Electroencephalography in Disorders of Consciousness

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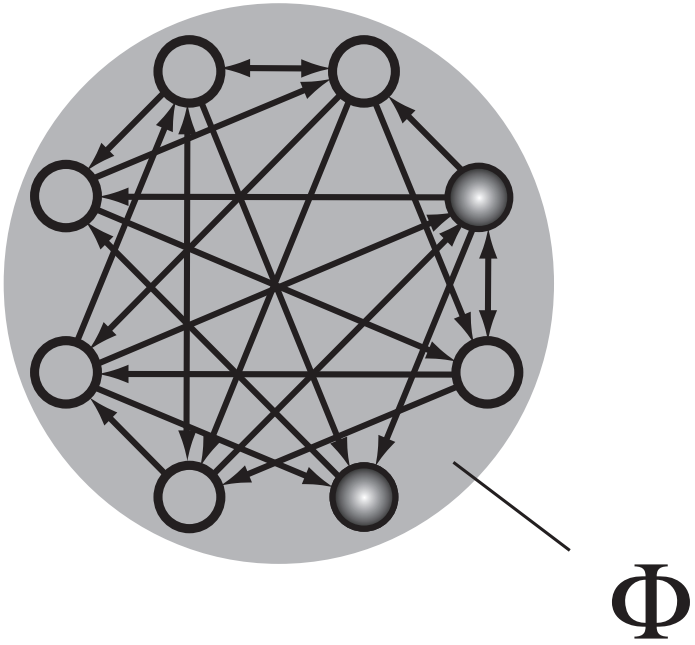
UNIVERSITY OF CAMBRIDGE

Consciousness as Information



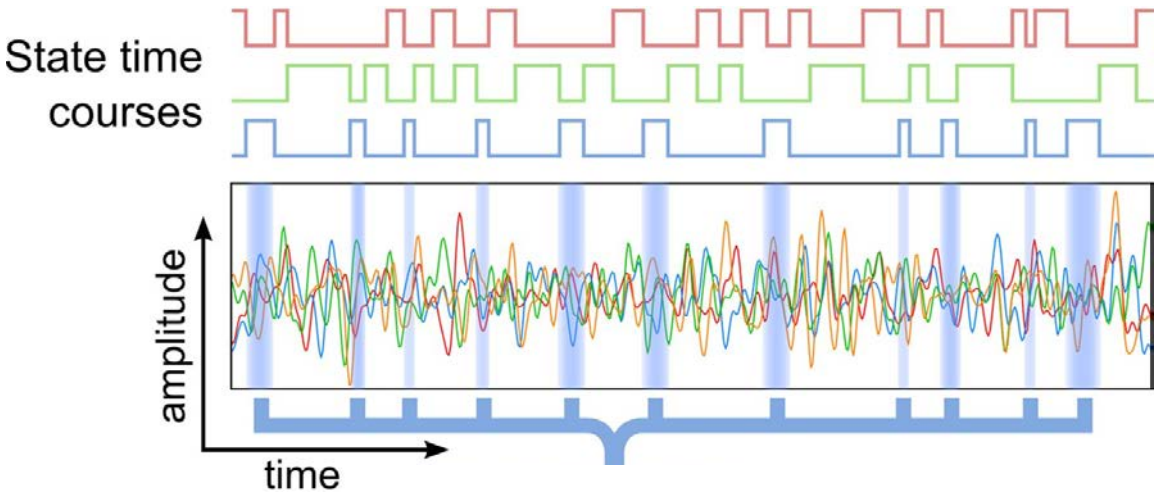
Consciousness is simultaneously

- differentiated – each conscious state is one amongst a vast repertoire
- integrated – each conscious state is unitary and indivisible

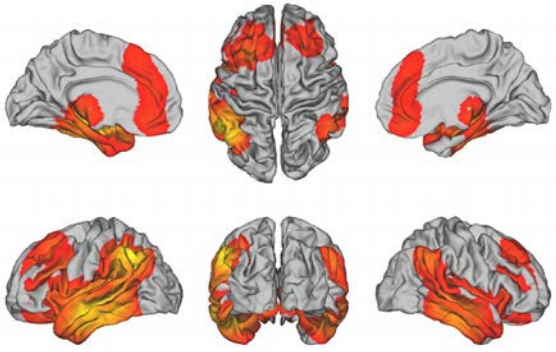
Quantity of consciousness is a function of balanced integration and differentiation of information

