Human consciousness

Beryl Li

Group Meeting Literature Review

September 22nd, 2021

Art credit: Tasuya Ishida

“Brain in a vat” in different cultures across the world

The material world is an illusion (“Maya”) over the soul

Hinduism (1200 BC)

“Suddenly he woke up … but he didn't know if he was Zhuang Zhou who had dreamt he was a butterfly, or a butterfly dreaming that he was Zhuang Zhou”

Taoist philosophy (300 BC)

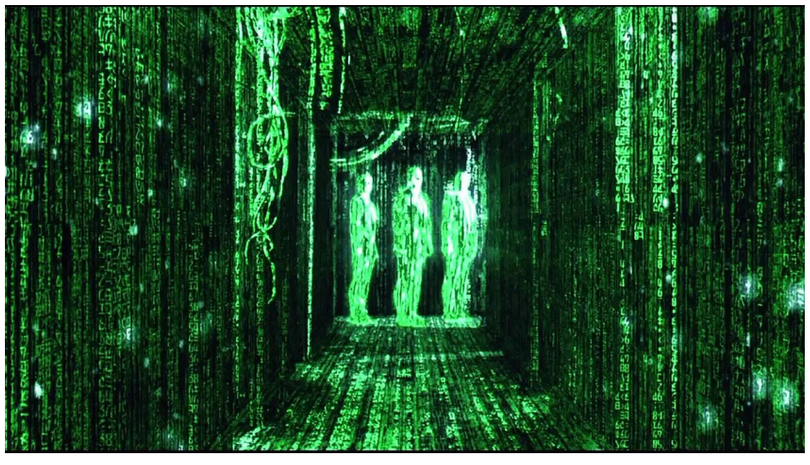
An evil demon of “the utmost power … to deceive me”

Descartes (1641)

Cartesian philosophy

The Allegory of the Cave

Plato (514 AD)



“If real is what you can feel, smell, taste and see, then 'real' is simply electrical signals interpreted by your brain”

The Matrix (2001)

“Brain in a vat” in different cultures across the world

An evil demon of “the utmost power … to deceive me”

Descartes (1641)
Cartesian philosophy

*Consciousness is our **only** interface with the world.*

René Descartes (1637)
“I think, therefore I am”

The “hard problem”

The “easy problem”

How the brain gives rise to

- Perception
- Cognition
- Learning
- Behavior

The “hard problem”

Why and how does this relate to consciousness?

The study of **human consciousness** may appear untenable at a glance.

Chalmers, D. *The Conscious Mind: in Search of a Fundamental Theory.* New York: Oxford University Press, **1996**.

The “hard problem”

The “easy problem”

How the brain gives rise to

- Perception
- Cognition
- Learning
- Behavior

The “hard problem”

Why and how does this relate to consciousness?

Without pretending it doesn’t exist

The *real* problem

How to account for various properties of consciousness in terms of biological mechanisms

Without worrying about explaining its ultimate origin

Chalmers, D. *The Conscious Mind: in Search of a Fundamental Theory.* New York: Oxford University Press, **1996**.

Historic parallels with the study of life

George Louis Leclerc (1749)
Hypothetical material units called "organic molecules"

René Descartes (1637)
"I think, therefore I am"

Neither is "one thing", but they have many potentially separable aspects

Encyclopedia Britannica (2020)
Life is defined as any system capable of performing functions such as eating, metabolizing, excreting, breathing, moving, growing, reproducing, and responding to external stimuli.

Modern studies of consciousness

Tirard, S.; Morange, M.; Lazcano, A. *Astrobiology* **2010**, *10* (10), 1003.

Outline

Conscious *level*

e.g. vividly awake vs. dreamless sleep

Conscious *content*

What populates your experience when you are awake

- sights, sounds, smells
- emotions, thoughts, beliefs

Conscious *self*

specific experiences of *being you*

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Conscious level

What are the fundamental brain mechanisms that underlie our ability to be conscious at all?

It is NOT…

- simply being awake

  (consider dreaming, or dream/wake cycles in vegetative states)

- the number of neurons

  (the cerebellum has 4X neurons as the rest of the brain, while barely involved in maintaining consciousness)

DiNuzzo, M.; Nedergaard, M. *Curr. Opin. Neurobiol.* **2017**, *47*, 65.

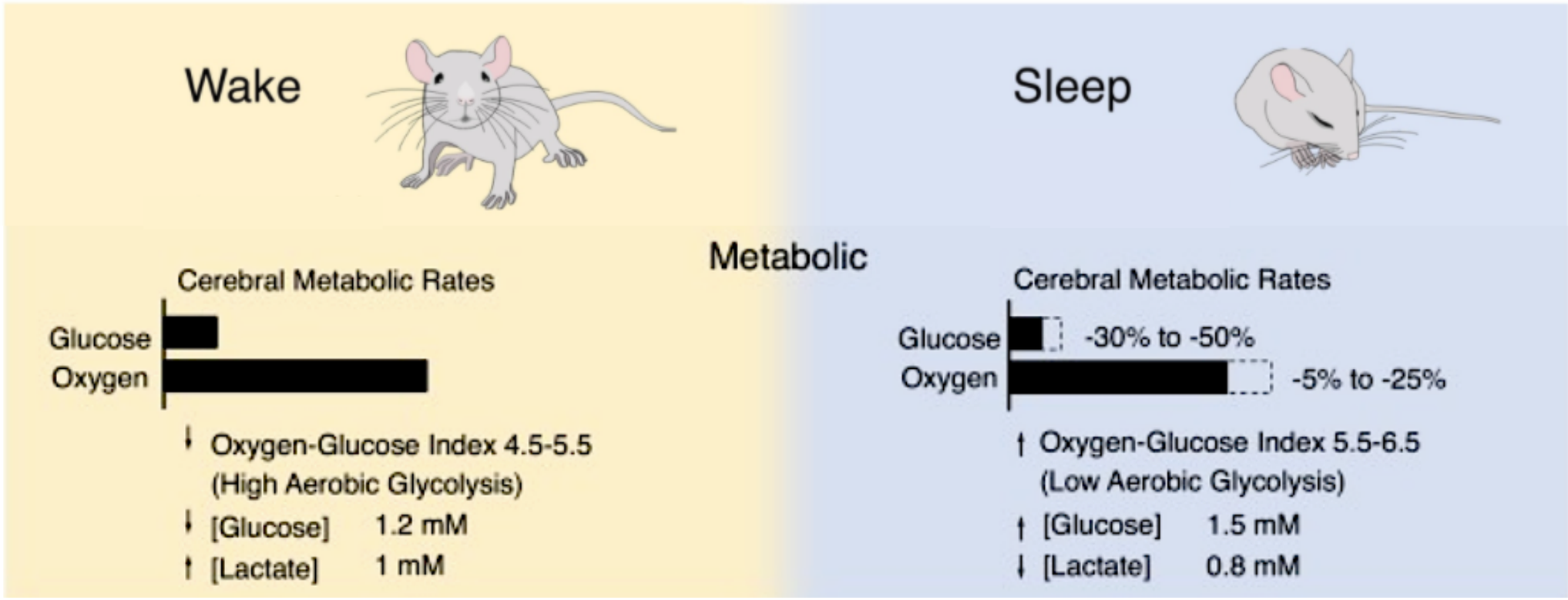
Conscious level

What are the fundamental brain mechanisms that underlie our ability to be conscious at all?

It is NOT…

- the overall level of neural activity

Energy use during non-rapid eye movement sleep is ~85% of that during waking state



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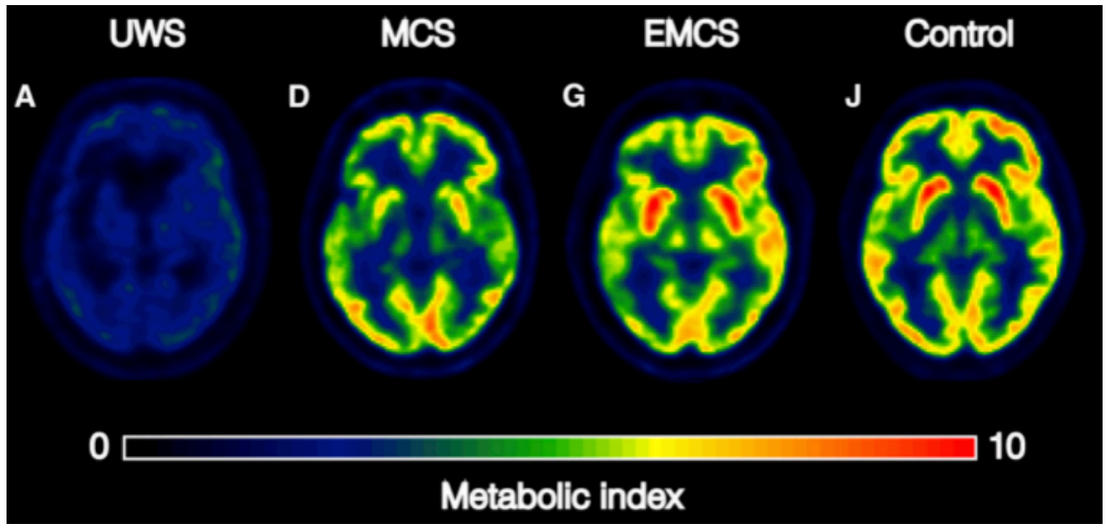
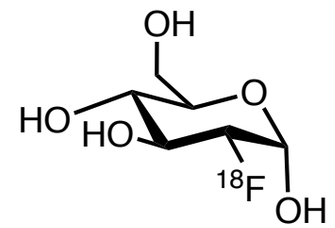


Representative PET images across different patients

[^{18}F]-fluorodeoxyglucose



UWS: unresponsive wakefulness syndrome
MCS: minimally conscious state
EMCS: emerging from MCS

Stender, J. *et al. Curr. Biol.* **2016**, *26*, 1497.

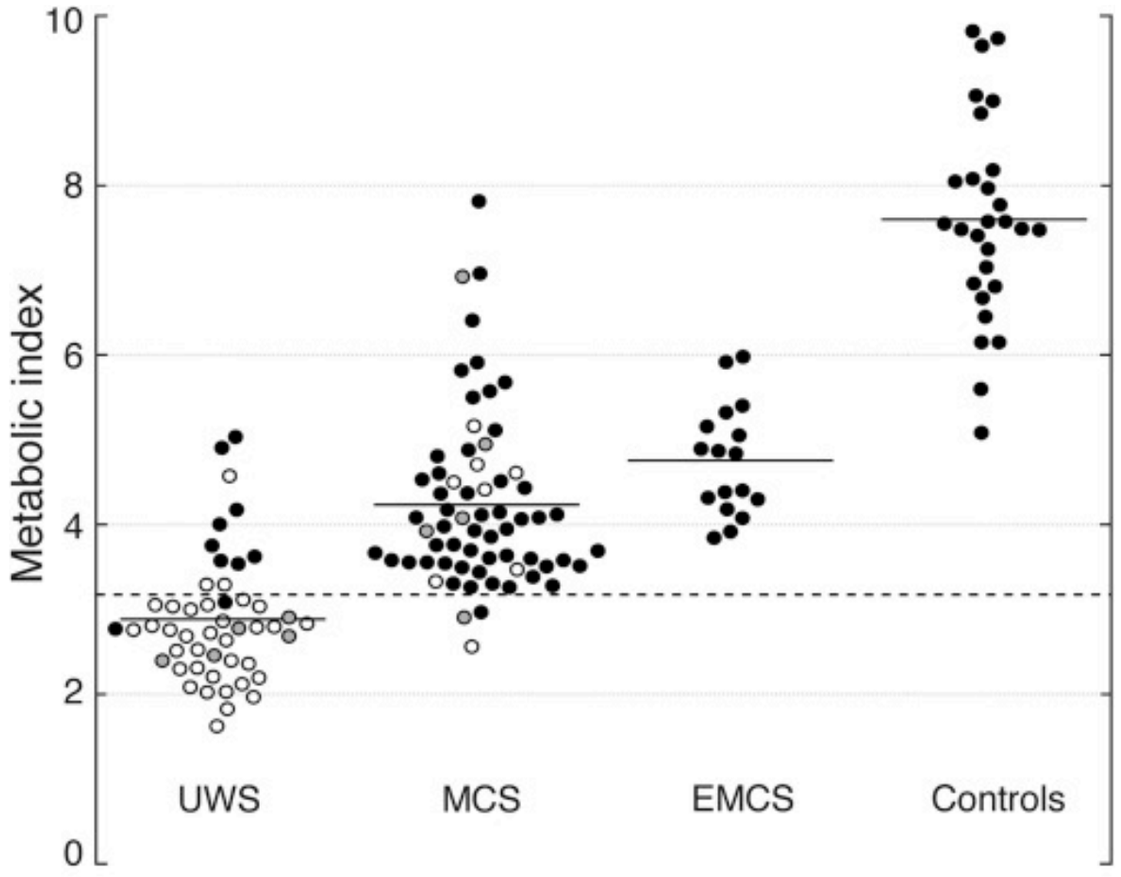
Conscious level

What are the fundamental brain mechanisms that underlie our ability to be conscious at all?

