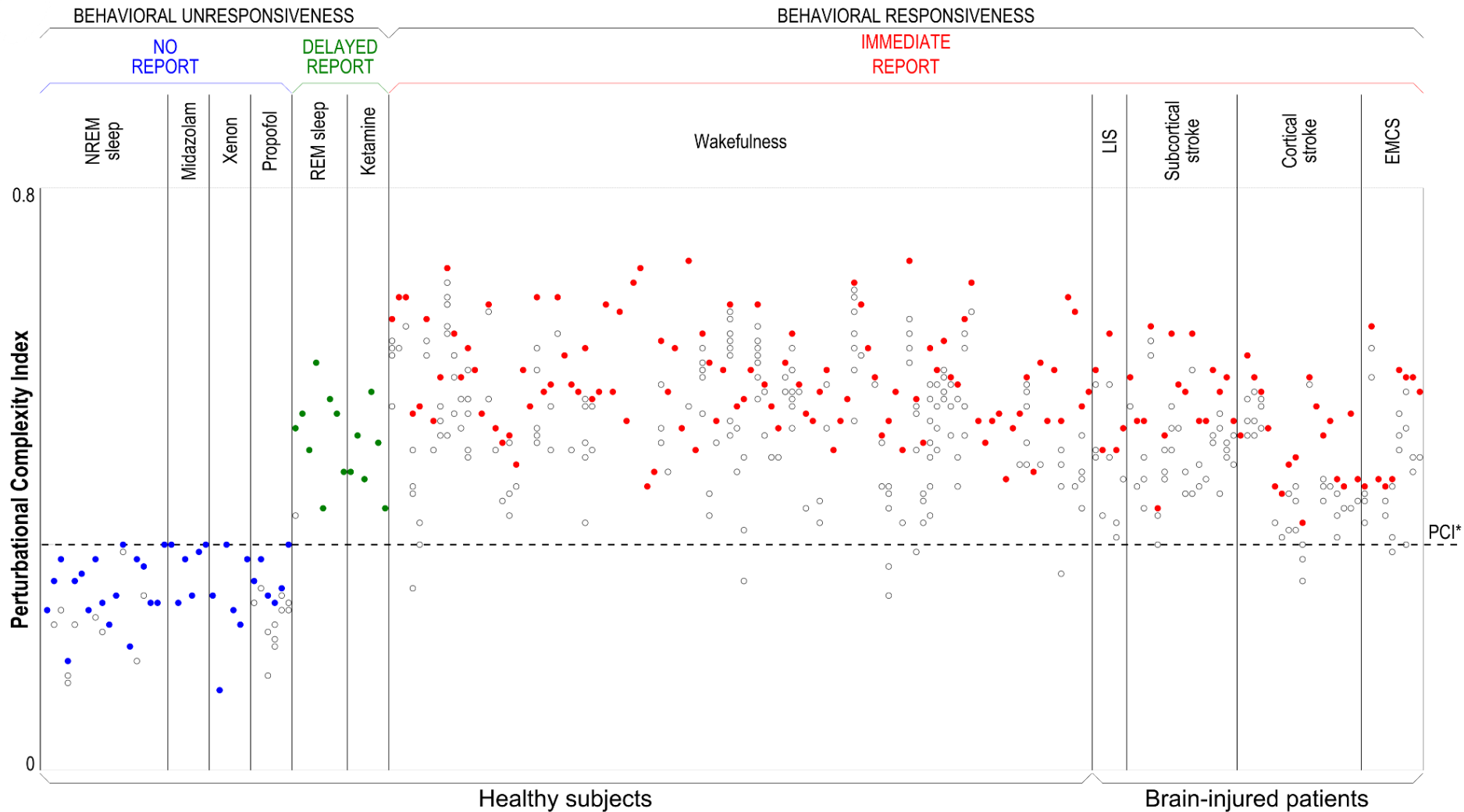


VALIDATION/CALIBRATION → STRATIFICATION

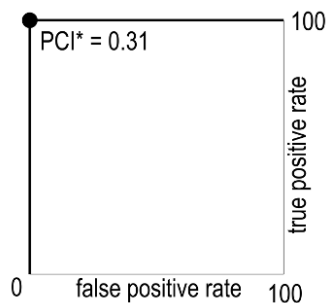