Tononi, 2008

Brain Networks in MEG

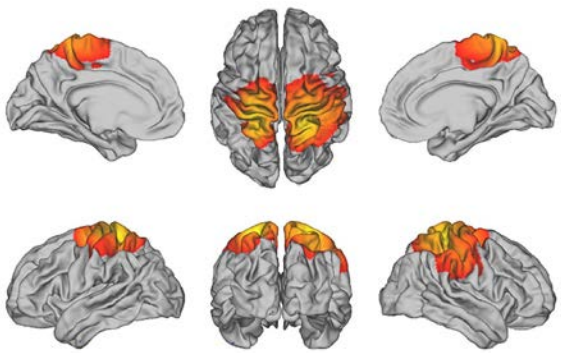


Source-reconstructed MEG brain networks from 10 minutes of resting state data



Default mode

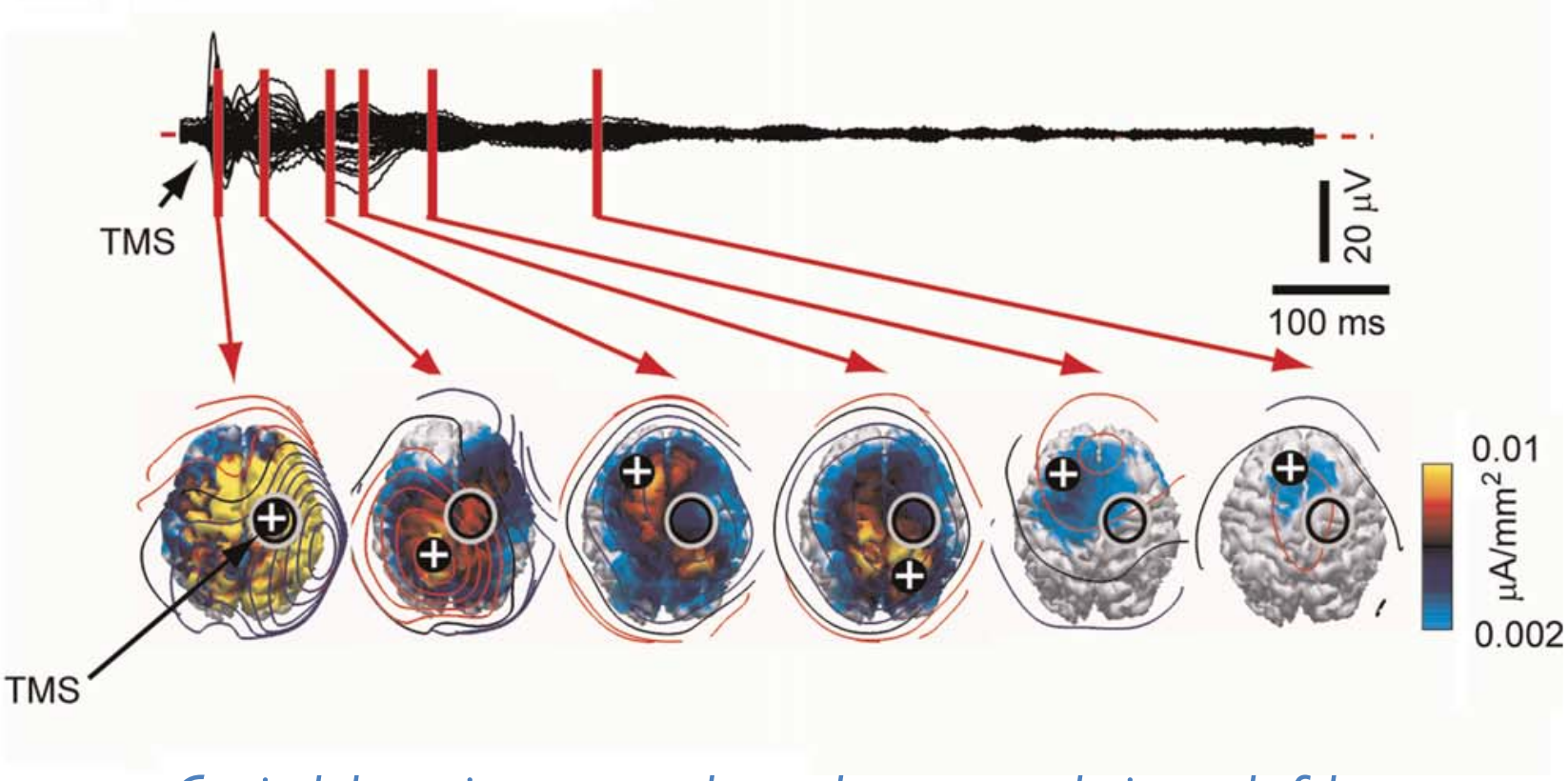
Visual



Sensorimotor

Baker et al., 2015

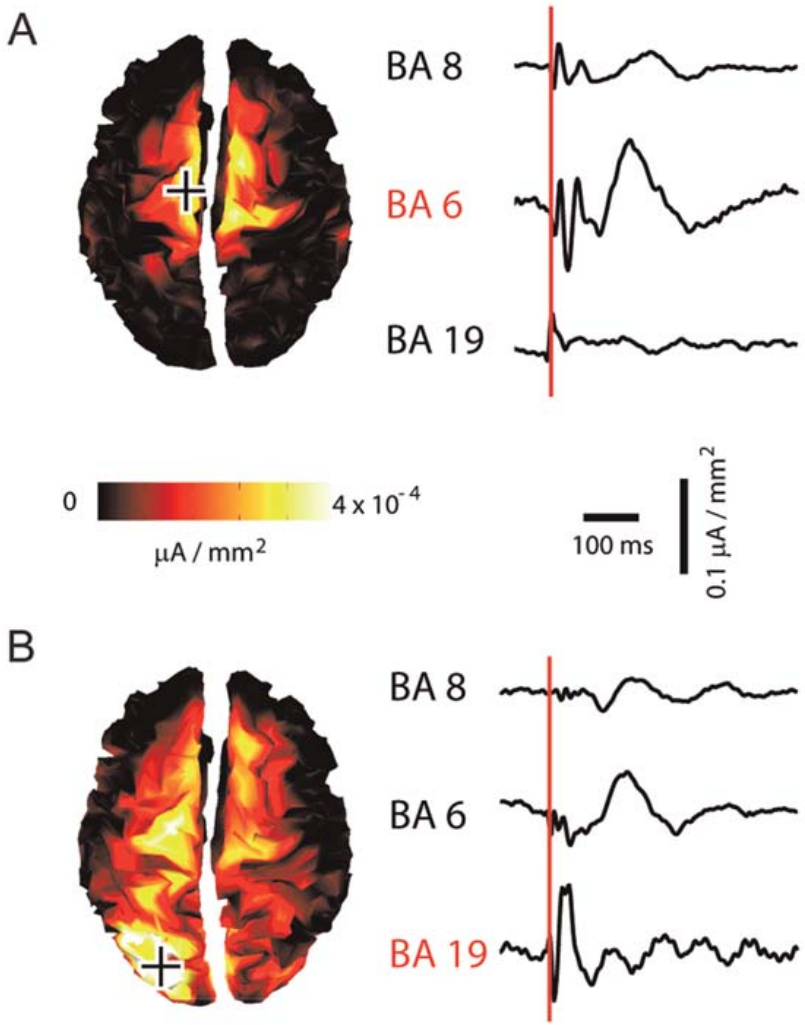
Integration



Cortical dynamics are complex and re-entrant during wakefulness

Massimini et al., 2009