It is NOT…

- the overall level of neural activity

Consciousness can be sustained <42% of the energy in healthy conscious individuals.



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Conscious level

What are the fundamental brain mechanisms that underlie our ability to be conscious at all?

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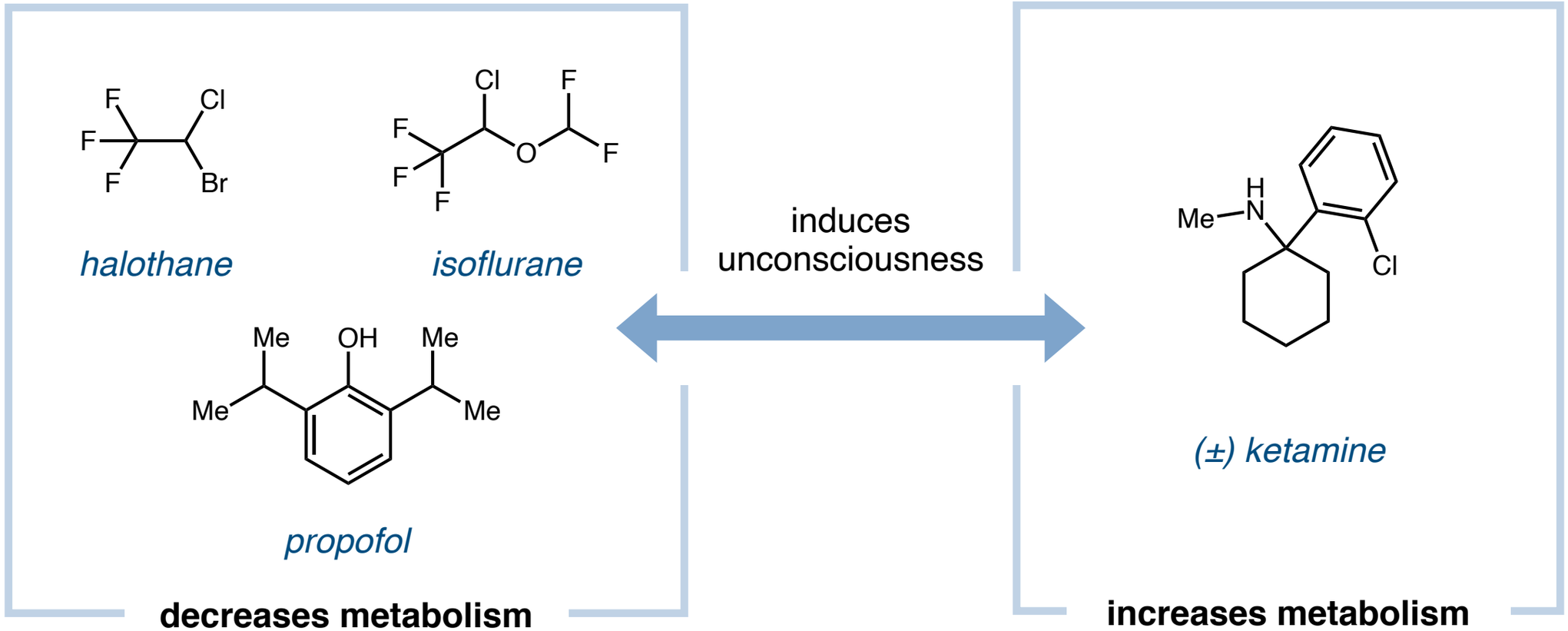
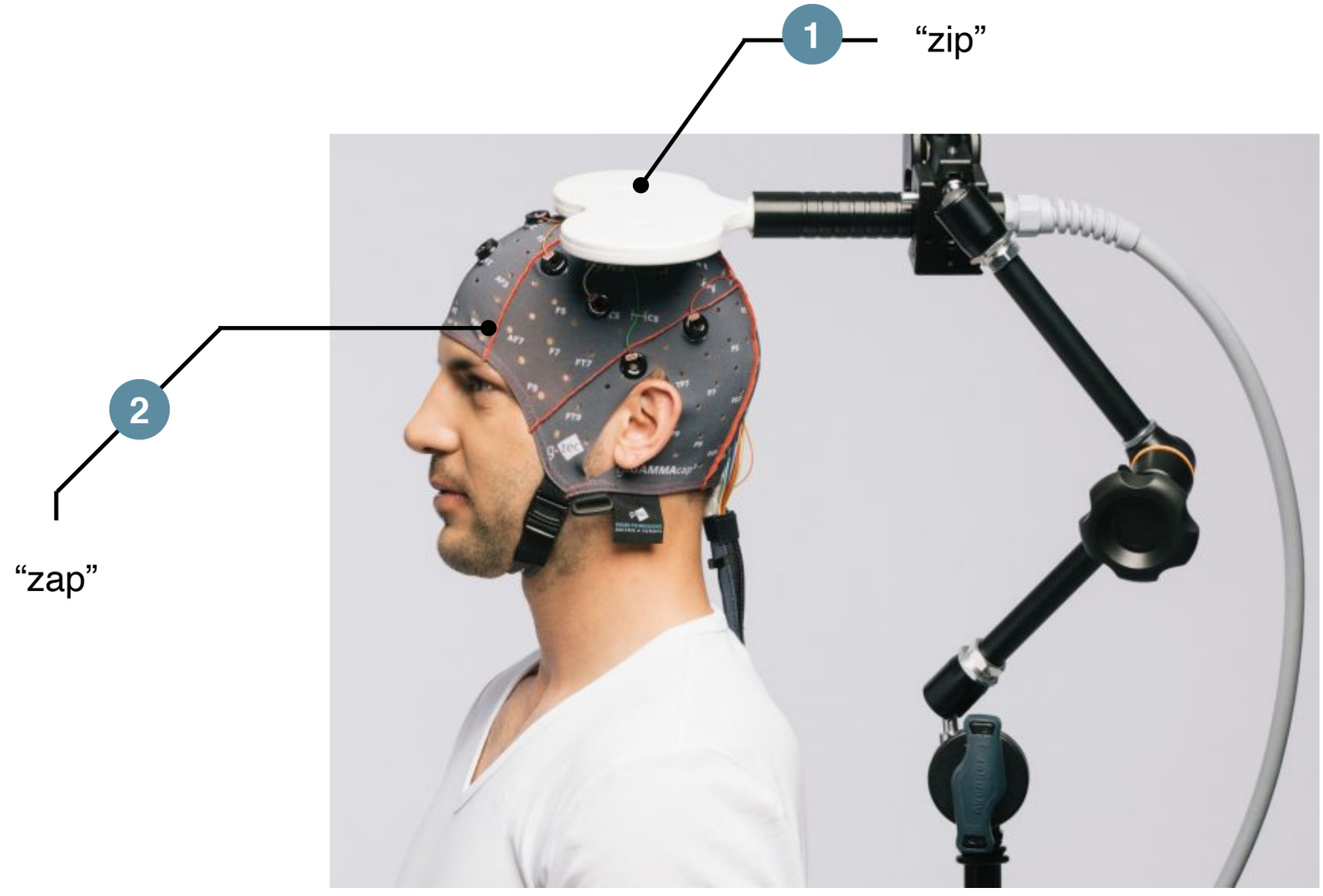
Unconsciousness induced by anesthetics does not correlate with brain metabolism.



Hudetz, A.G. *Brain Connect.* **2012**, *2* (6), 291.
Pai, A.; Heining, M. *Contin. Educ. Anaesth. Crit. Care Pain* **2007**, *7*, 59.

Conscious level reflected by crosstalk between different sections of the brain



*Pioneered by **Giulio Tononi** (University of Wisconsin, Madison) and **Marcello Massimini** (University of Milan)*

Photo credit: g.tec medical engineering GmbH Austria

Napolitani, M. *Brain Inj.* **2014**, *28*, 1180.

Conscious level reflected by crosstalk between different sections of the brain

1

Transcranial magnetic stimulation (TMS)

Magnetic pulses

2

Electroencephalography (EEG)

Cascaded ion movements across neurons propagate to the scalp in the form of a wave, then detected by electrodes.

Secondary ionic currents in neurons

Localized depolarization

*Pioneered by **Giulio Tononi** (University of Wisconsin, Madison) and **Marcello Massimini** (University of Milan)*

Photo credit: g.tec medical engineering GmbH Austria

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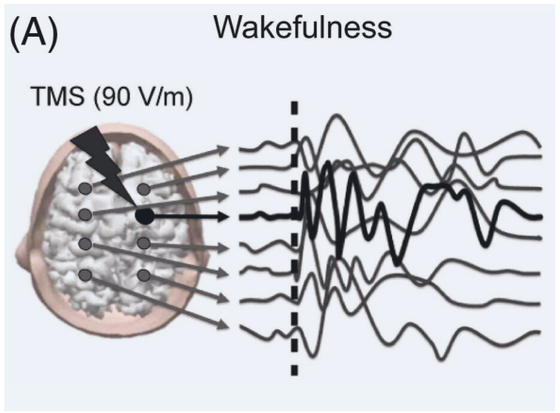


EEG signal at location of TMS stimulus

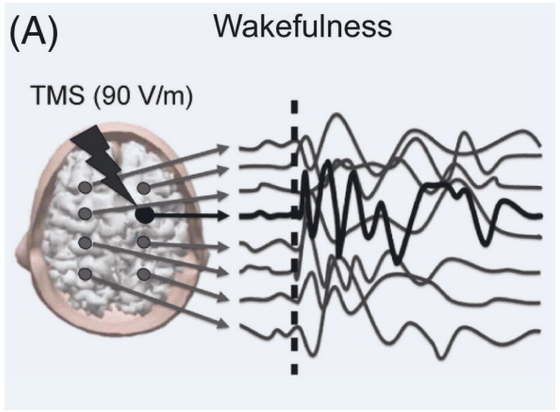
EEG signal other areas of the brain

Conscious *Complex resonances across the brain*	**Wakefulness**

MCS: minimally conscious state

Napolitani, M. *Brain Inj.* **2014**, *28*, 1180.

Conscious level reflected by crosstalk between different sections of the brain



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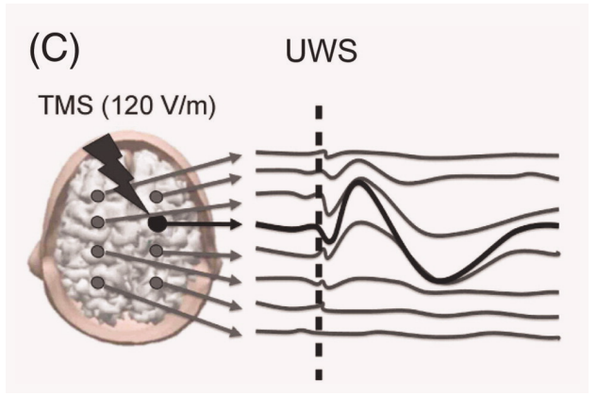
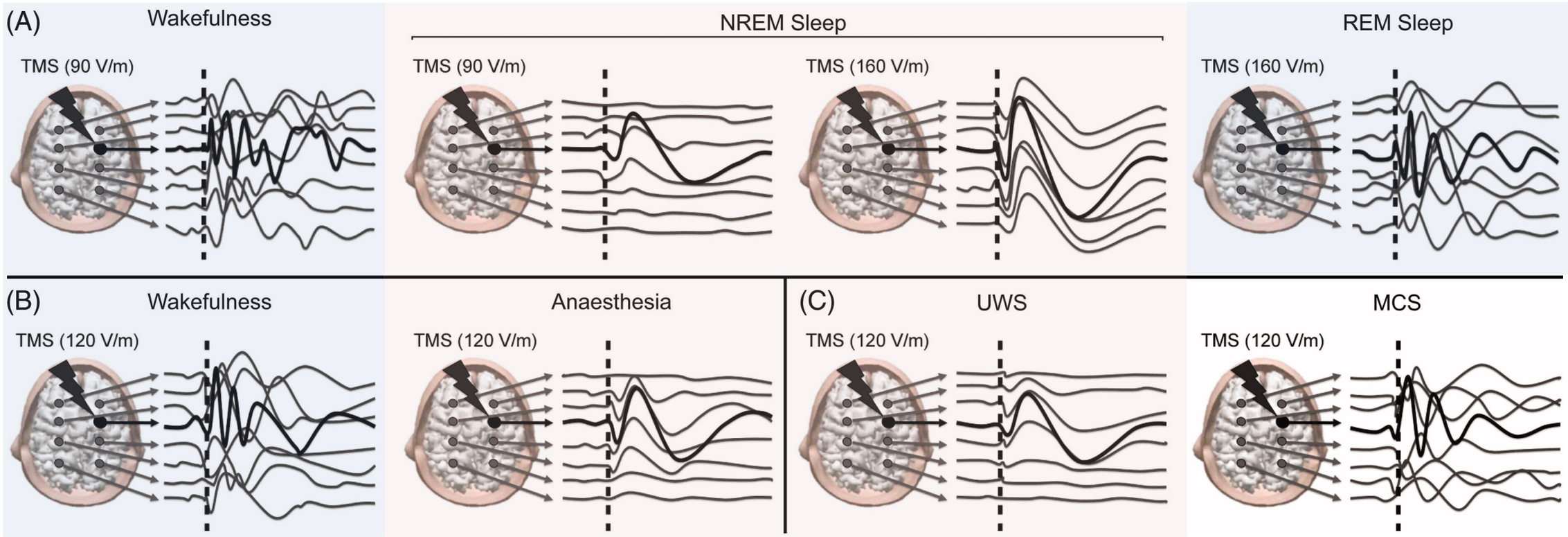


Conscious *Complex resonances across the brain*	**Wakefulness**	***Unconscious*** *simple echo to stimulus*
	UWS: unresponsive wakefulness syndrome	

Napolitani, M. *Brain Inj.* **2014**, *28*, 1180.