Benchmark: ABLE TO REPORT

Target: UNABLE TO REPORT



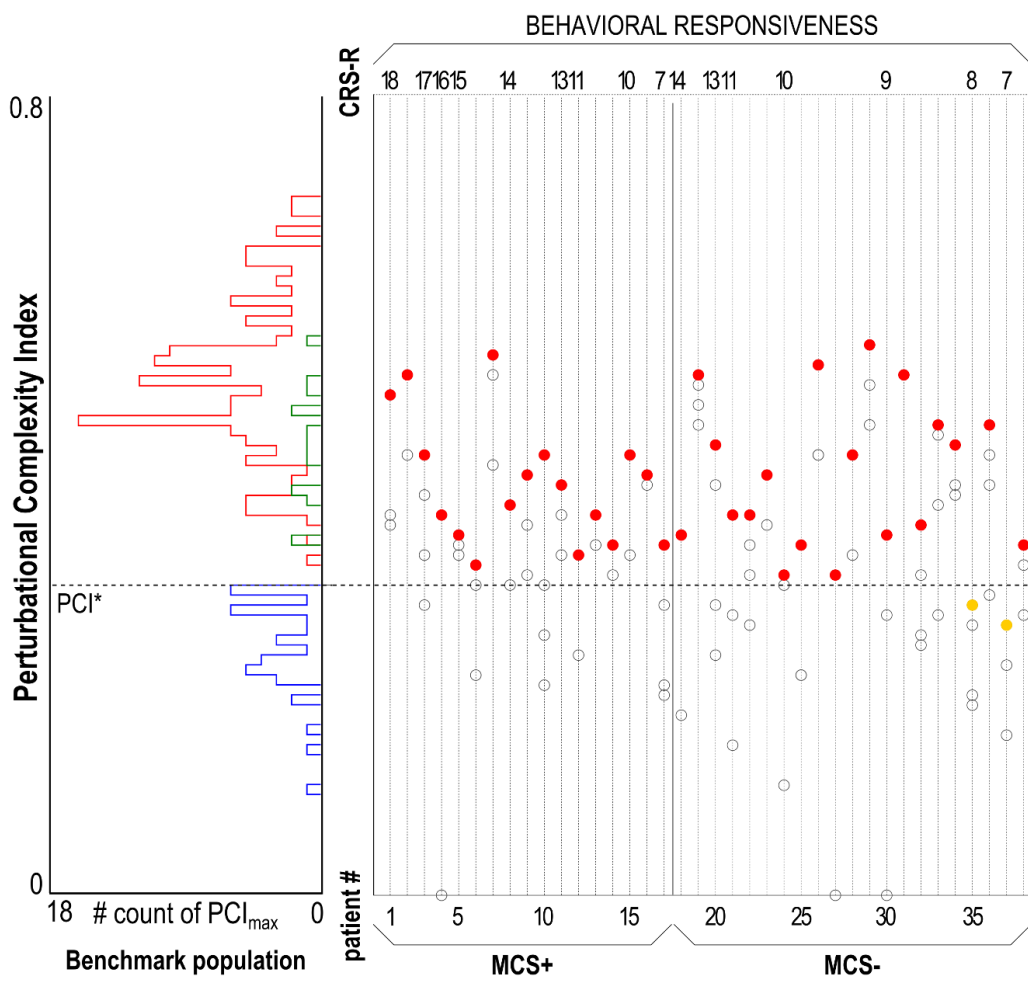