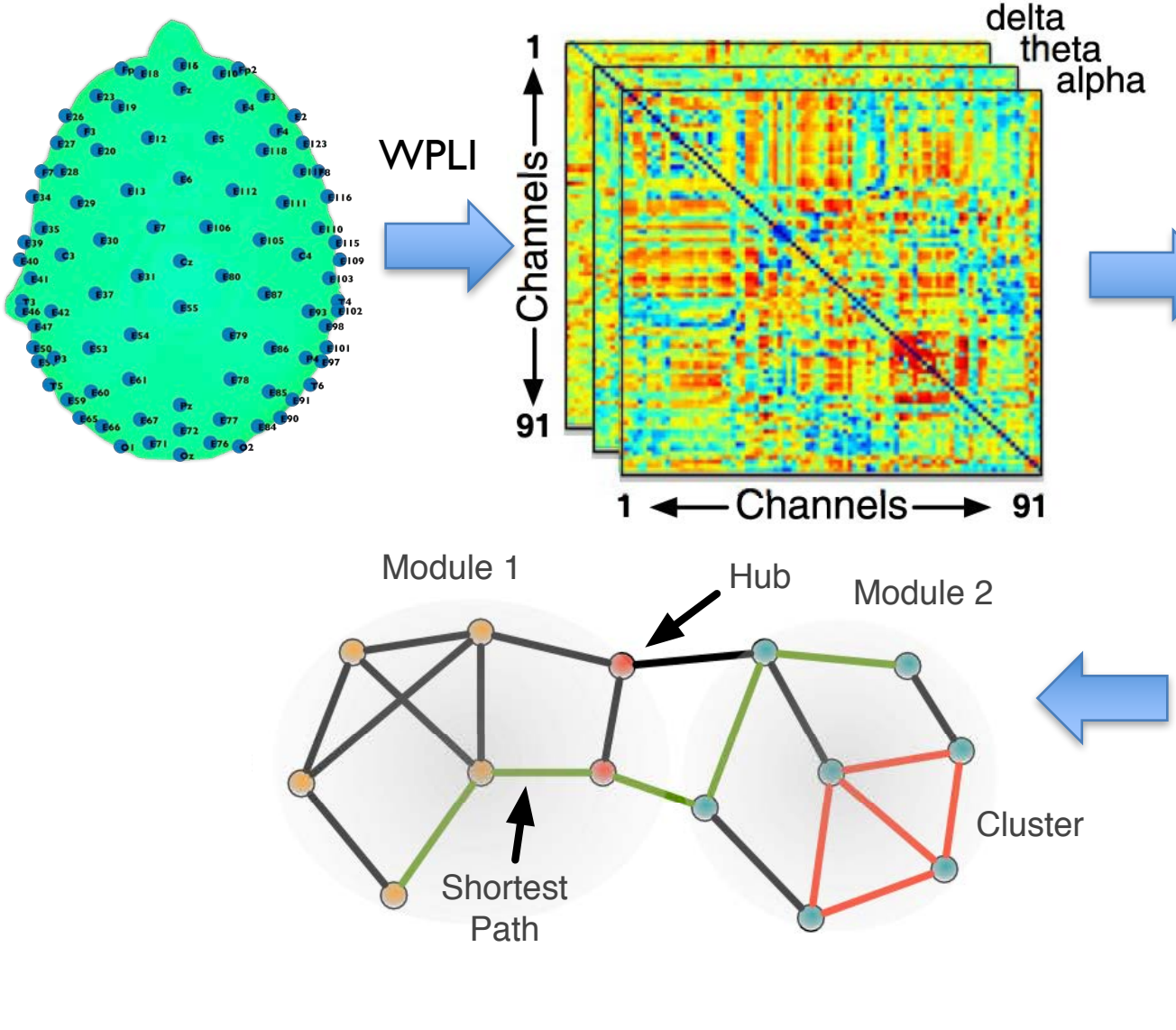
Differentiation



Cortical dynamics are spatially differentiated during wakefulness

Massimini et al., 2009

Methodology



Quantifying Consciousness

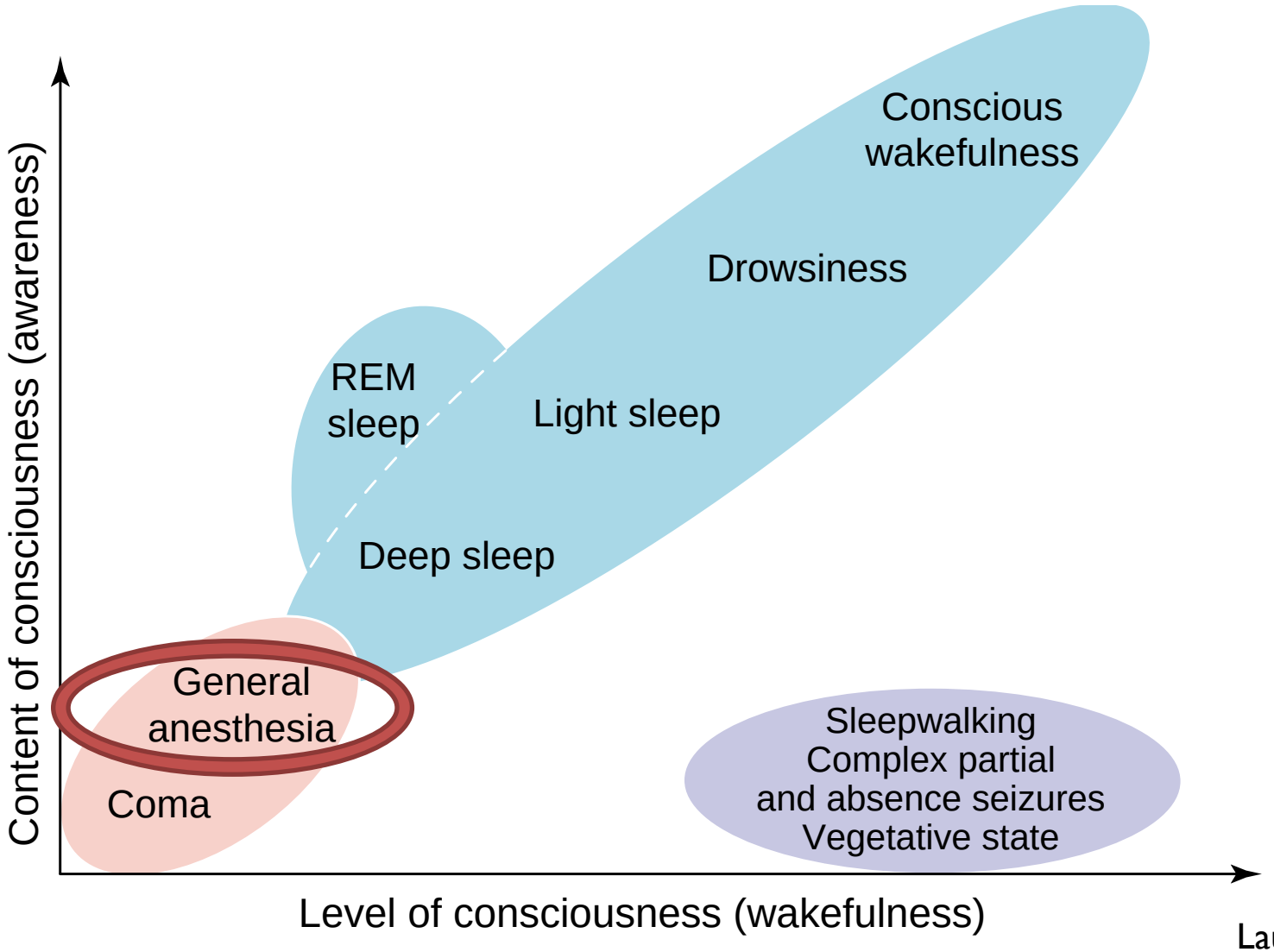
Spectral Decomposition

Weighted Phase Lag Index
Chennu et al., 2014

Information Theory

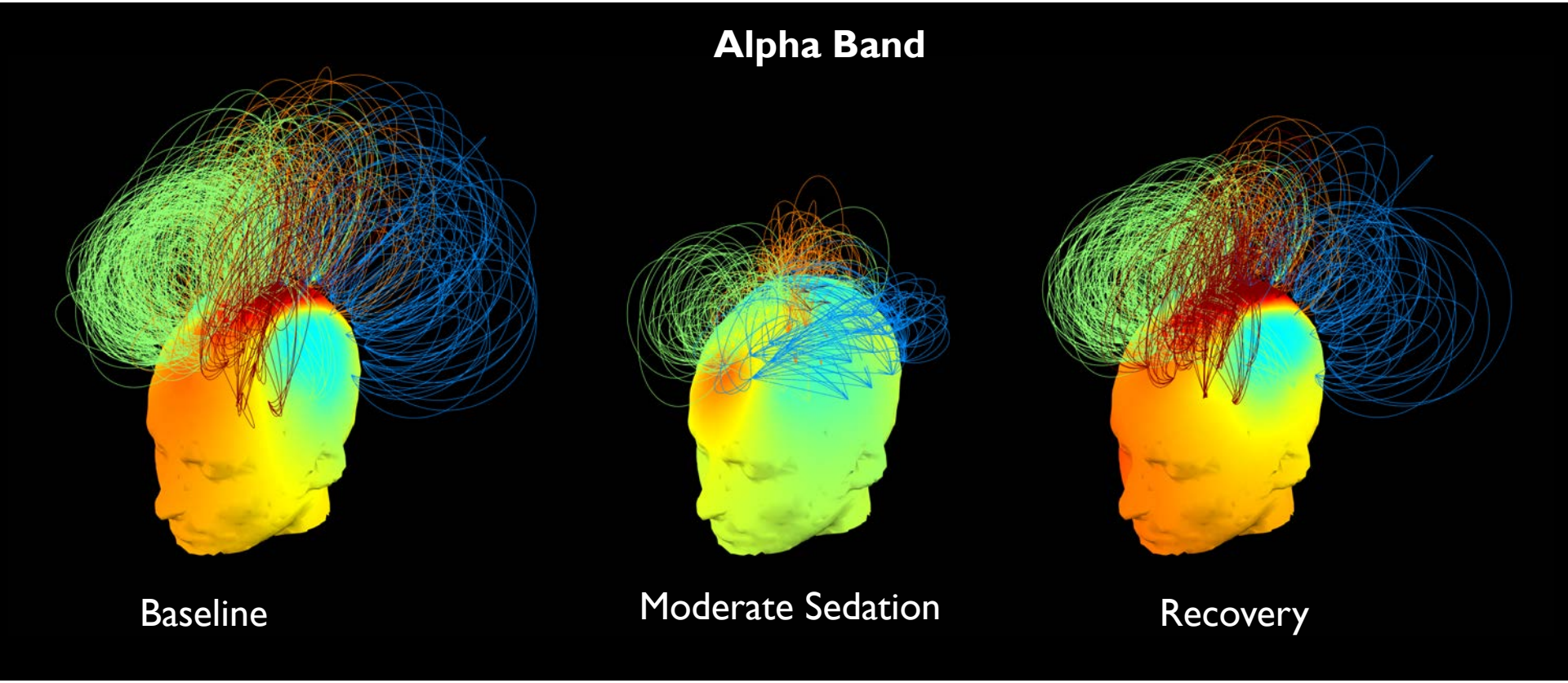
Symbolic Mutual Information
King et al., 2016