Conscious level reflected by crosstalk between different sections of the brain



Conscious
Complex resonances across the brain

Wakefulness
REM: rapid eye movement (dreaming)

NREM sleep: non-rapid eye movement (not dreaming)
Anesthesia
UWS: unresponsive wakefulness syndrome

Unconscious
simple echo to stimulus

MCS: minimally conscious state

Napolitani, M. *Brain Inj.* **2014**, *28*, 1180.

There is a clinical need to reliably and objectively assess the level of consciousness of patients.

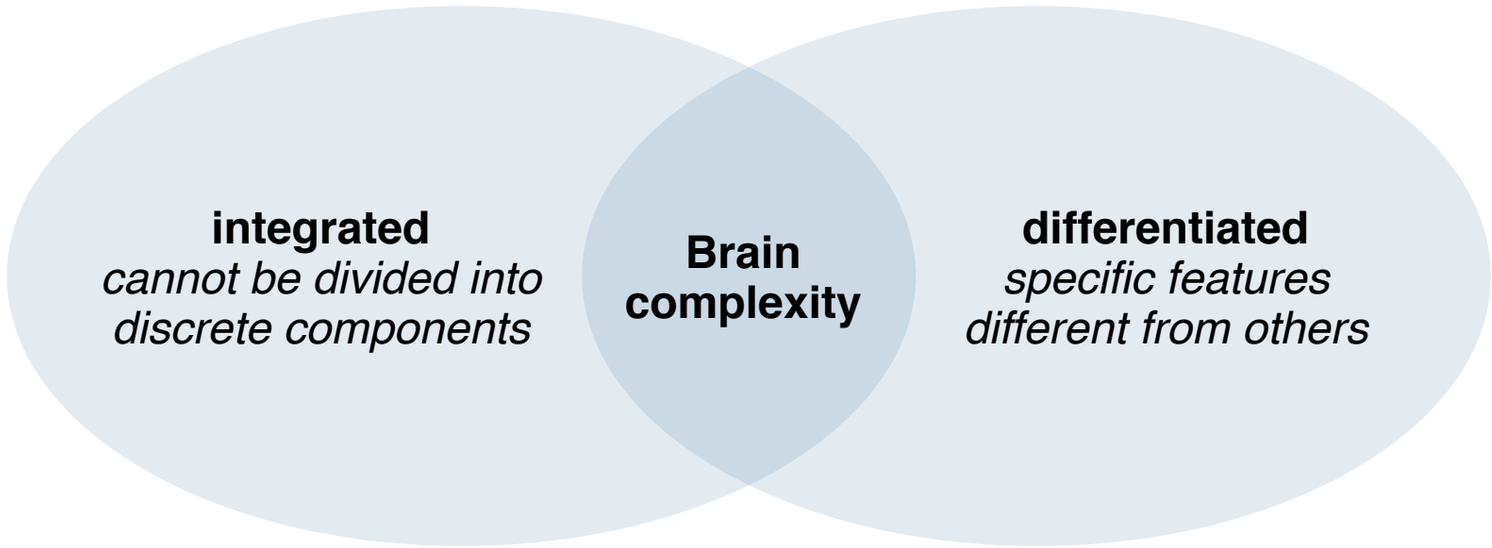
(e.g. locked-in syndrome)

How can we *quantify* consciousness level?

"In physical science the first essential step in the learning of any subject is to find principles of numerical reckoning and practicable methods for measuring some quality connected with it."

–Lord Kelvin, on the development of accurate thermometers

Two key attributes to quantifying consciousness

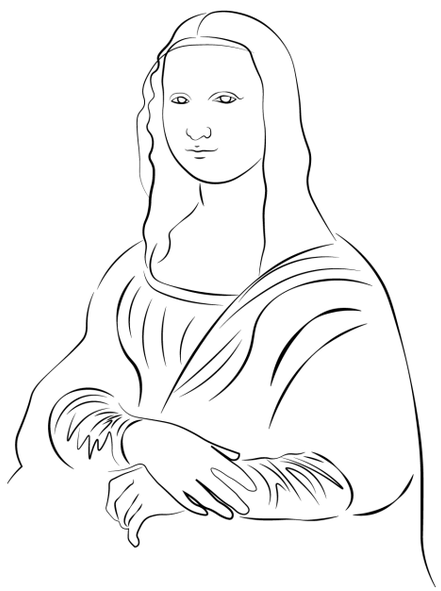


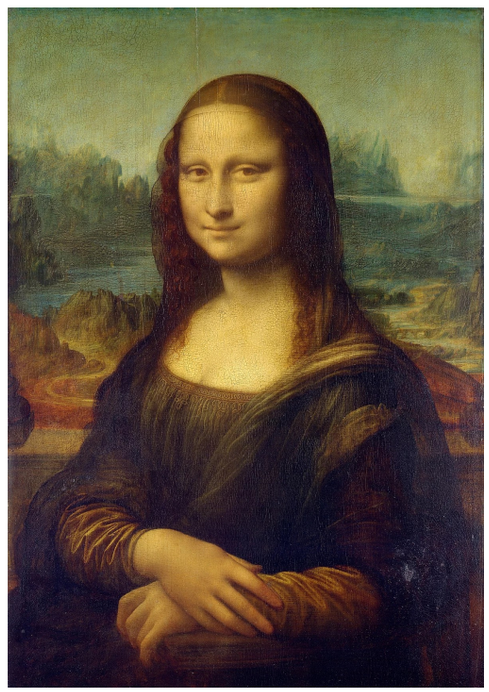
Key theoretical insight:

consciousness requires an optimal balance of **functional integration** and **functional differentiation**

Casali, A. G. *Sci. Transl. Med.* **2013**, *5*, 198ra105.

Perturbational complexity index (PCI) to quantify conscious level





low complexity → *high complexity*

Key theoretical insight:

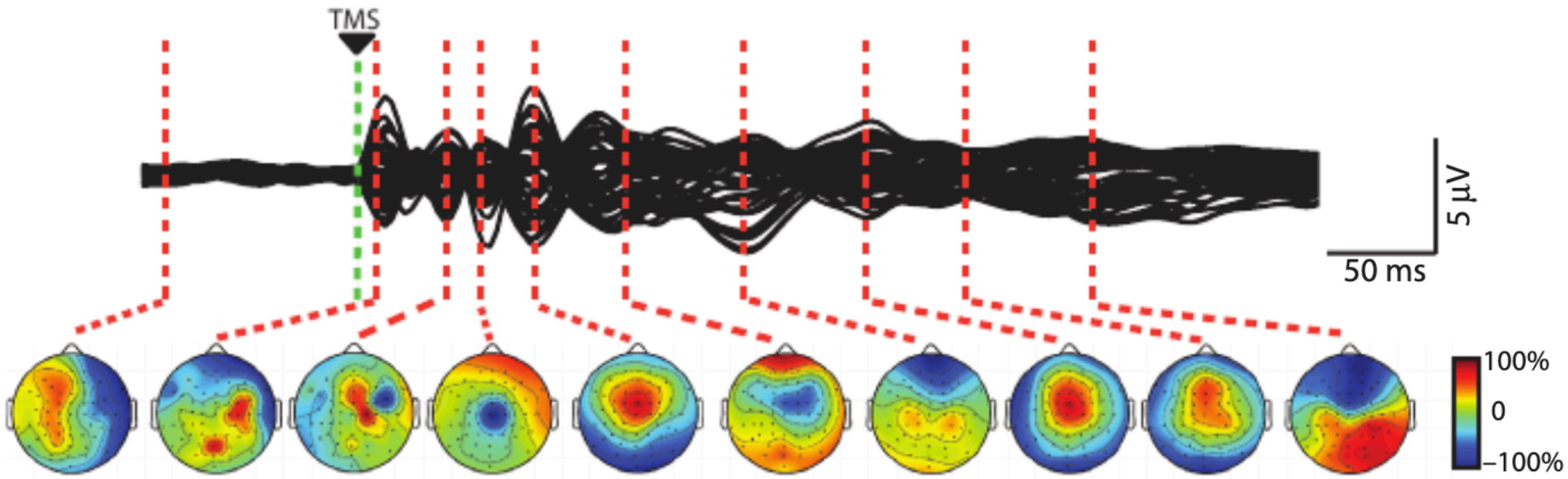
consciousness requires an optimal balance of **functional integration** and **functional differentiation**

quantified by how "compressible" they are, similar to how digital photos are compressed

Casali, A.G. *et al. Sci. Transl. Med.* **2013**, *5*, 198ra105.

Perturbational complexity index (PCI) to quantify conscious level

1 Transcranial magnetic stimulation (TMS)

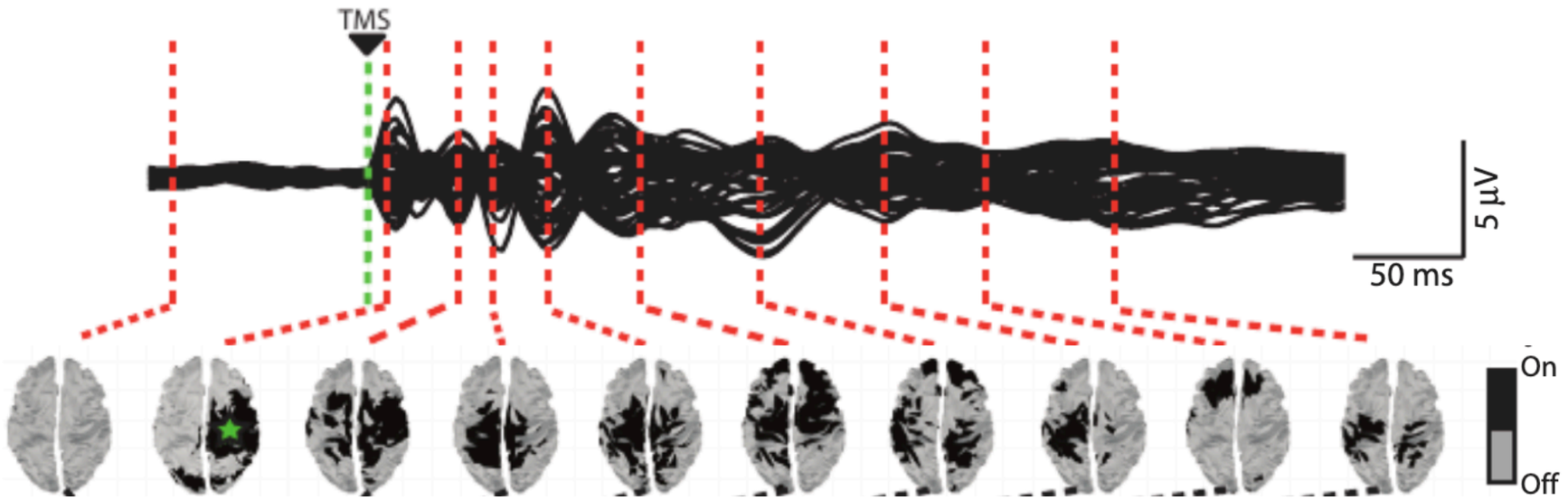


2 Electroencephalography (EEG) signal across 60 electrodes

Casali, A.G. *et al. Sci. Transl. Med.* **2013**, *5*, 198ra105.