ROC analysis



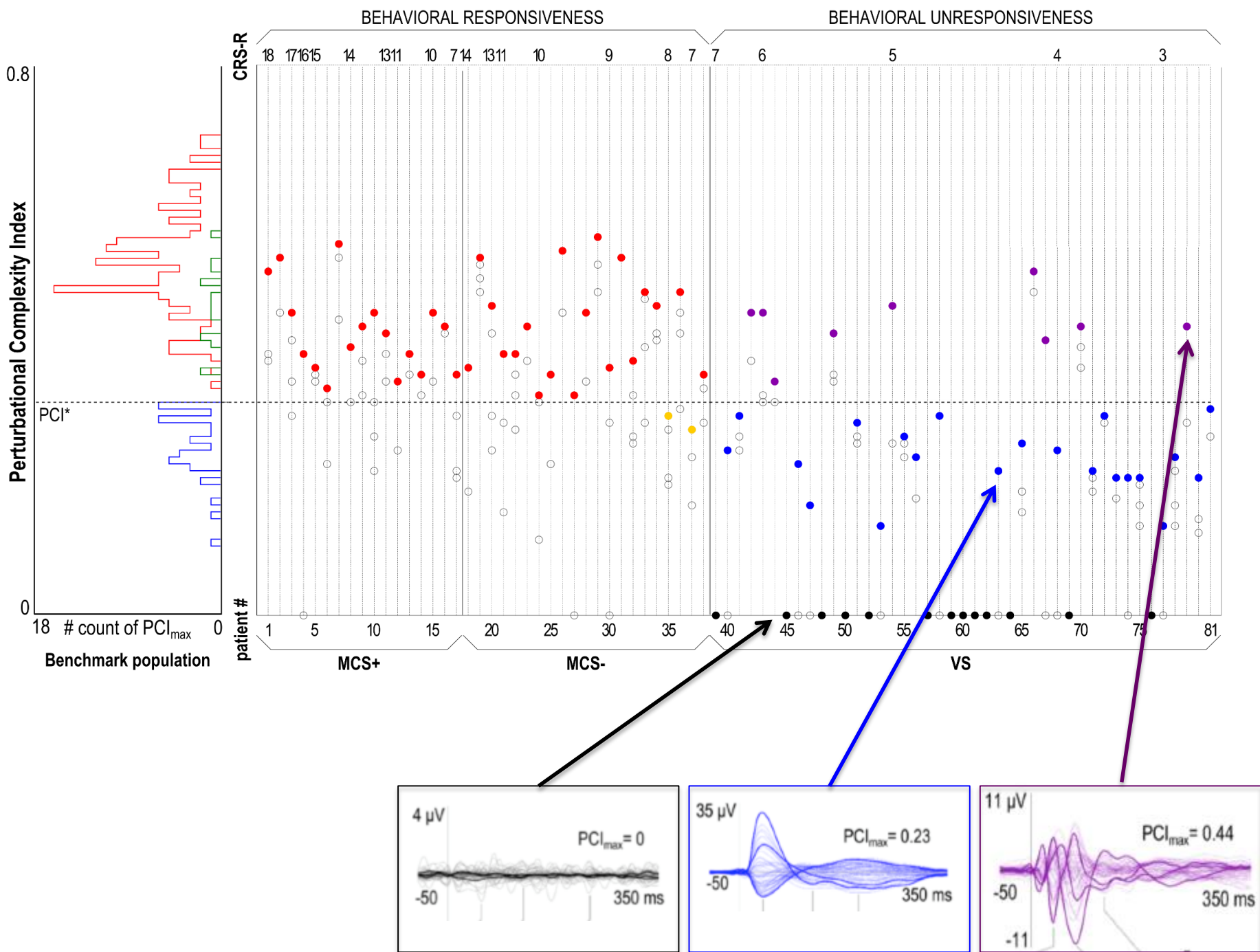
AUC = 100 %
sensitivity = 100%
specificity = 100%