Conscious Levels vs. Contents



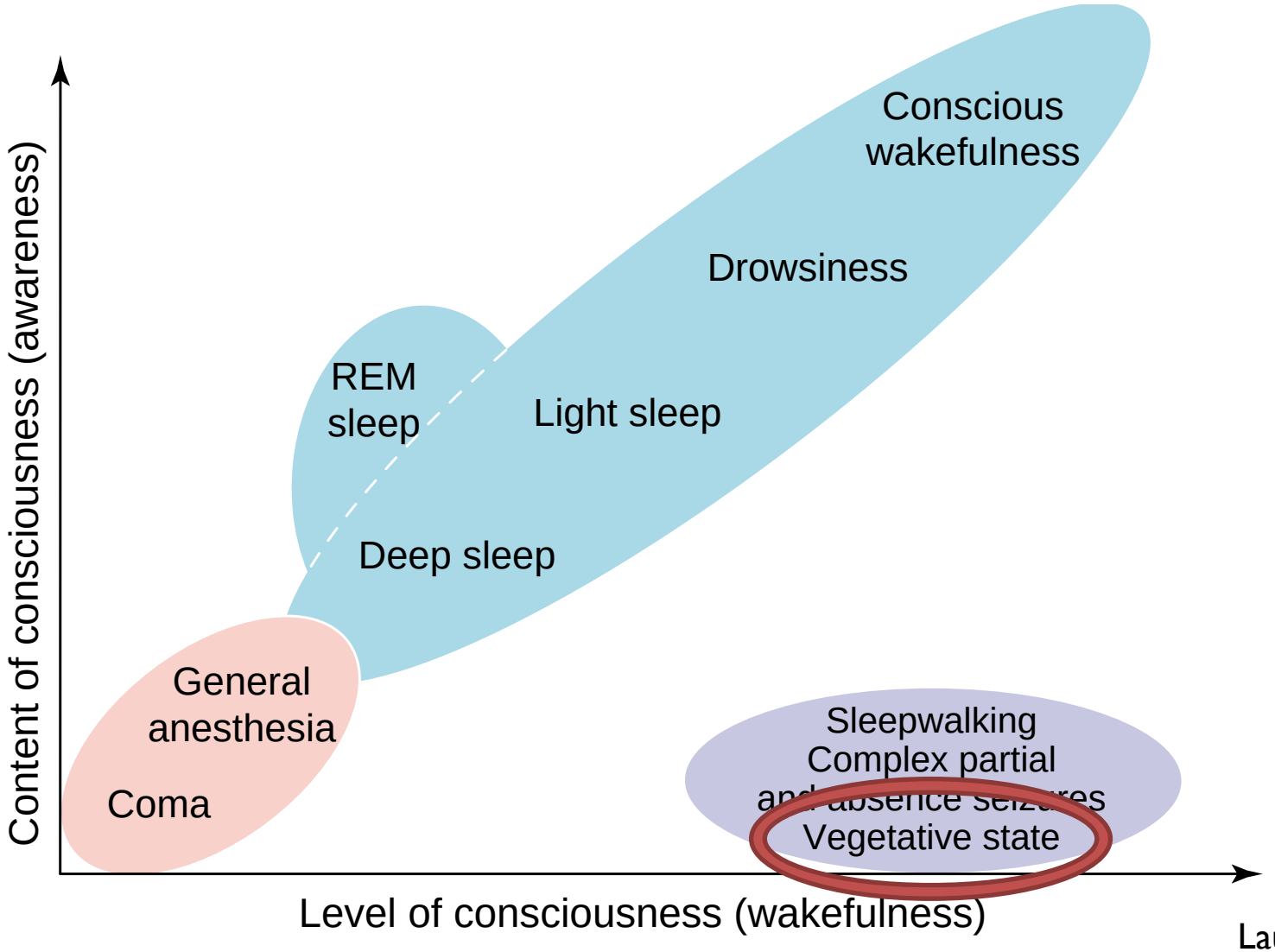
Laureys, 2005

Brain Networks in Sedation



Chennu et al., 2016

Conscious Levels vs. Contents



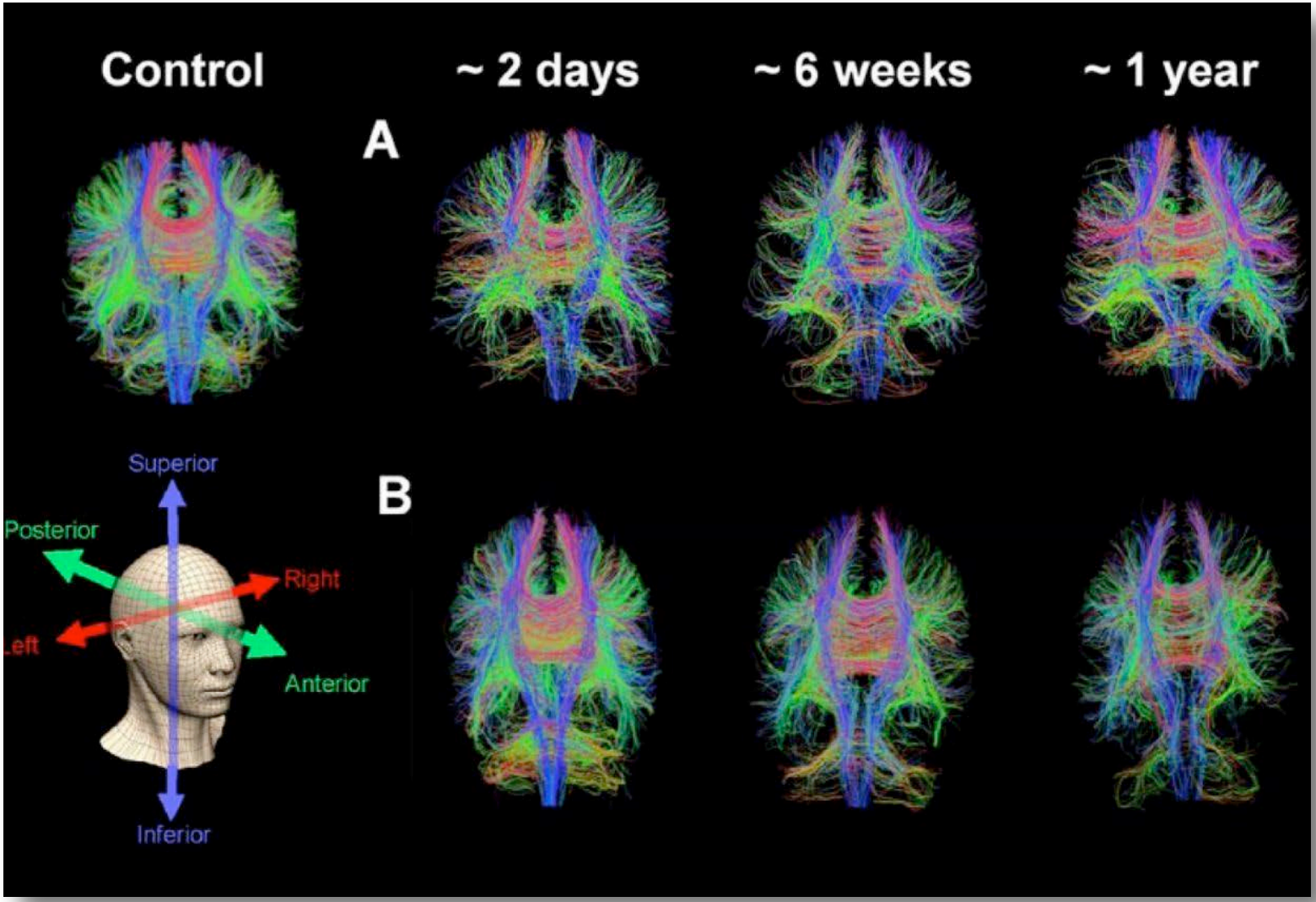
Laureys, 2005

After the ICU

Addenbrooke's Hospital

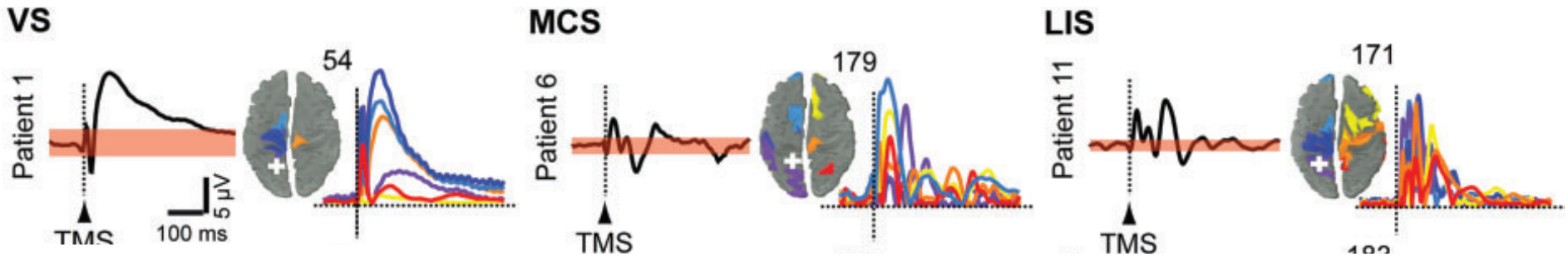
Long-term Neurorehabilitation

Progressive Changes

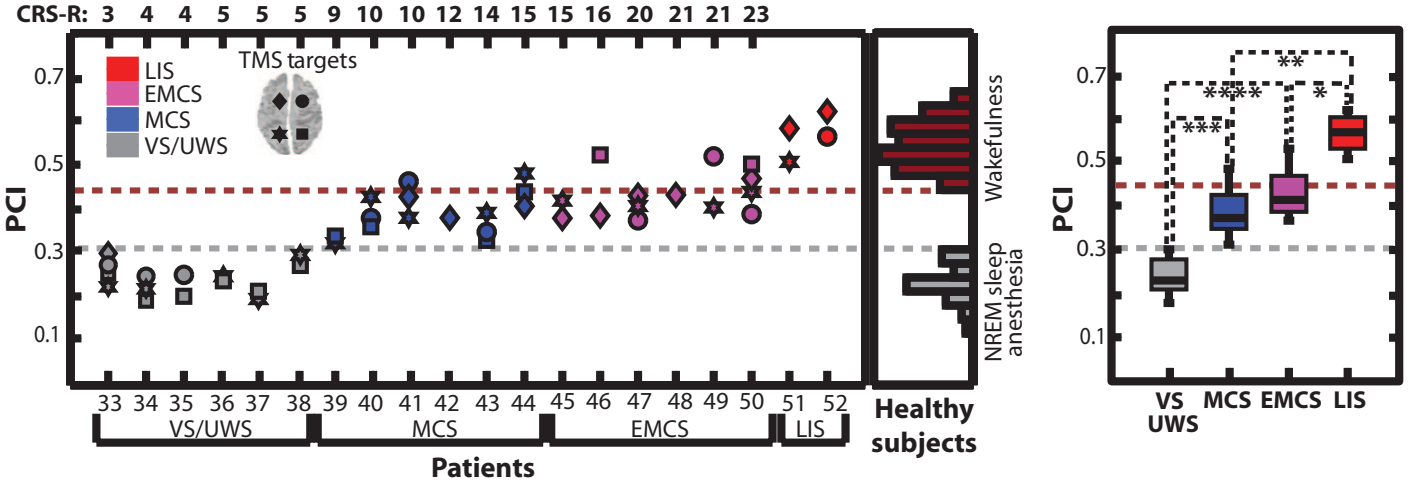


Newcombe et al., 2015

Transcranial Magnetic Stimulation

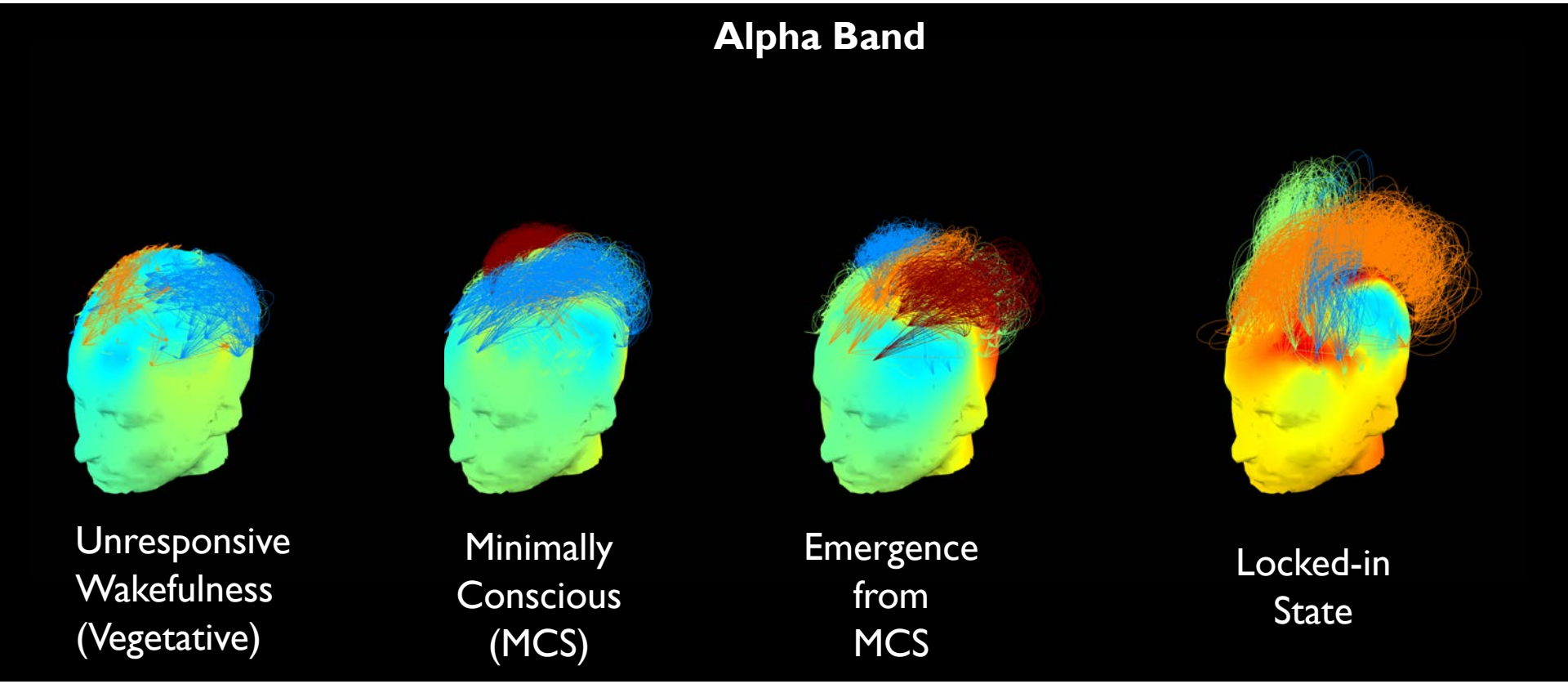


Balance between integration and differentiation of brain networks improves with level of consciousness



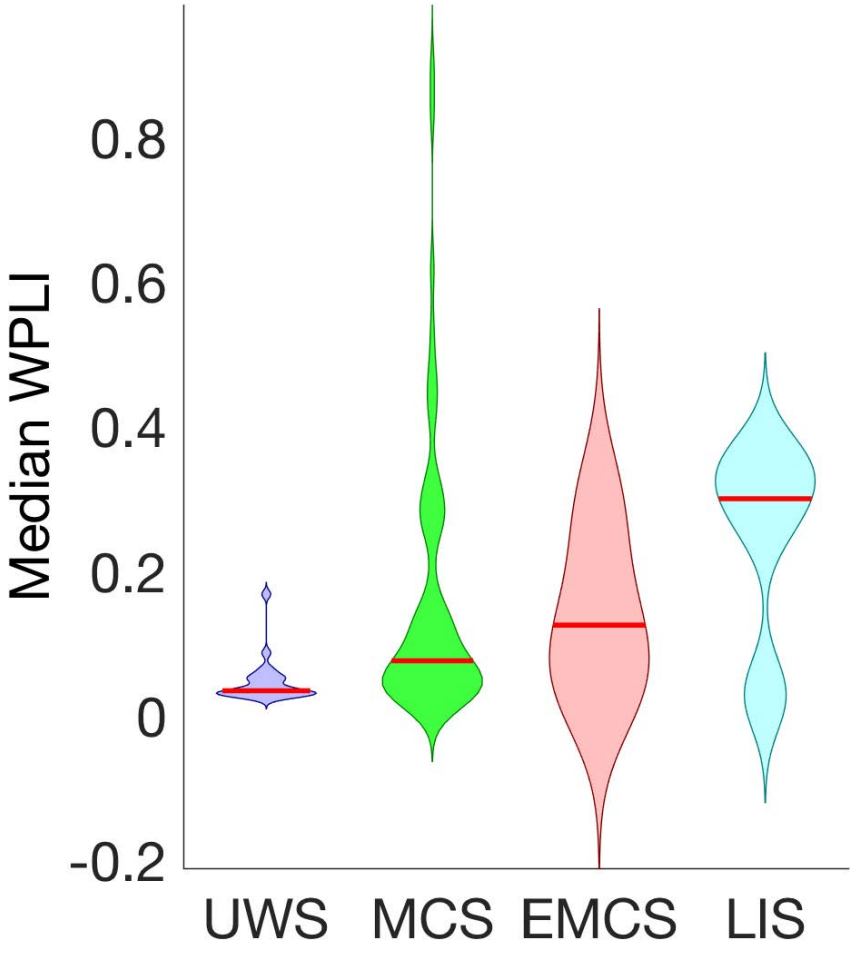
Rosanova et. al., 2012, Casali et al., 2013