Perturbational complexity index (PCI) to quantify conscious level

3 Mathematical manipulations to arrive at a binary distribution
(weighted minimum norm inverse solution and nonparametric bootstrap-based statistical procedure)



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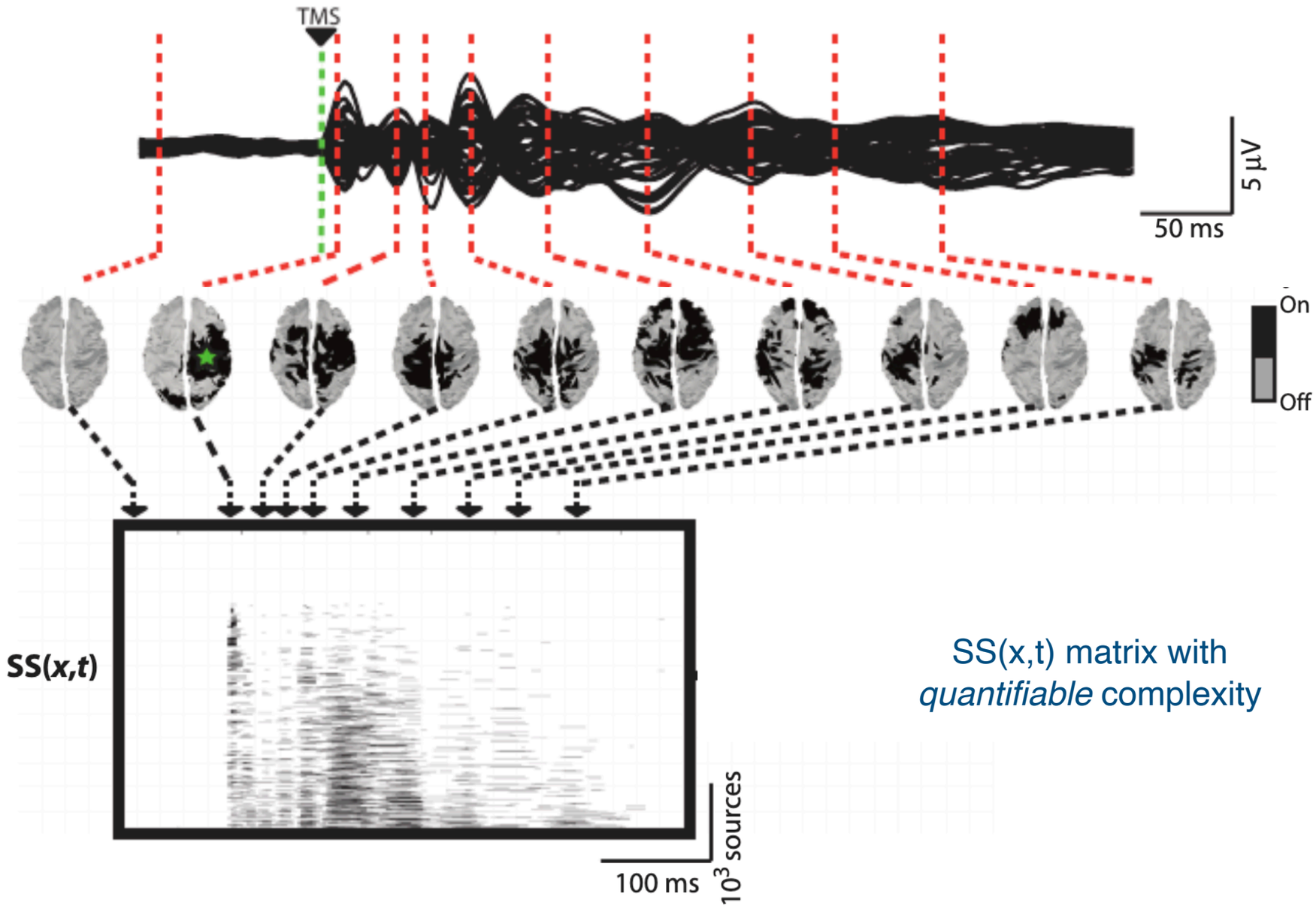

SS(x,t) matrix with
quantifiable complexity

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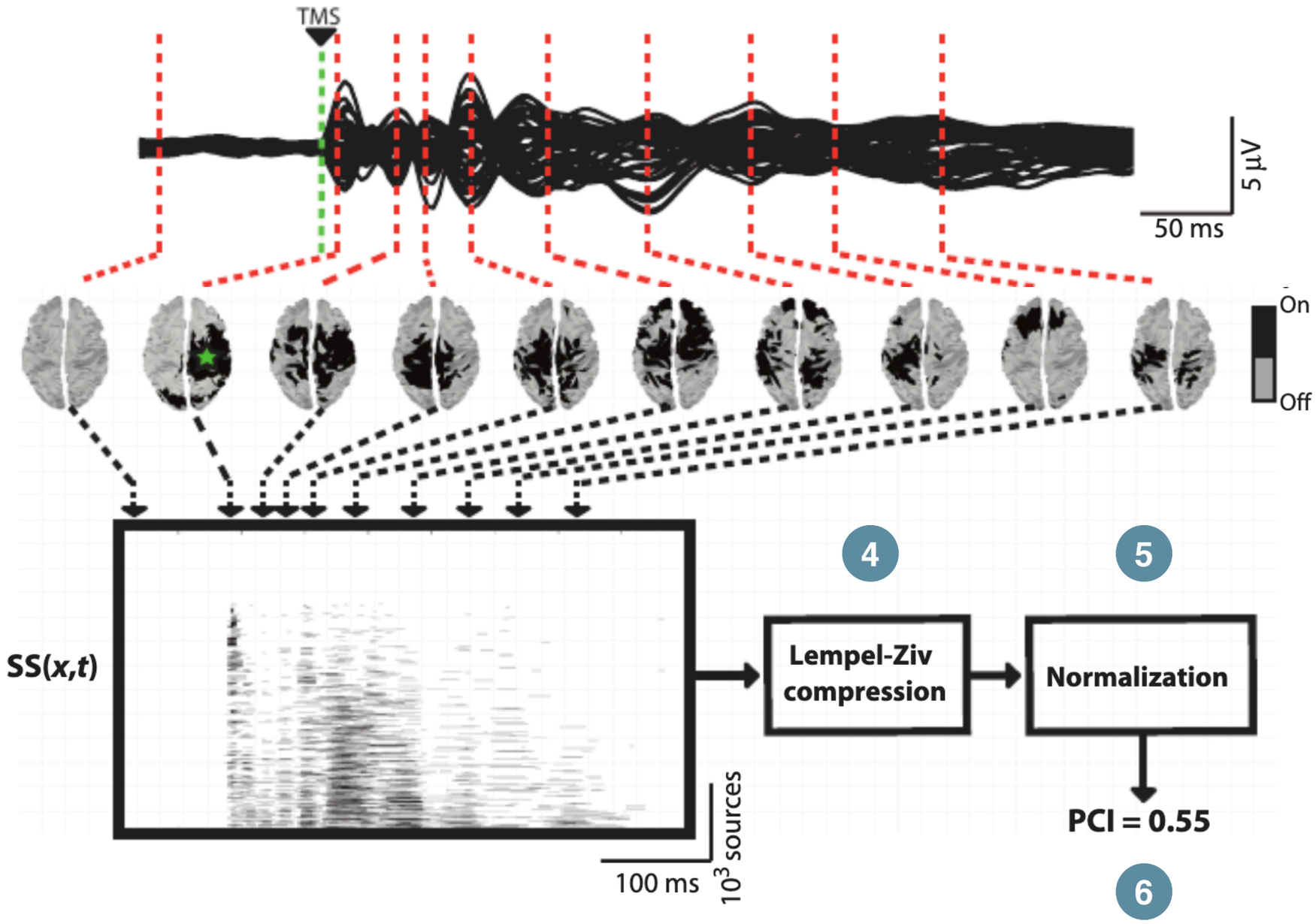
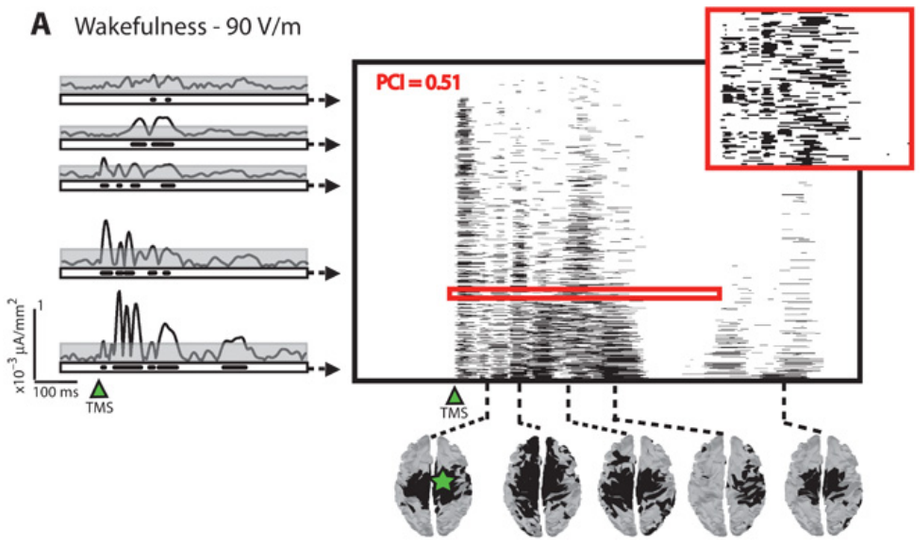
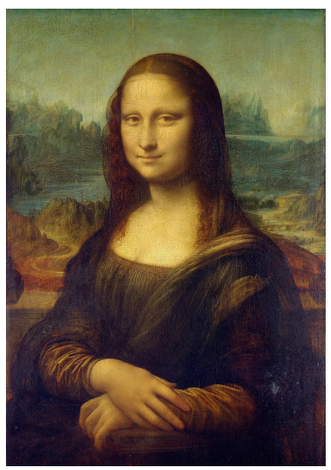


Casali, A.G. *et al. Sci. Transl. Med.* **2013**, *5*, 198ra105.

PCI is independent stimulus strength

High complexity

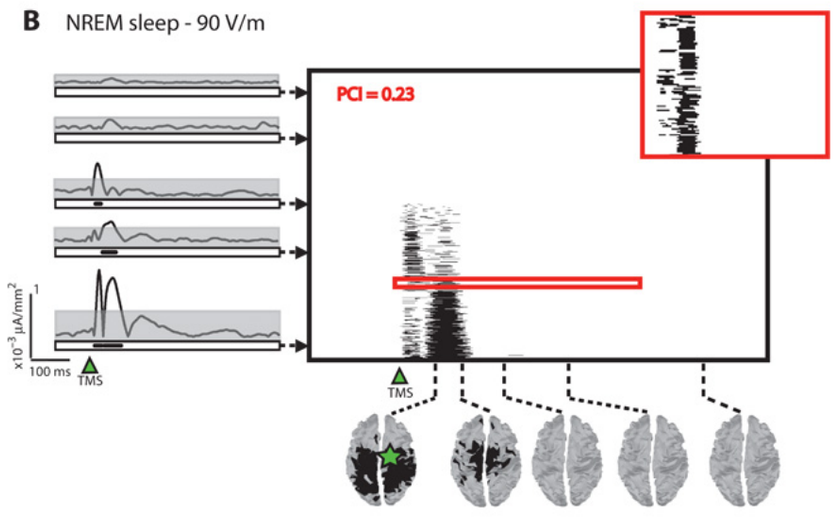


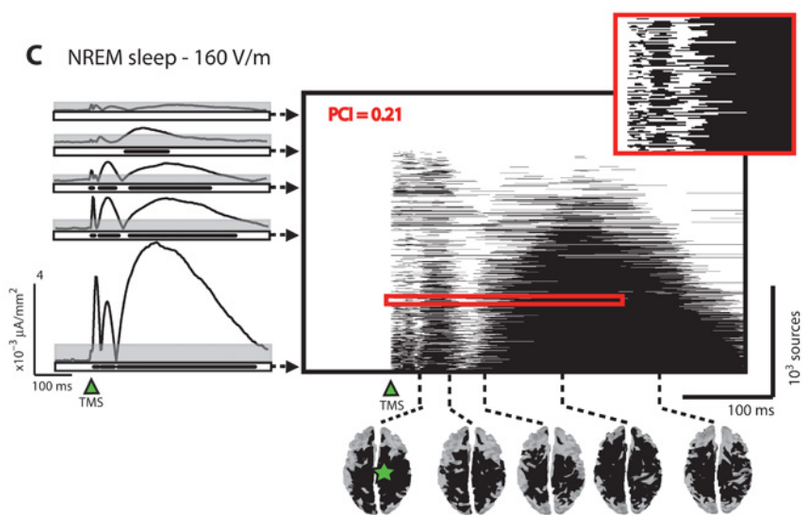


PCI is expected to be low if:

- reduced interaction among cortical areas (integration)
- perturbations all behave in a stereotypical way (differentiation)