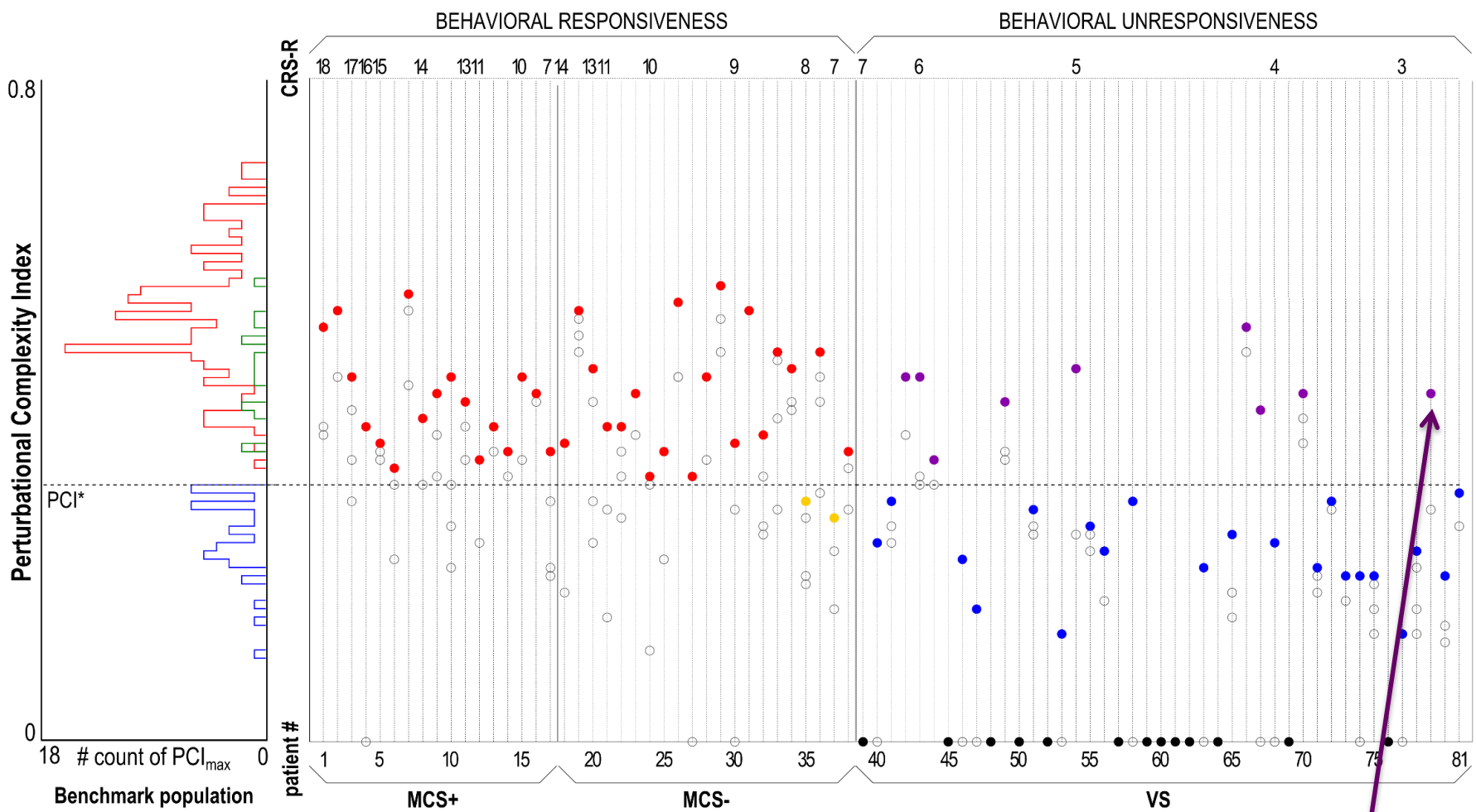
	report			
	no	delayed	immediate	
$>PCI^*$	0	14	150	164
$\leq PCI^*$	36	0	0	36
	36	14	150	200