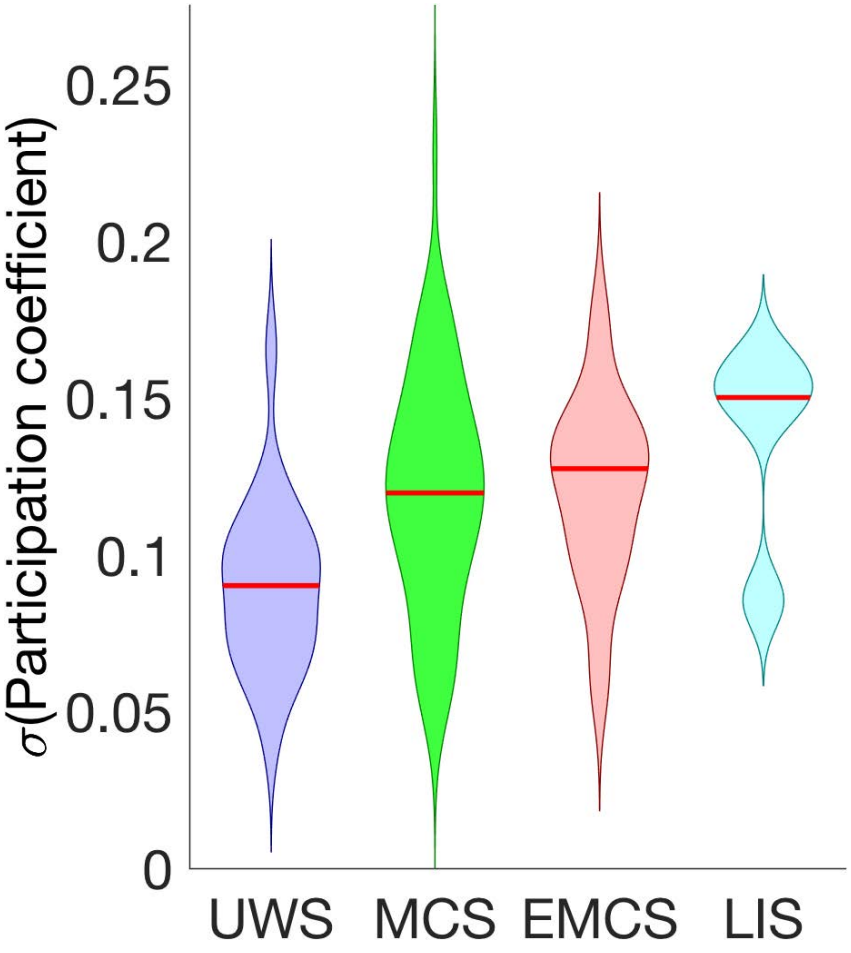
Brain Networks in DoC



Chennu et al., 2014; Chennu et al, *in prep*

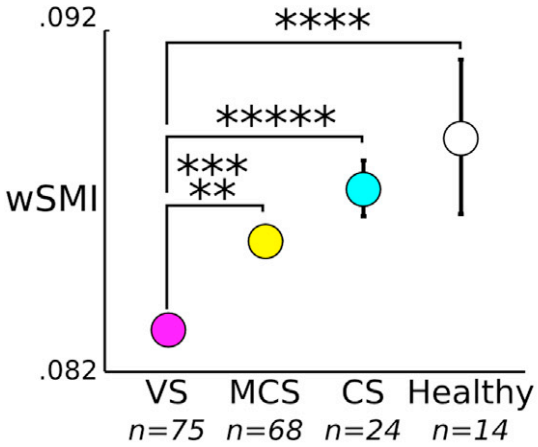
Brain Connectivity in DoC





Brain Networks in DoC

Healthy



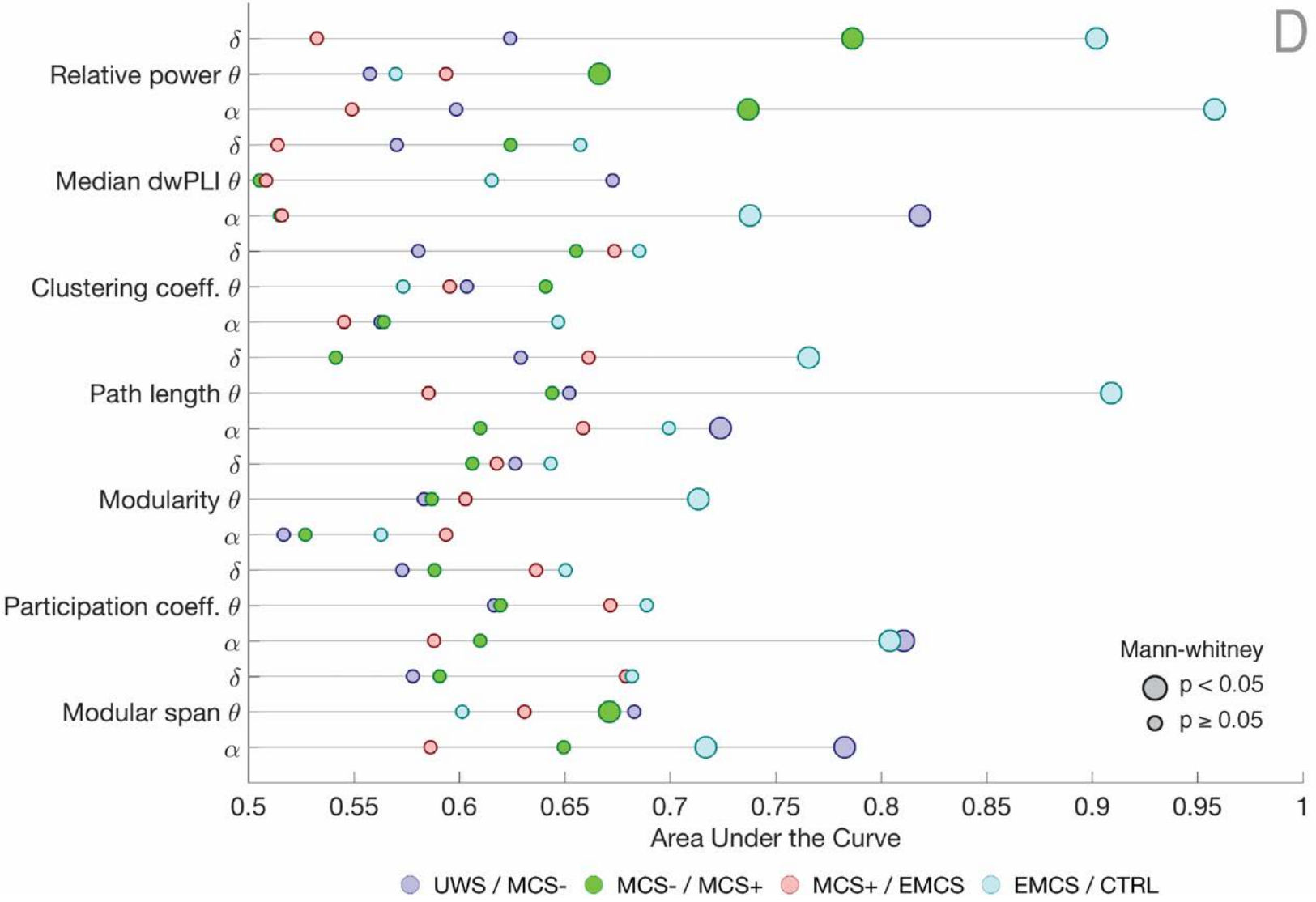
Long-distance information sharing characterises consciousness in states of low awareness