Low complexity regardless of the extent of response to TMS

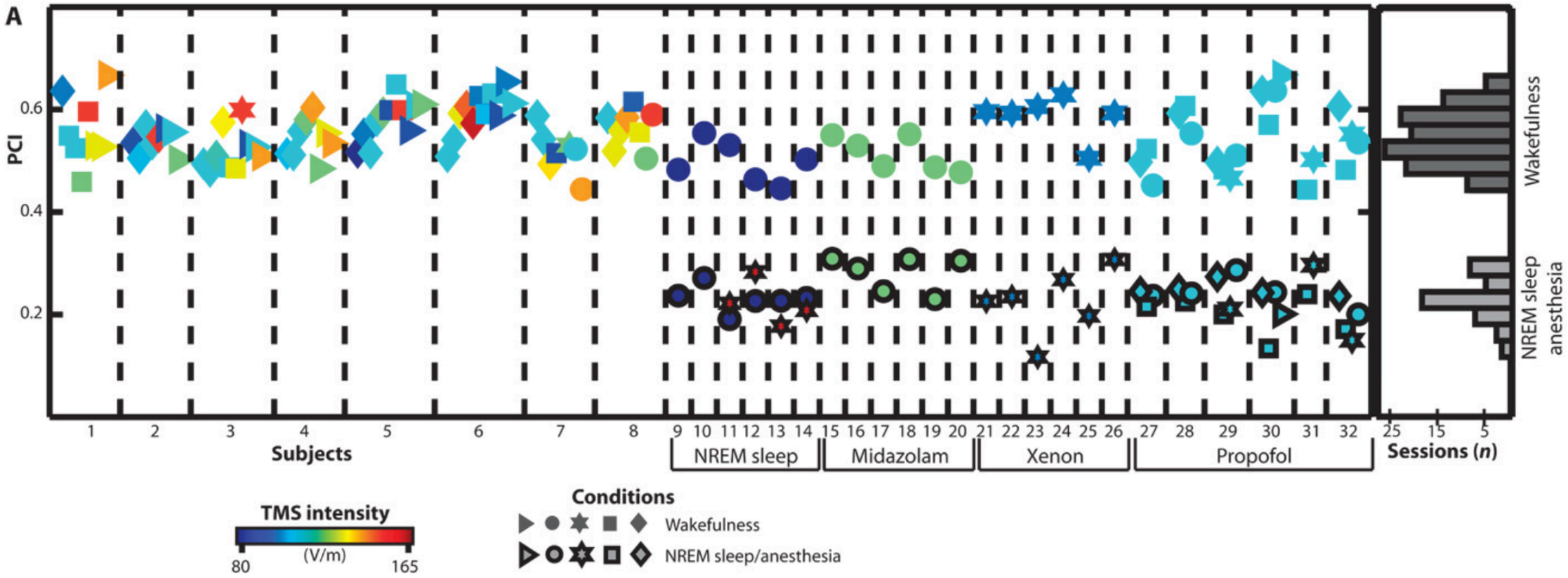




Casali, A.G. *et al. Sci. Transl. Med.* **2013**, *5*, 198ra105.

PCI is independent stimulus location

32 healthy subjects, 152 measurements (“sessions”)



TMS targets

- BA08
- BA06
- BA04
- BA07
- BA19

- *middle superior frontal gyrus (BA08)*
- *rostral portion of the premotor cortex (BA06)*
- *superior parietal gyrus (BA07)*
- *midline sensorimotor cortex (BA04)*
- *superior occipital gyrus (BA19)*

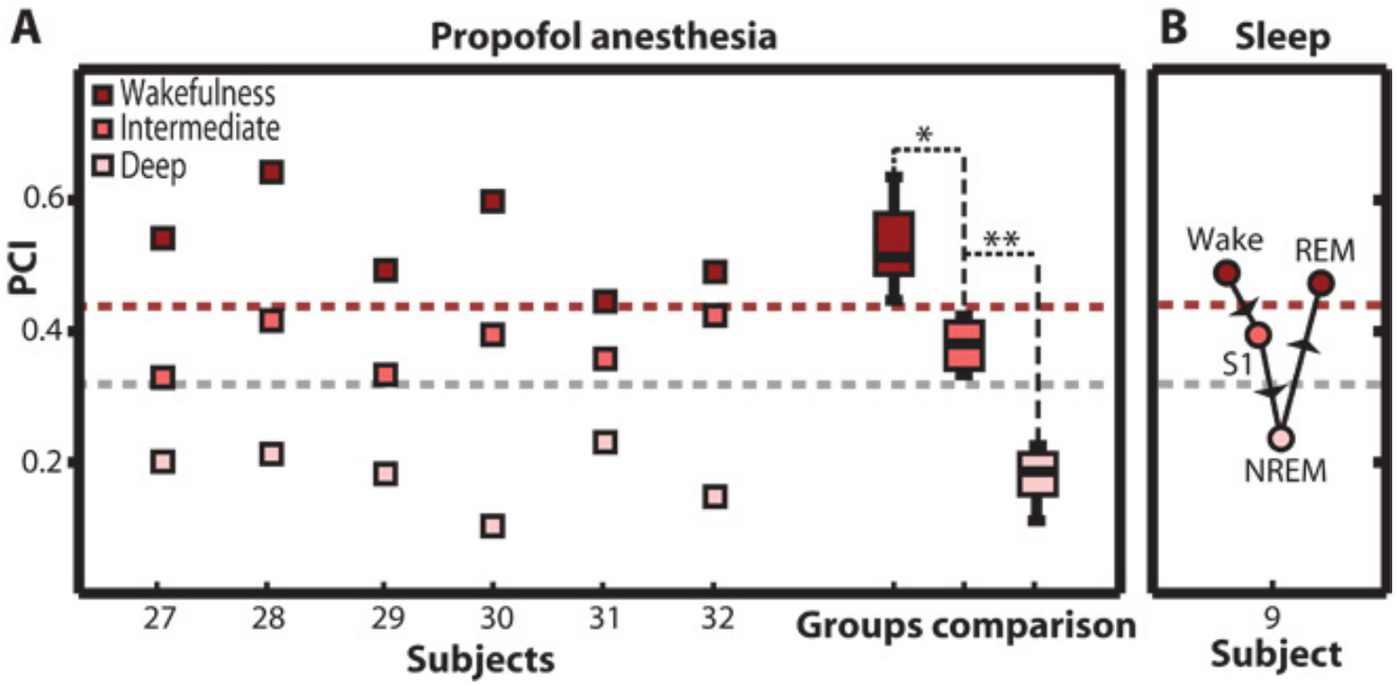
Casali, A.G. *et al. Sci. Transl. Med.* **2013**, *5*, 198ra105.

PCI is sensitive to gradient changes in consciousness

Modified Observer's Alertness/Sedation scale (MOAA/S)

Score	Description
5	Responds readily to name spoken in normal tone
4	Lethargic response to name spoken in normal tone
3	Responds only after name is called loudly and/or repeatedly
2	Responds only after mild prodding or shaking
1	Responds only after painful trapezius squeeze
0	No response after painful trapezius squeeze

Clear distinction between "intermediate" (2–3) and "deep" (0–1) anesthesia



REM: rapid eye movement (dreaming)

NREM: non-rapid eye movement (not dreaming)

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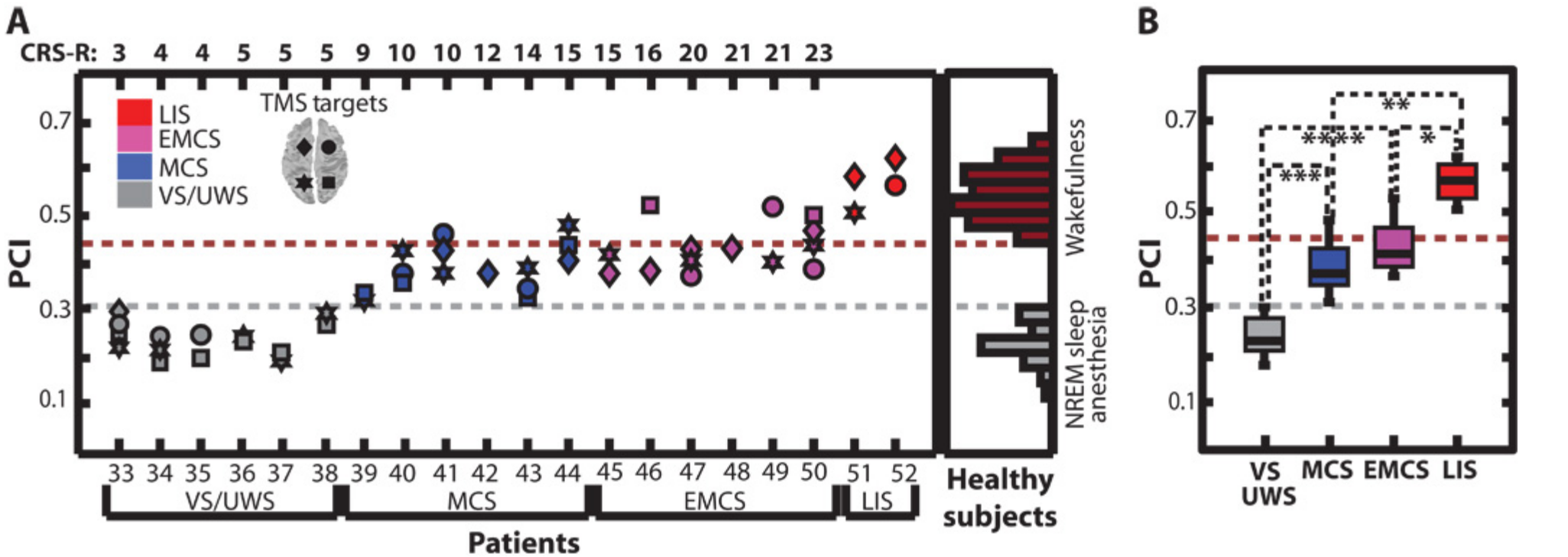
PCI useful for brain-injured patients



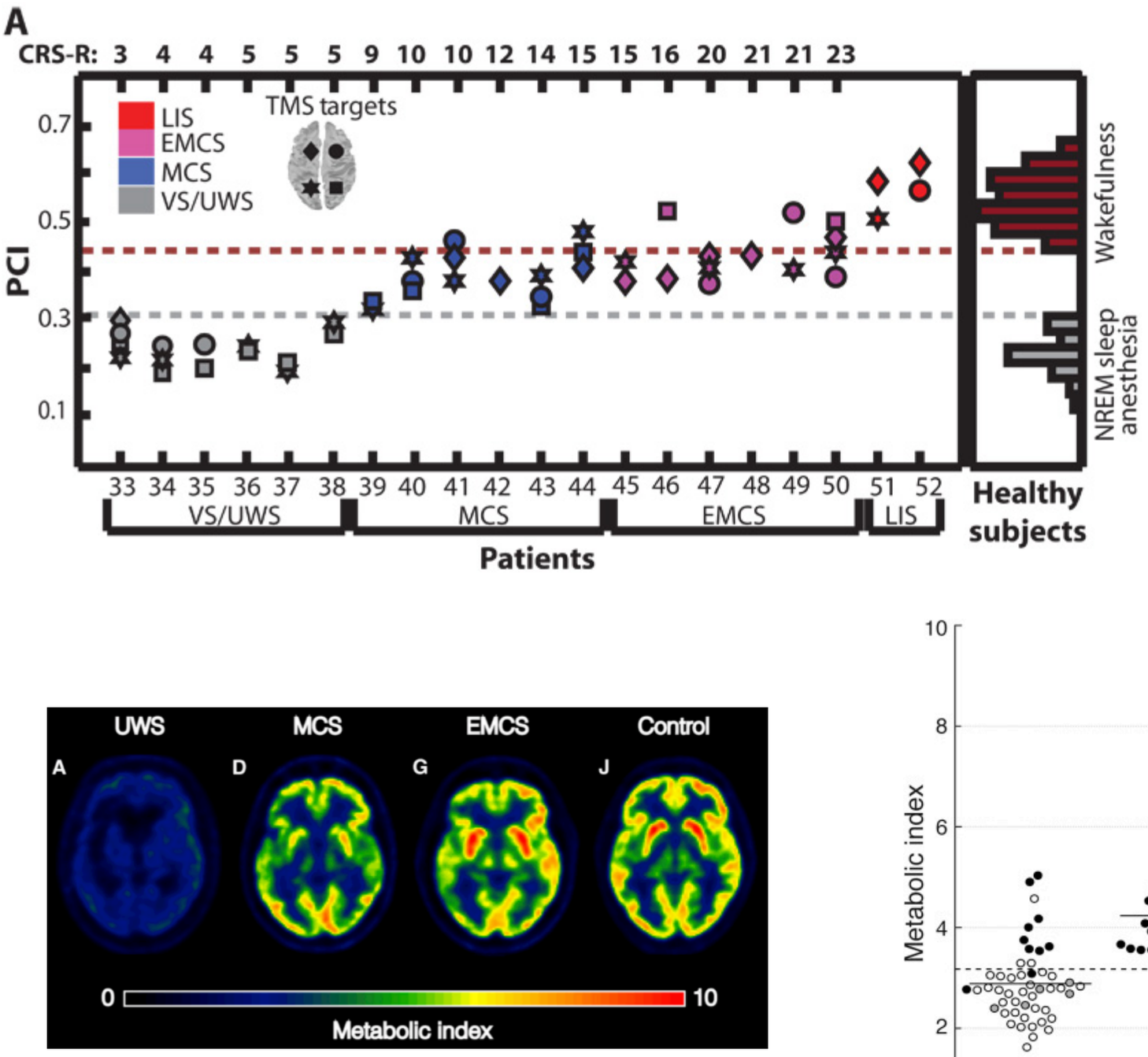
Unconscious	**VS/UWS**: vegetative state/unresponsive wakefulness syndrome	
	MCS: minimally conscious state	
	EMCS: emerging from MCS	***Conscious***
	LIS: Locked-in syndrome	