clinical diagnosis	
PCI_{max}	MCS
	>PCI* 36
	\leq PCI* 2
	= 0 0
38	

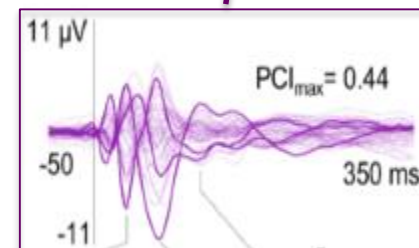
94.7% sensitivity



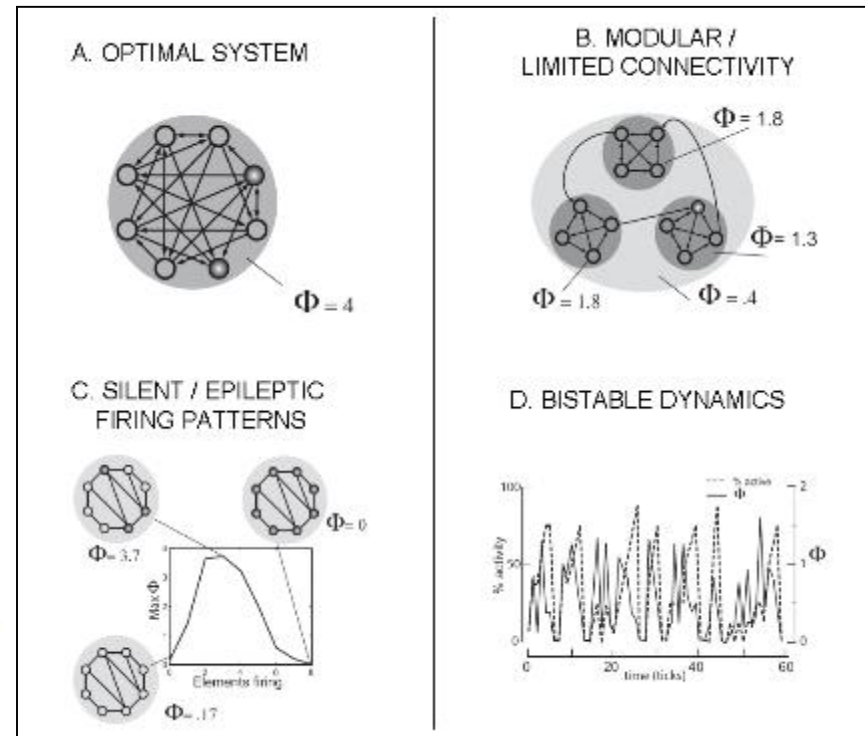
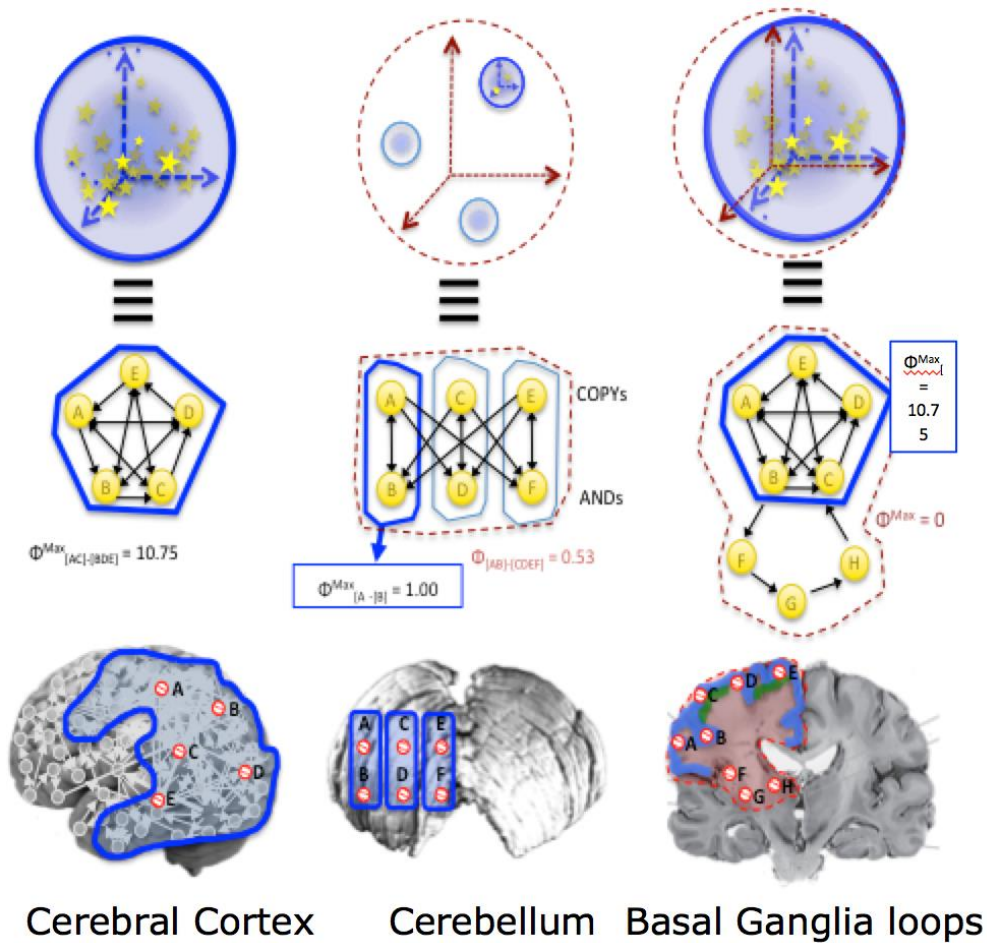