Minimally Conscious

Vegetative

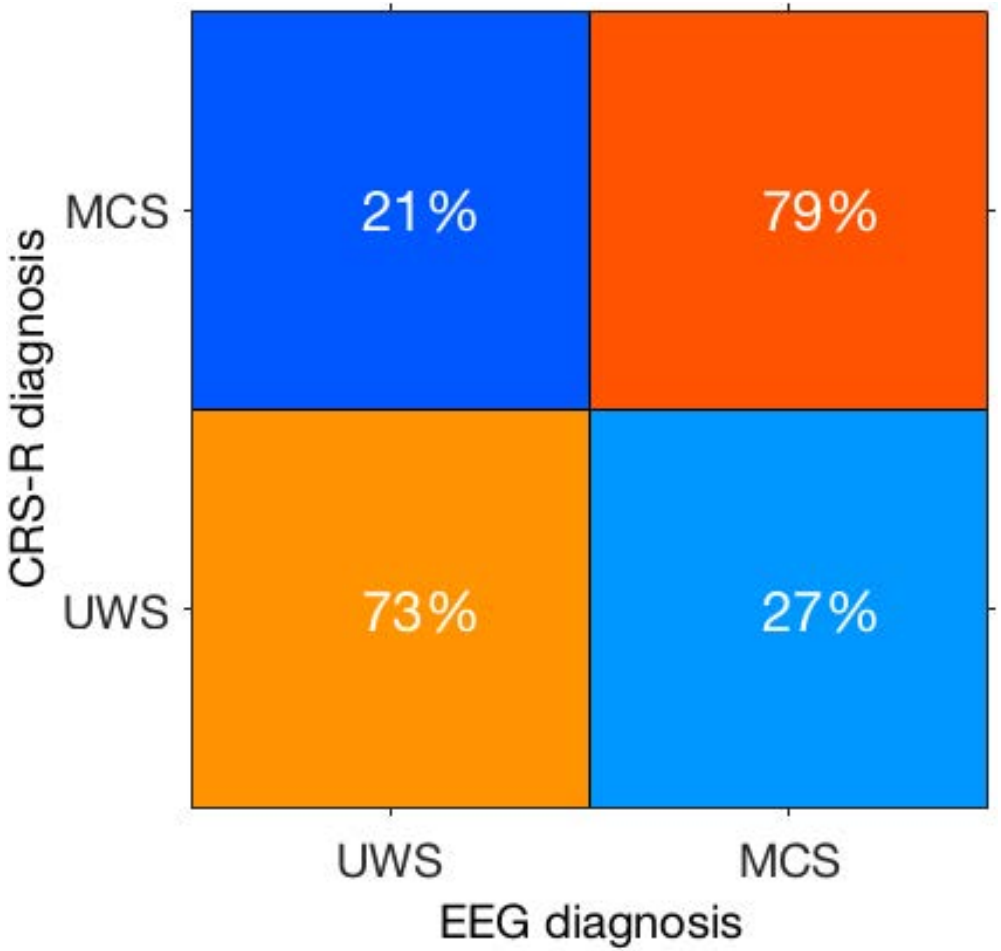
King et al., 2013; Sitt et al., 2014

Discriminating Levels of Consciousness



Sitt et al., 2014; Chennu et al, *in prep*

Classifying Behavioural Consciousness

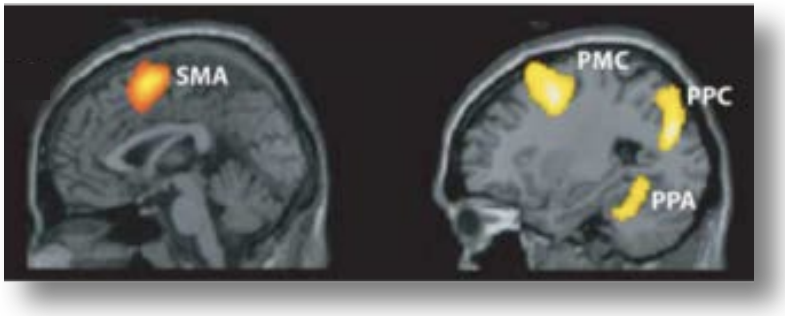


$\chi^2 = \mathbf{19.91}$, $p < 0.0001$

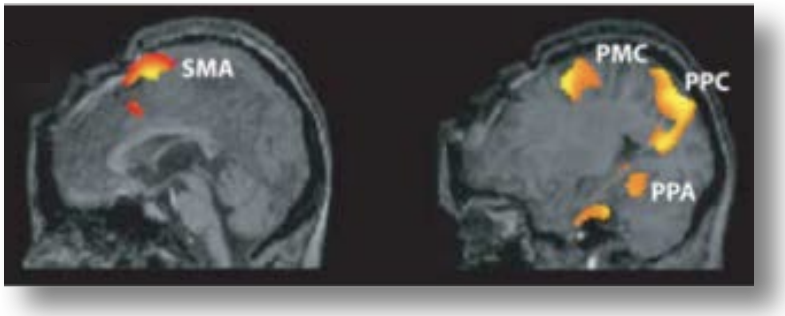
Hidden Awareness in the Vegetative State