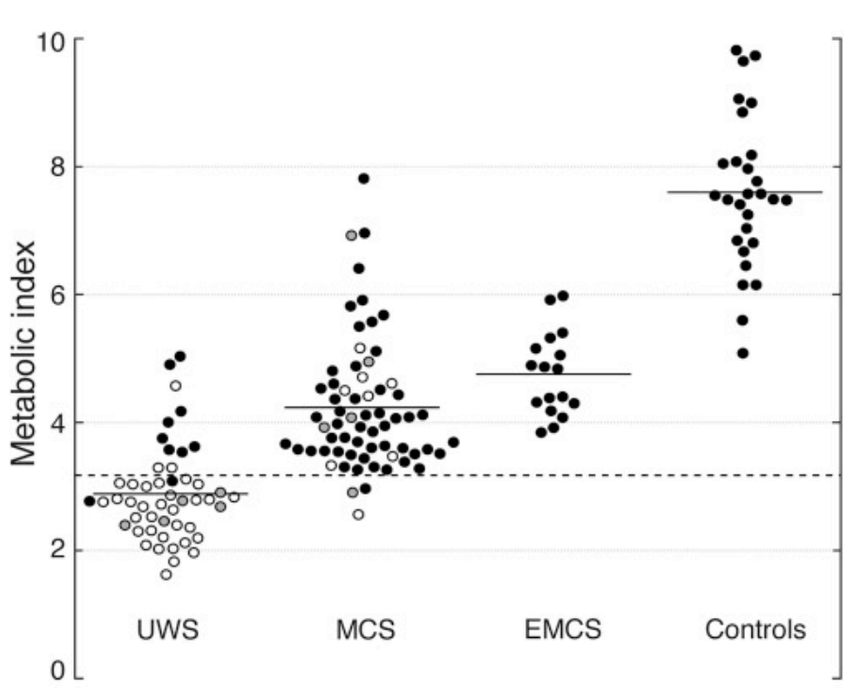
Statistical significance evaluated by a linear mixed model

$^{*}P = 0.002$, $^{**}P = 0.0001$, $^{***}P = 2 \times 10^{-5}$, $^{****}P = 8 \times 10^{-7}$

Casali, A.G. *et al. Sci. Transl. Med.* **2013**, *5*, 198ra105.

Large improvement over measuring energy consumption





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What populates your experience when you are awake

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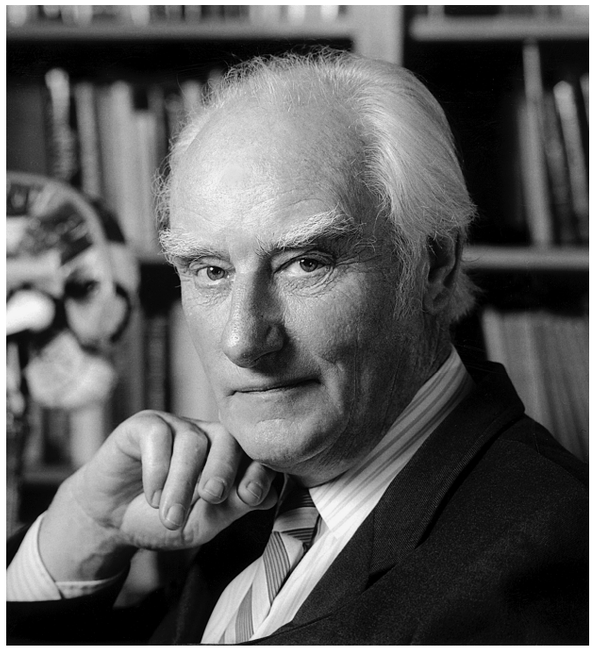
Neural correlates of consciousness (NCC)

*NCC: the **minimum** neural mechanisms sufficient for any one specific conscious percept*



Francis Crick
1996–2004

Christof Koch
1956–present

Crick, F.; Koch C. Towards a neurobiological theory of consciousness. *Seminar Neurosci.* **1990**, *2*, 263.
Crick, F.; Koch C. The problem of consciousness. *Sci Amer.* **1992**, *267*, 110.
Crick, F.; Koch C. Are we aware of neural activity in primary visual cortex? *Nature* **1995**, *375*, 121.
Crick, F.; Koch C. Why neuroscience may be able to explain consciousness. *Sci Amer.* **1995**, *273*, 66.
Crick, F.; Koch C. Constraints on cortical and thalamic projections: the no-strong-loops hypothesis. *Nature* **1998**, 391, 245.
Crick, F.; Koch C. Consciousness and neuroscience. *Cereb Cortex.* **1998**, *8*, 97.
Crick, F.; Koch C. The zombie within. *Nature* **2001**, *411*, 893.
Crick, F.; Koch C. A framework for consciousness. *Nature Neurosci.* **2003**, *6*, 119.
Crick, F.; Koch C.; Kreiman, G.; Fried, I. Consciousness and neurosurgery. *Neurosurgery* **2004**, *55*, 273.
Crick, F.; Koch C. What is the function of the claustrum? *Philos. Trans. Roy. Soc. B* **2005**, *360*, 1271.

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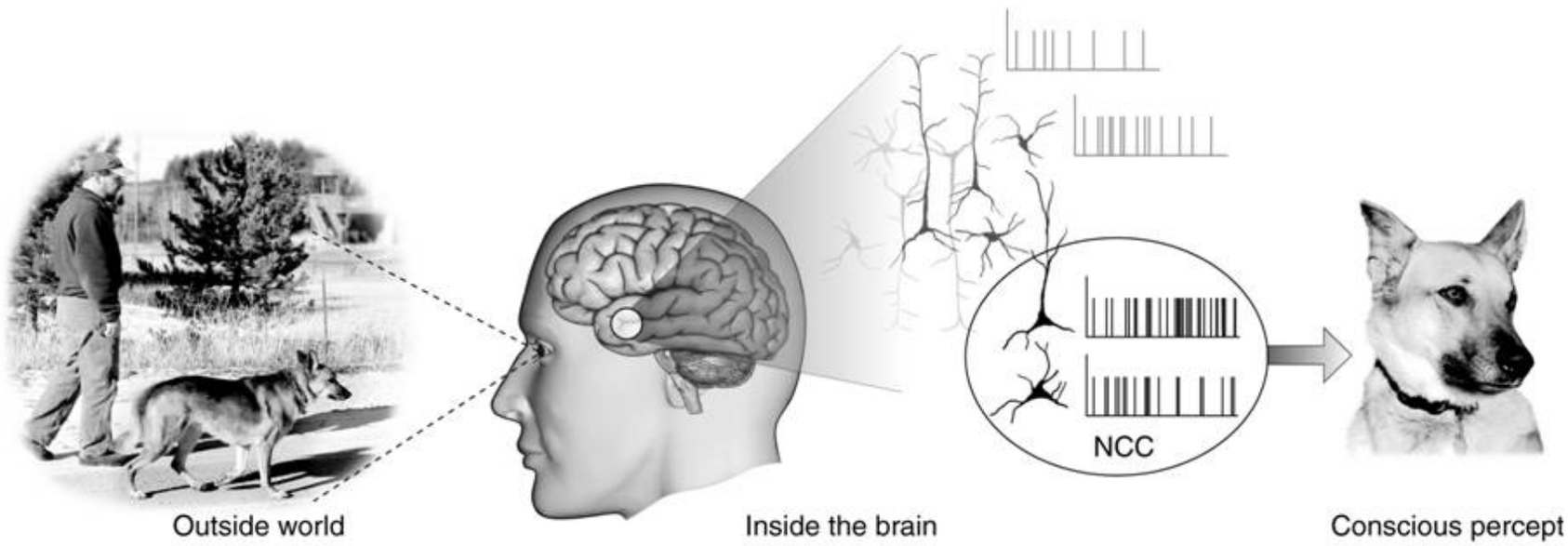
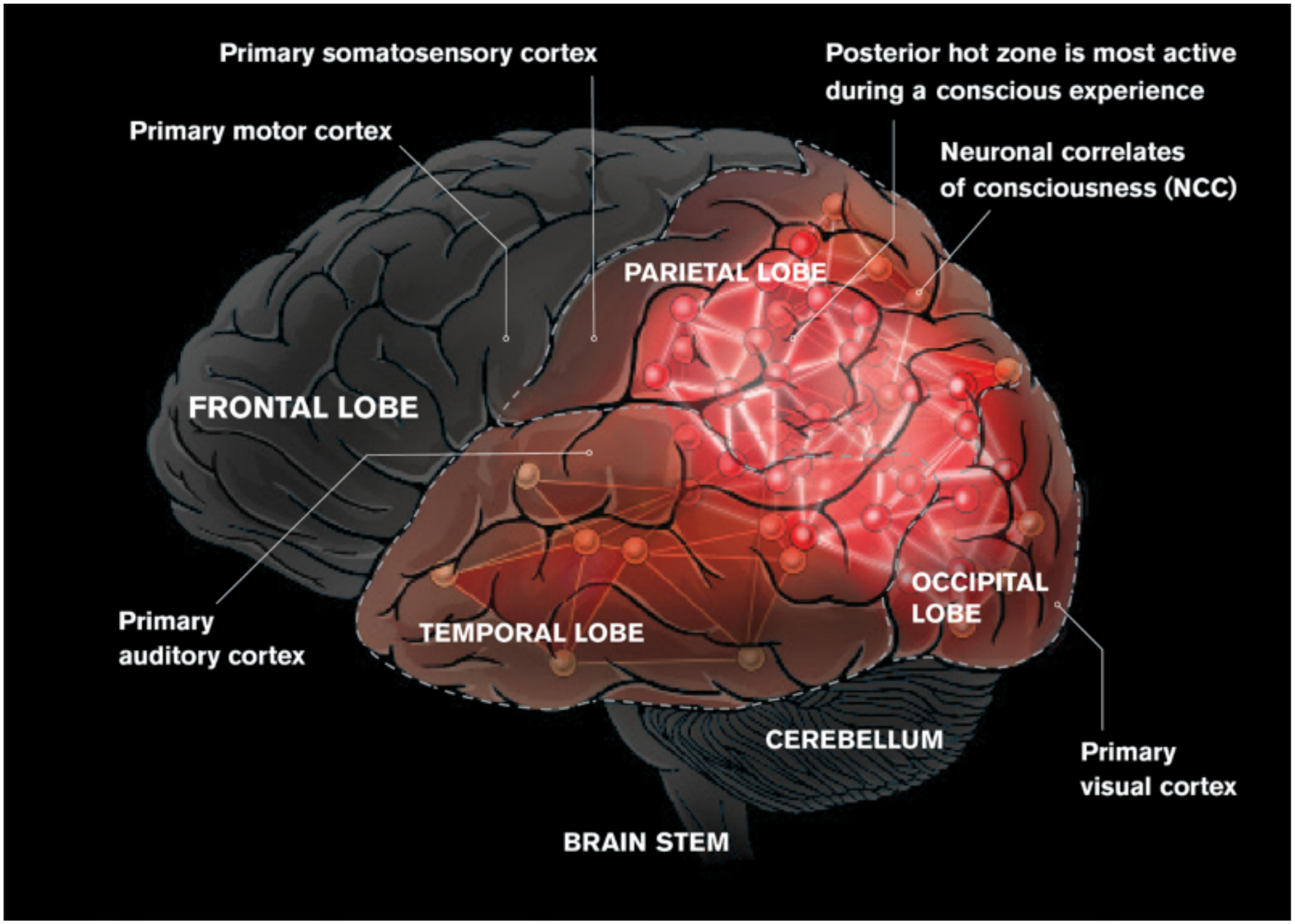


Aims to specifically identify the regions of the brain that are responsible for different aspects of consciousness

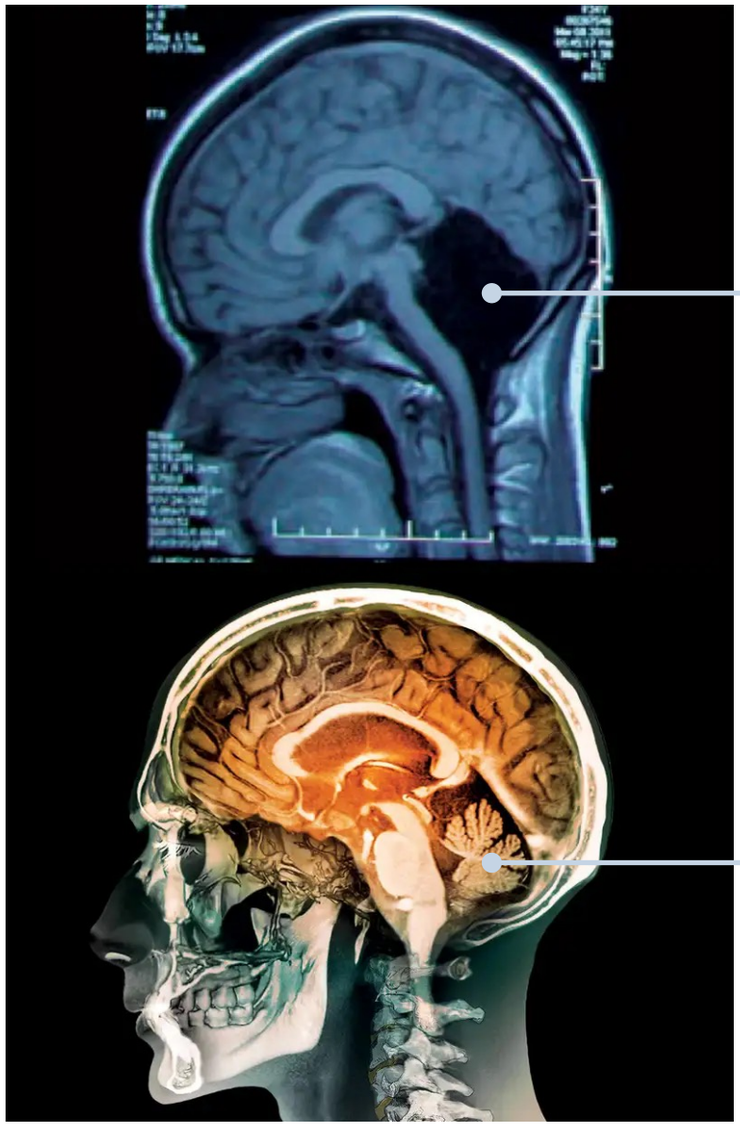
Koch, C.; Massimini, M.; Boyl, M.; Tononi, G. *Nat. Rev.* **2017**, 17, 307.