clinical diagnosis		
	MCS	VS
$PCI_{max} > PCI^*$	36	9
$PCI_{max} \leq PCI^*$	2	21
$PCI_{max} = 0$	0	13
	38	43

→ **19%**

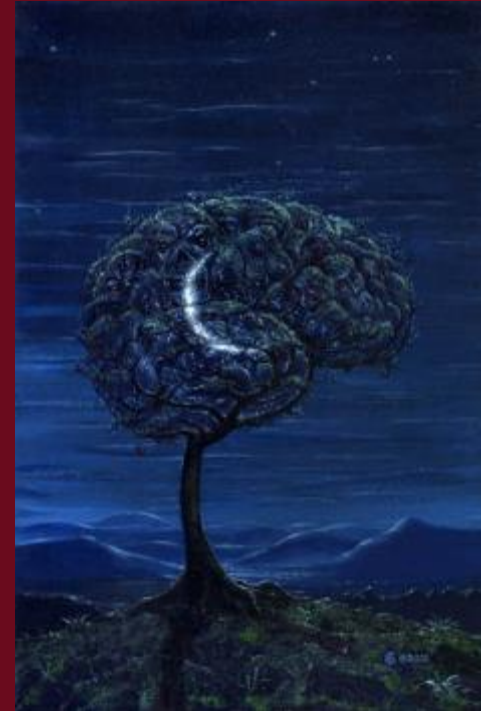


Explanatory power

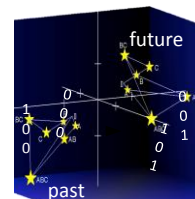


3

Conclusions



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Conclusions

- 1) Consciousness should be distinguished from responsiveness, and increasing evidence suggests that it can be.
- 2) Lesion data and within-state paradigms provide evidence that many of the areas contributing to specific contents of experience are in a posterior 'hot zone' of the cerebral cortex.
- 3) IIT predicts that the neural substrate of consciousness must be both highly integrated and differentiated. This prediction has led to the development of a sensitive and specific consciousness-meter, the perturbational complexity index (PCI).
- 4) Explaining, predicting, and extrapolating the presence of consciousness requires a principled, systematic and quantitative approach starting from the essential properties of experience itself.

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Allen Institute

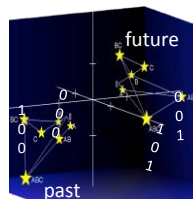
Christoph Koch

We thank the participating patients and their families



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**Summer School on Consciousness, Abbazia di Novacella in
Bressanone, Italy, September 17-24, 2016**

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www.nsas.it/consciousness