fMRI

Healthy Volunteer

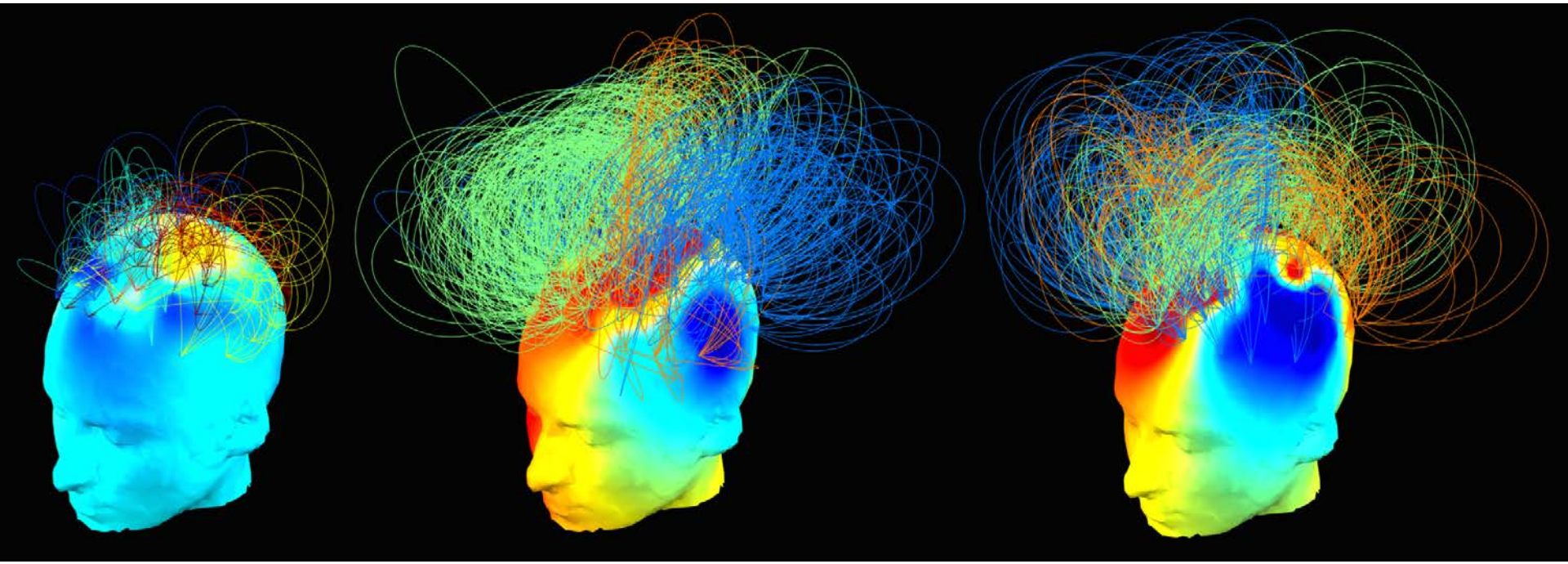


Vegetative Patient



Owen et al., Science, 2006, Monti et al., NEJM, 2010

Brain Networks in the Vegetative State



VS Patient

Tennis -ve

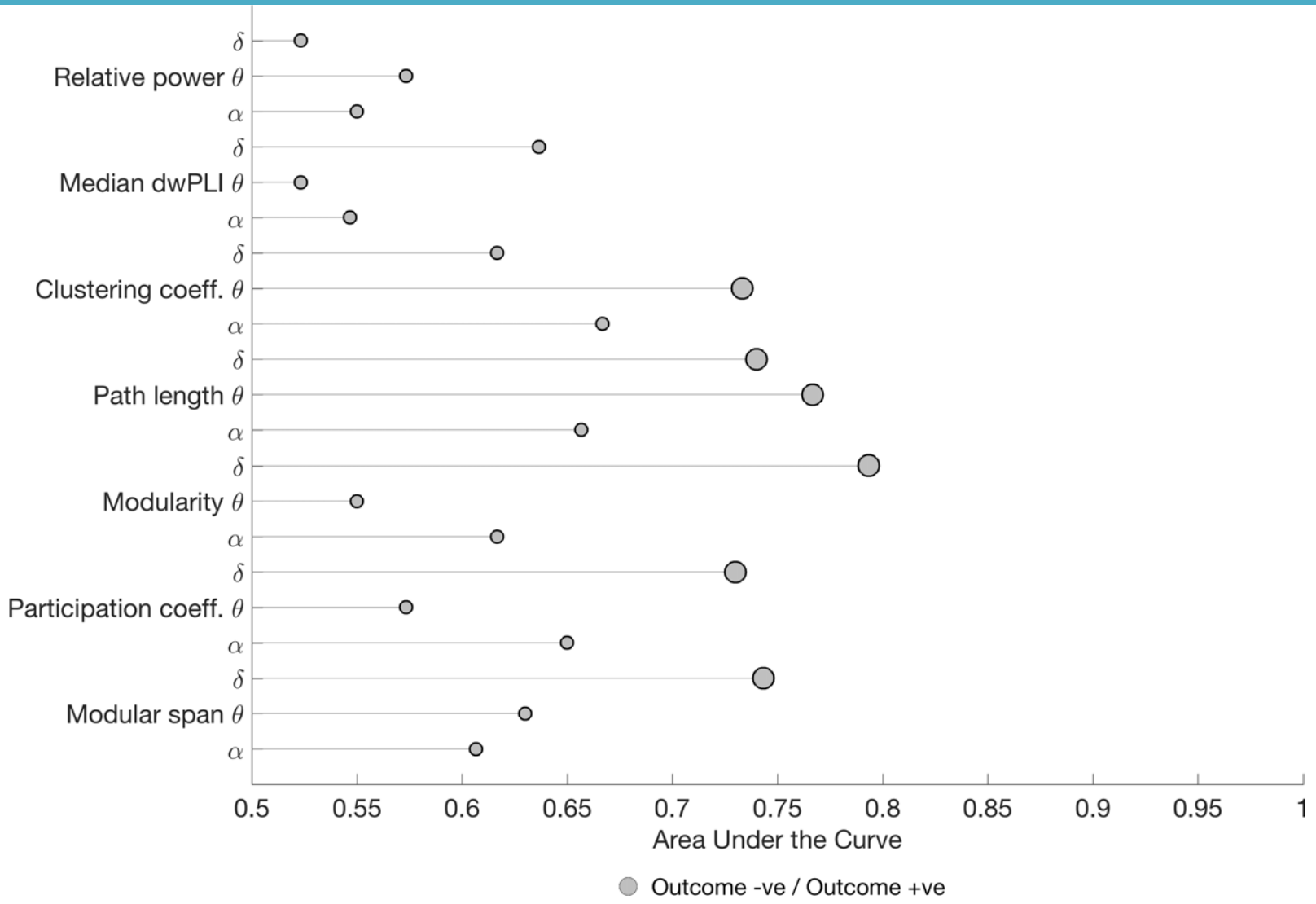
VS Patient

Tennis +ve

Healthy adult

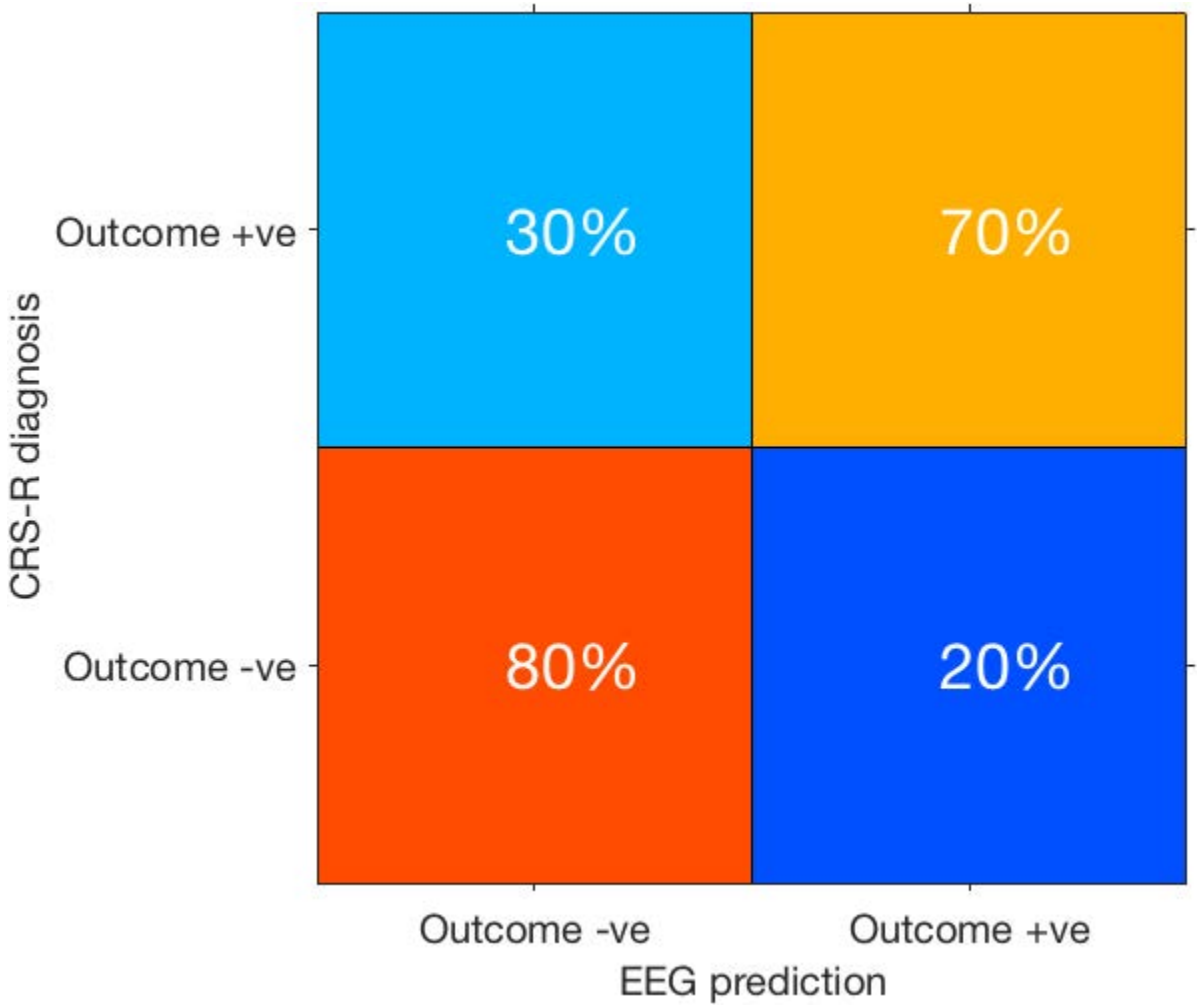
Chennu et al., 2014

EEG predicts Outcomes



EEG characteristics predict GOS-E outcomes one year after assessment

EEG predicts Outcomes

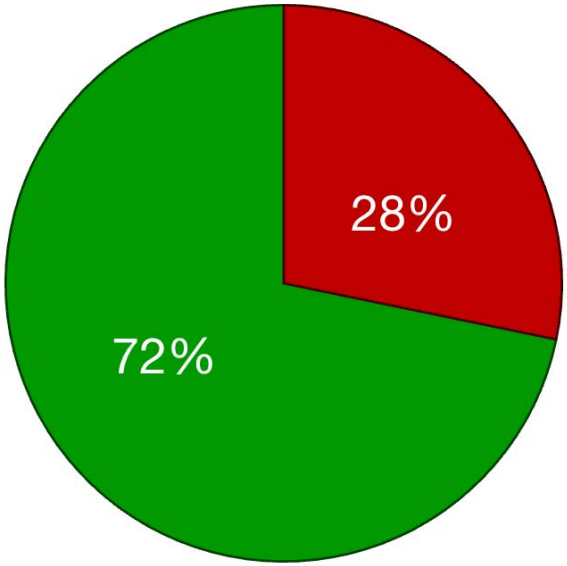


Chi2 = 8.58, p = 0.003

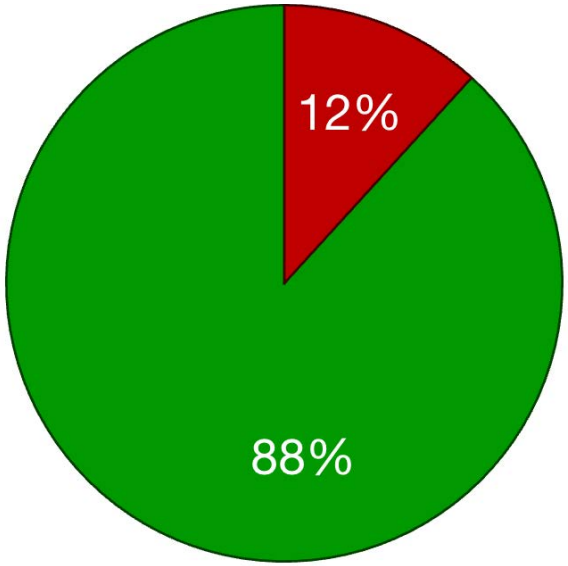
EEG characteristics predict one-year outcomes

EEG and Admission Diagnosis

Admission diagnosis



Admission + EEG diagnosis



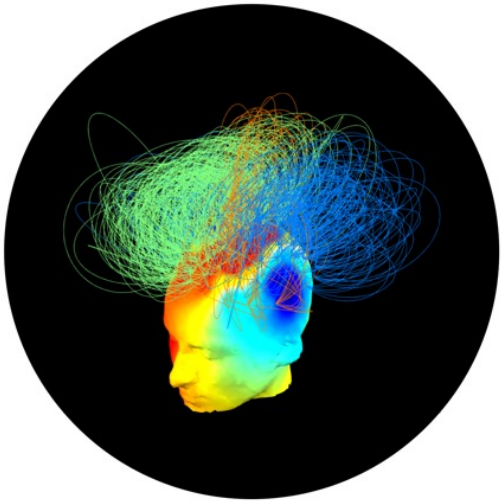
Fisher's exact test odds ratio = 0.34, p = 0.01

Accurate clinical diagnosis
Misdiagnosed

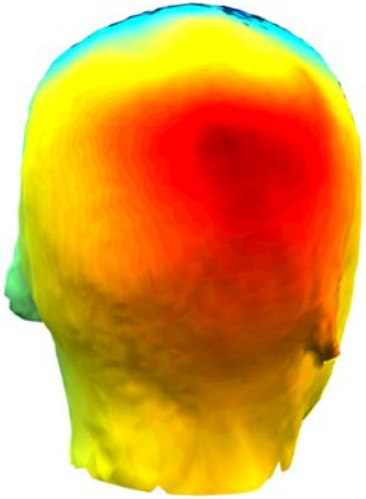
Accurate clinical or EEG diagnosis
Misdiagnosed