The posterior cortex "hot zone"



Koch, C. *Nature* **2018**, 557, S8.

Consciousness remains despite absence of cerebellum



24 year-old women, who walked into a hospital complaining of dizziness, leading to her diagnosis

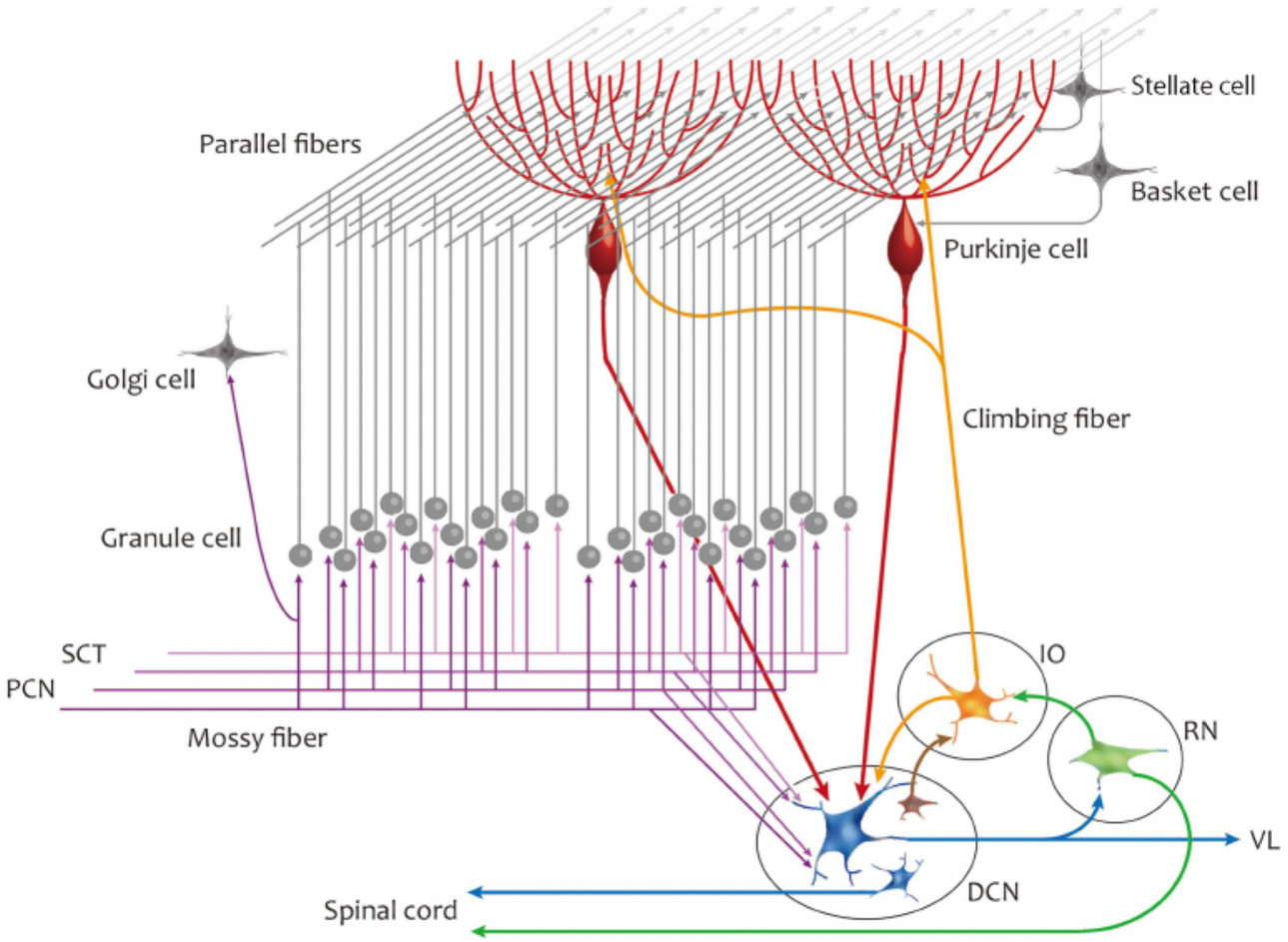
Cerebellum

- contains 50% of the brain's neurons (69 billion!)
- controls balance, motor actions, speech, etc.

Healthy brain

Yu, F.; Jiang, Q.-j.; Sun, X.-y.; Zhang, R.-w. *Brain* **2015**, *138* (5), e353.

Cerebellum contains highly parallel circuitry



15 million Purkinje cells

50 billion granule cell

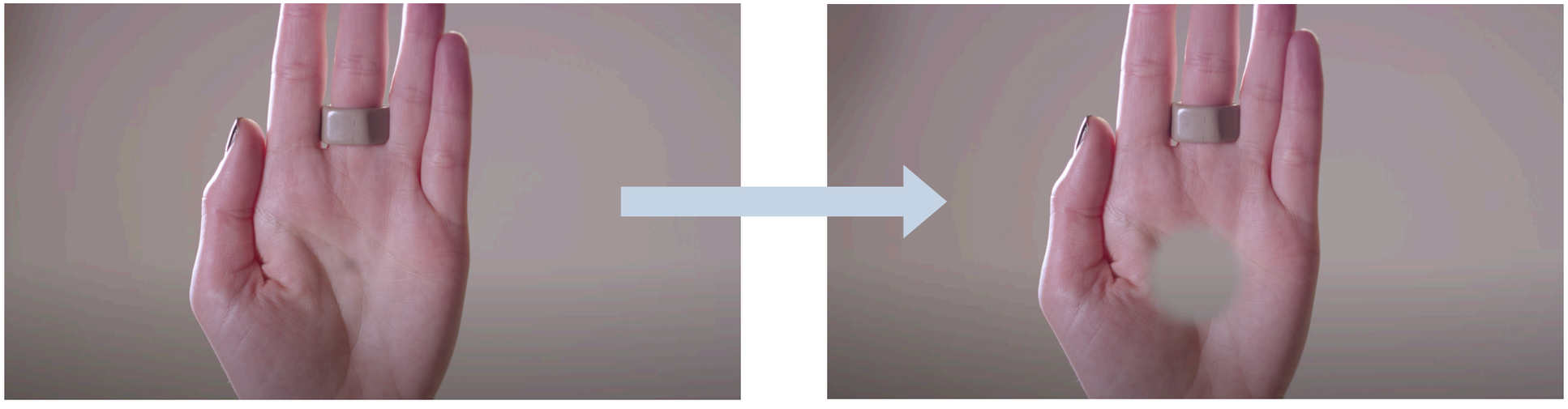
25 million mossy fiber

Sensory information

- Feed forward system, with no complex feedback loop
- Each unit operates in parallel, with distinct inputs and outputs

Tada, M. Nishizawa, M.; Onodera, O. *J. Neurol. Neurosurg. Psychiatry* **2015**, *0*, 1.

Binocular Rivalry as an example to investigate NCC



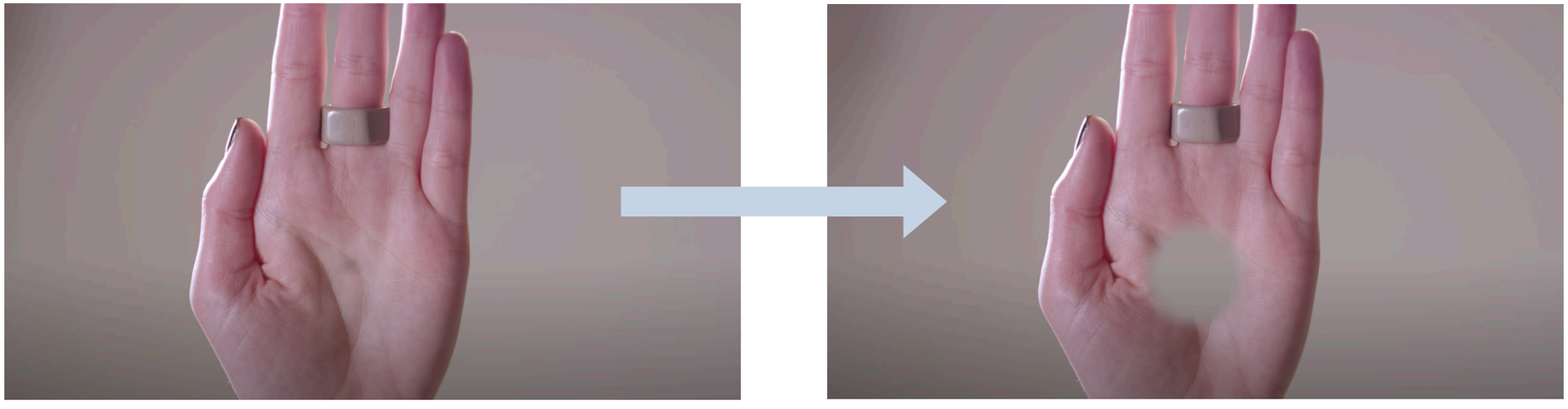
time

Photo credit: “One Weird Visual Illusion Explained” *BrainCraft* (Youtube, **2016**)

Blake, R.; Brascamp, J.; Heeger, D.J. *Phil. Trans. R. Soc. B* **2014**, *369*, 20130211.

Binocular Rivalry as an example to investigate NCC

The combination of **unchanging physical stimulation** and **varying awareness** allows a comparison of neural events between moments that differ specifically with regard to conscious state.



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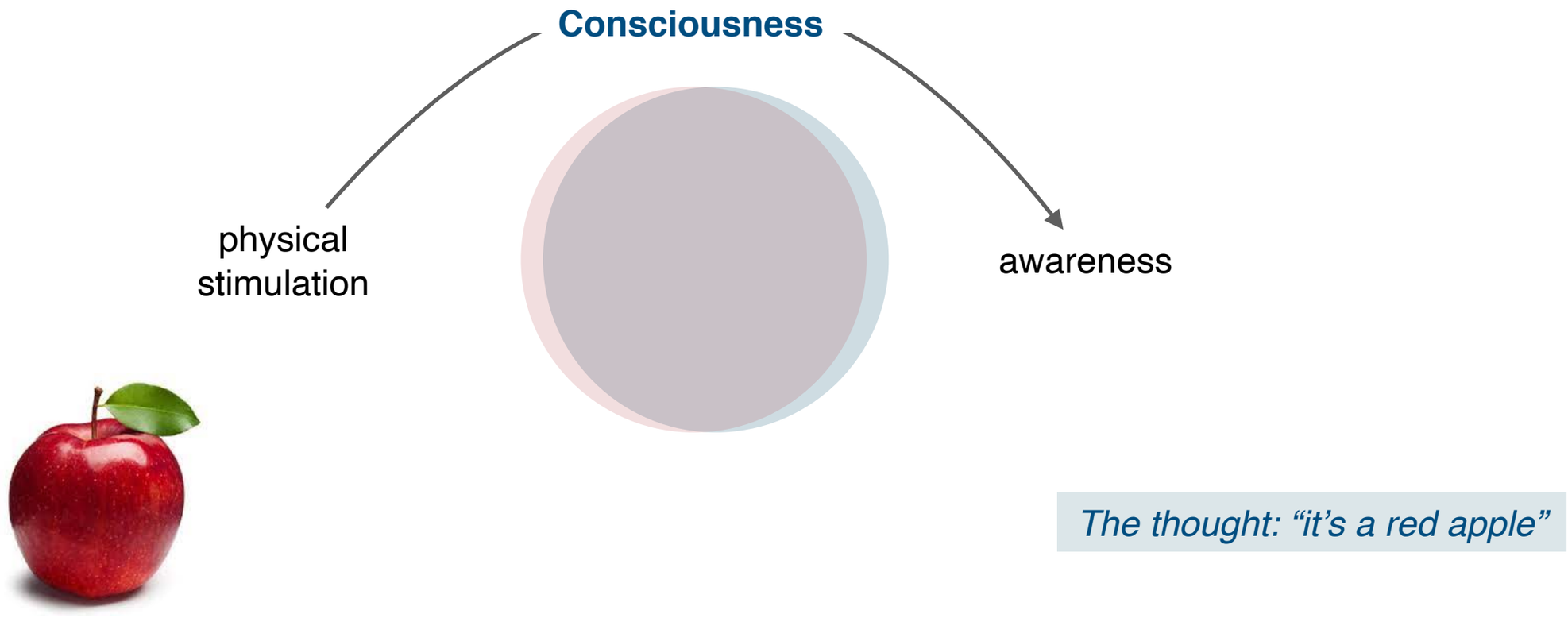

The thought: “it’s a red apple”

Blake, R.; Brascamp, J.; Heeger, D.J. *Phil. Trans. R. Soc. B* **2014**, *369*, 20130211.