EEG significantly improves accuracy of admission diagnosis

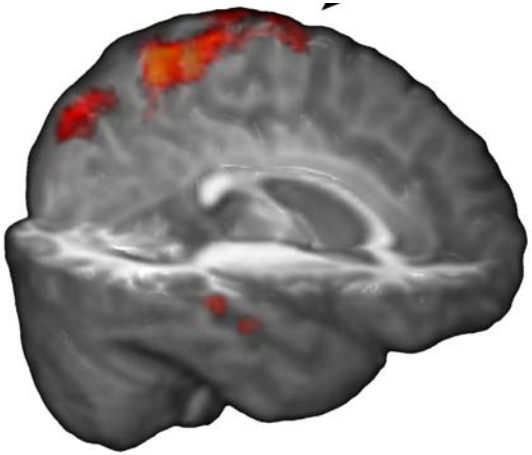
Convergence in Individual Patients



Robust Small-world networks



P300b



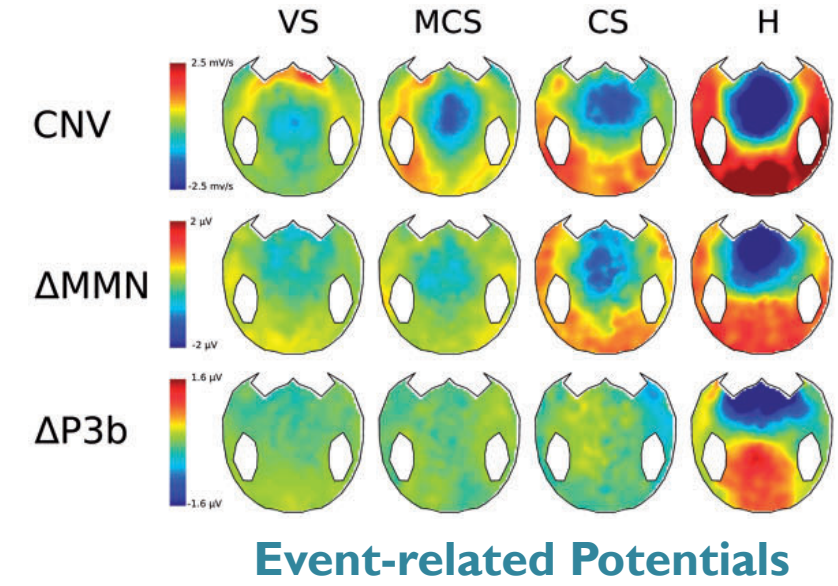
Tennis imagery

Promising convergent evidence in a vegetative patient who was

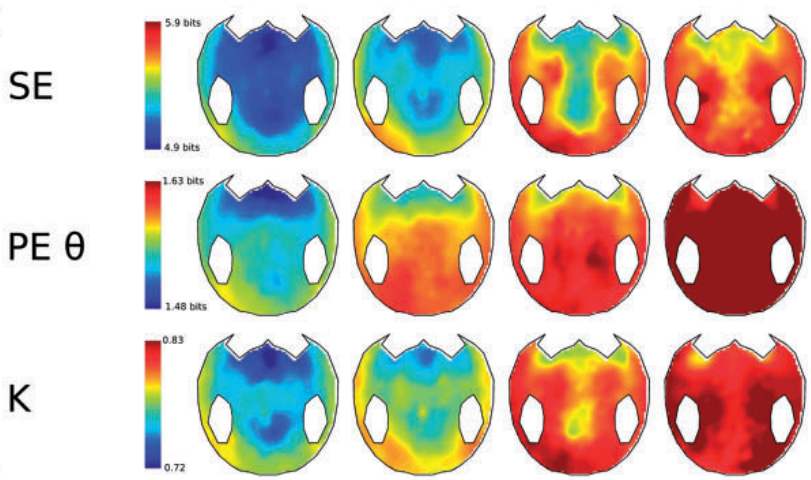
[redacted] discharged on 23rd September 2011. He was in coma throughout his stay at Addenbrooke's and his neurological state on discharge was again coma with a Glasgow Coma Score of E1, VT, M3.

but made a behavioural recovery to full consciousness within a year.

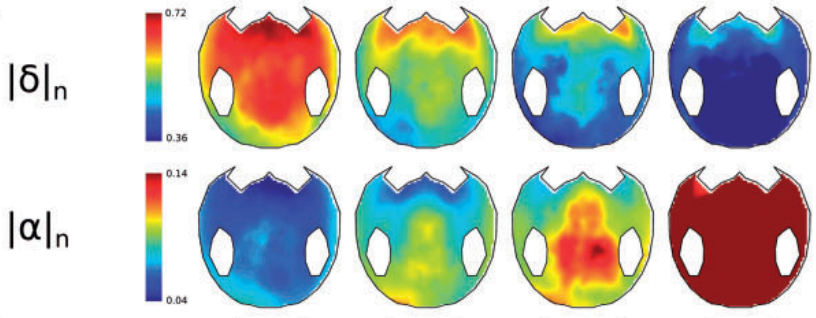
Neural Signatures of Consciousness



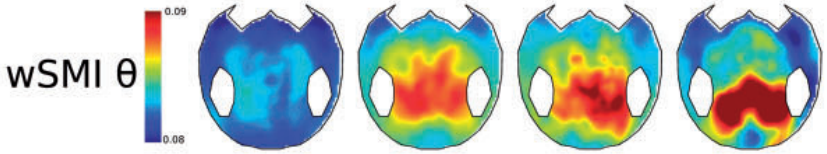
Event-related Potentials



Signal complexity



Power



Brain Connectivity

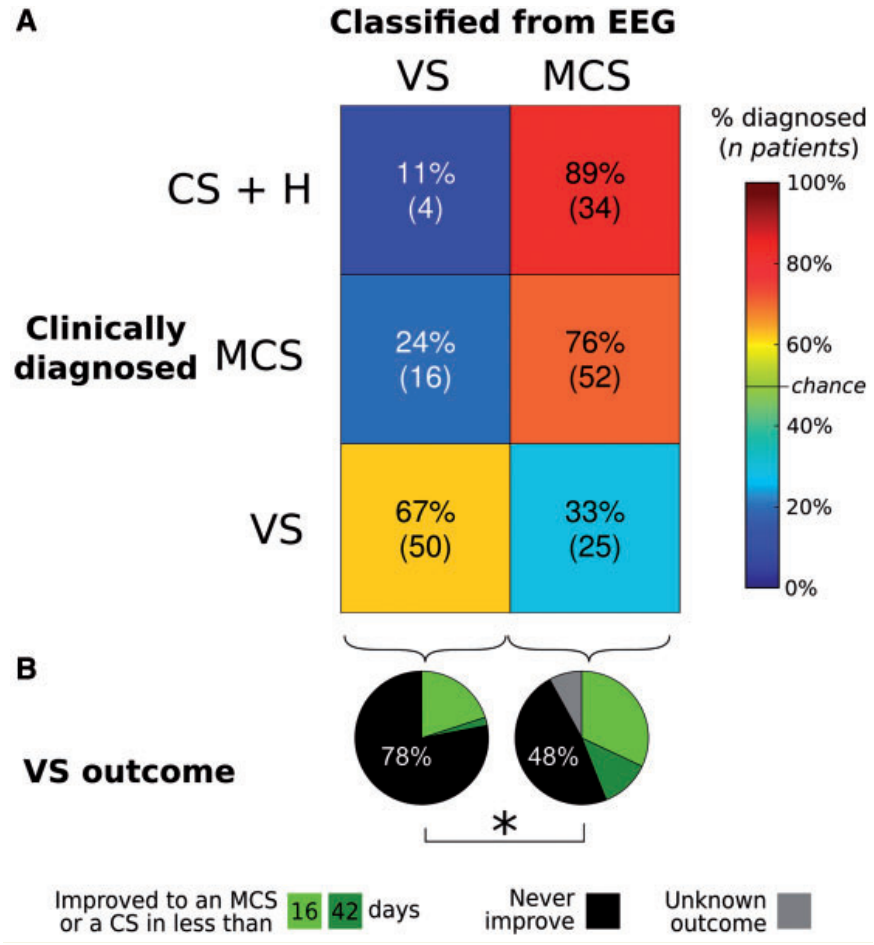
A range of EEG-derived brain measures track the level of consciousness
Machine-learning to develop classification tools available at the bedside

Sitt et al., 2014

Current Challenges

- Machine learning has been applied to detect consciousness using EEG
- Significant **divergence** due to
  - Arousal variation
  - Motivation and cognitive state
  - Signal quality and reliability

– A current research challenge
  - Fundamental requirement for clinical utility
  - And **bedside deployment** alongside clinical assessment



Sitt et al., 2014

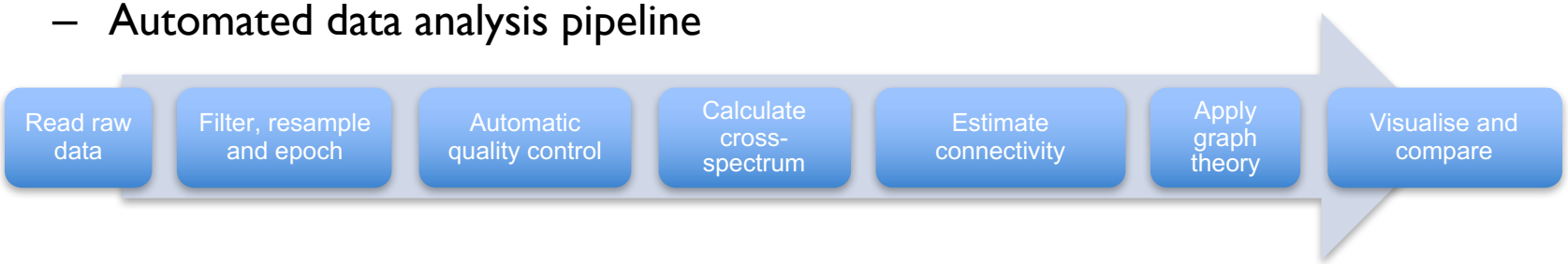
Summary

- **EEG Connectomics**
  - Applications in Disorders of Consciousness
- **Shadows of underlying cortical networks**
  - Correspondence with resting networks from fMRI
- **Applications**
  - Clinical diagnostics and prognostics
  - Bedside monitoring

Evelyn Trust Project

Recently funded Evelyn Trust funded project to develop

- Feasible frameworks to take EEG to the patient
- Aim to **longitudinally** acquire and analyse functional EEG
  - right at the patient's beside, in rehabilitation centres in Cambridgeshire
  - Automated data analysis pipeline



- Develop clinically valuable EEG metrics and visualisations
  - Assess their diagnostic and prognostic utility
  - And relevance to individual patient trajectories

The Evelyn Trust

Multi-centre Research

UNIVERSITY OF CAMBRIDGE

University of Kent

James S. McDonnell Foundation

NHS National Institute for Health Research

The Evelyn Trust

John Pickard

Judith Allanson

David Menon

Thanks!

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Cambridge

Adrian Owen

Canada