Binocular Rivalry as an example to investigate NCC

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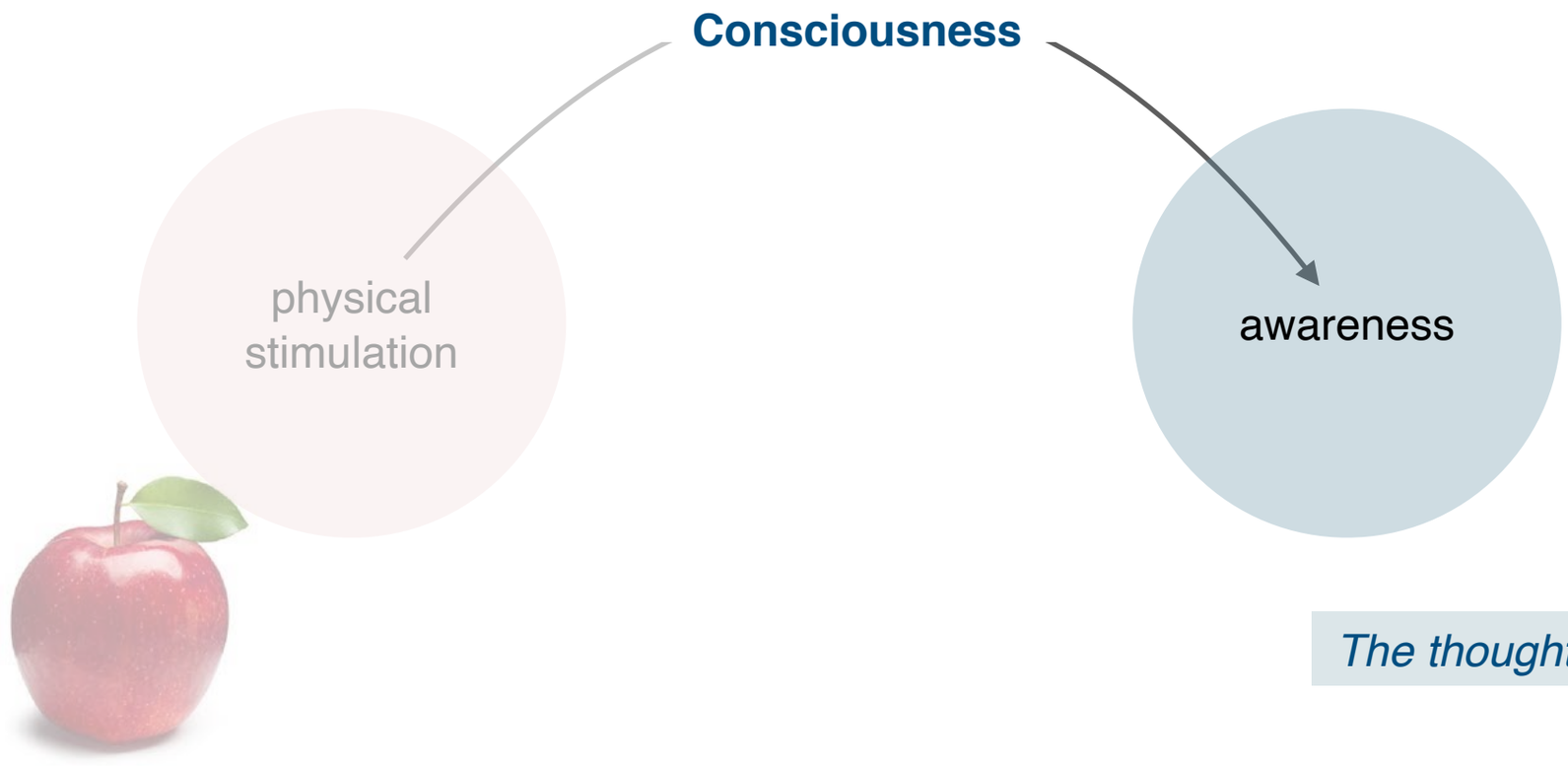

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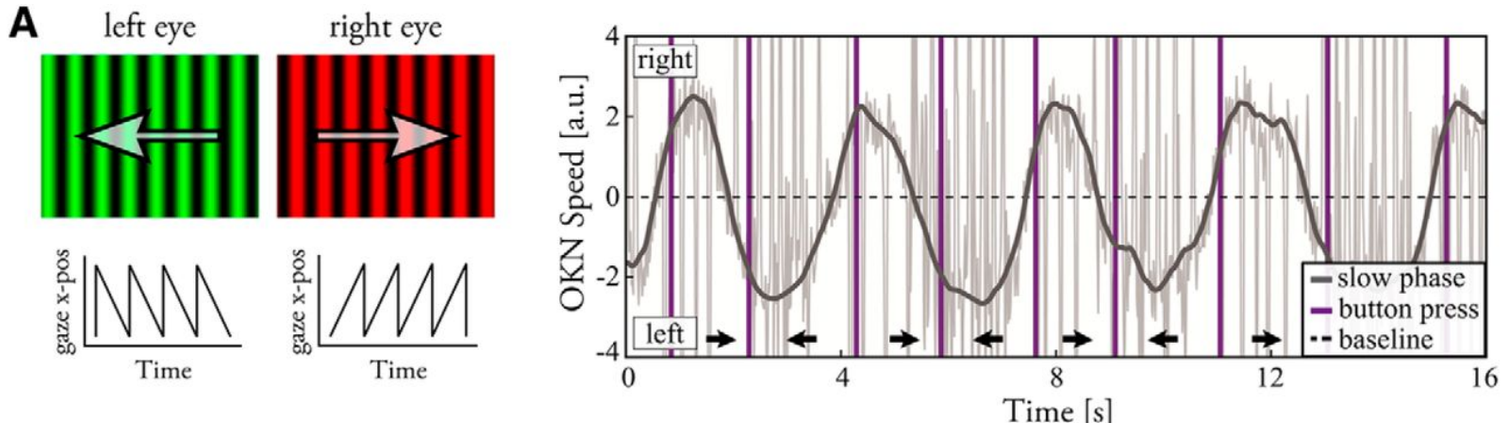
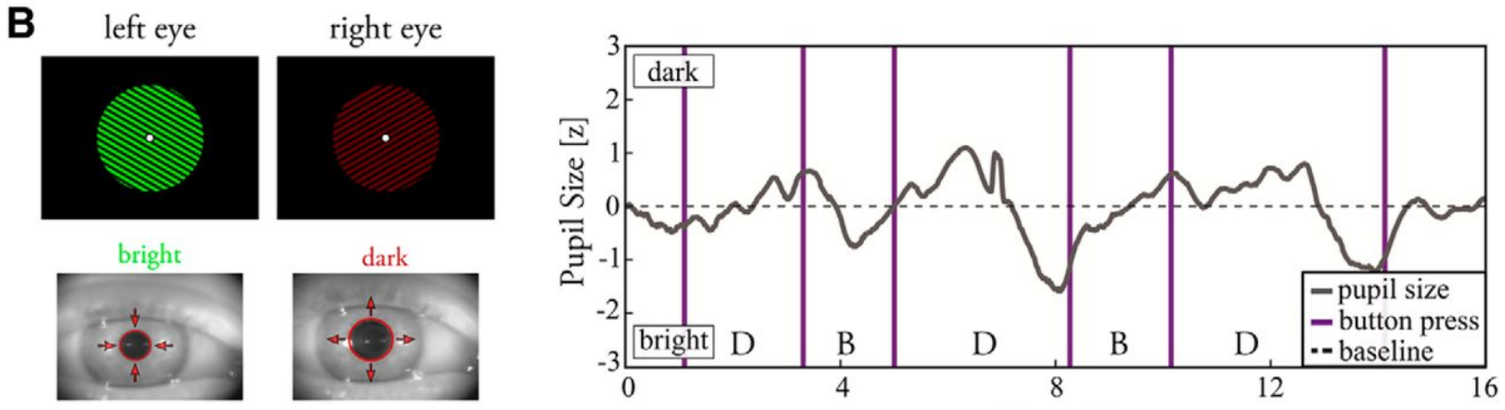
Binocular Rivalry: frontal activity relates to report, not perception

***Optokinetic nystagmus (OKN)**: left or right movement of the pupil*



Replaces subject *report* of perception with an objective measure.

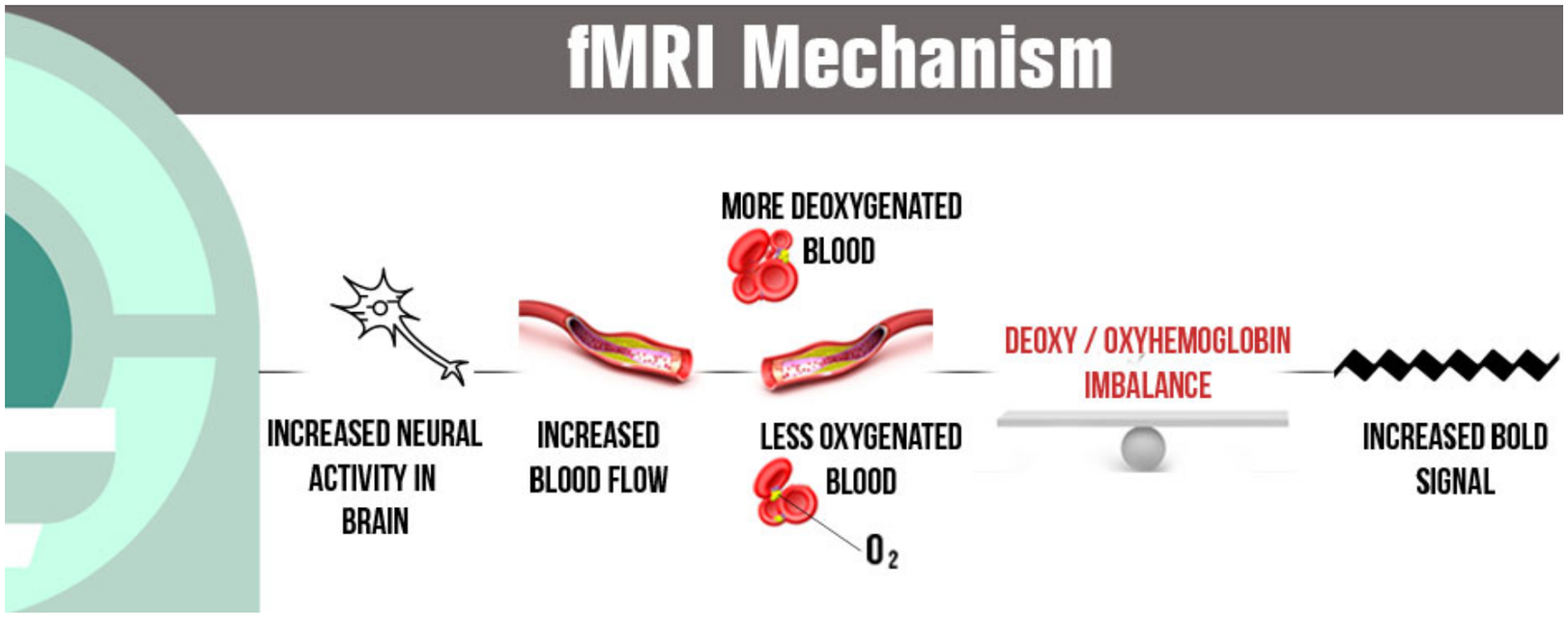


***Pupil reflex:** constriction or dilation of the pupil*

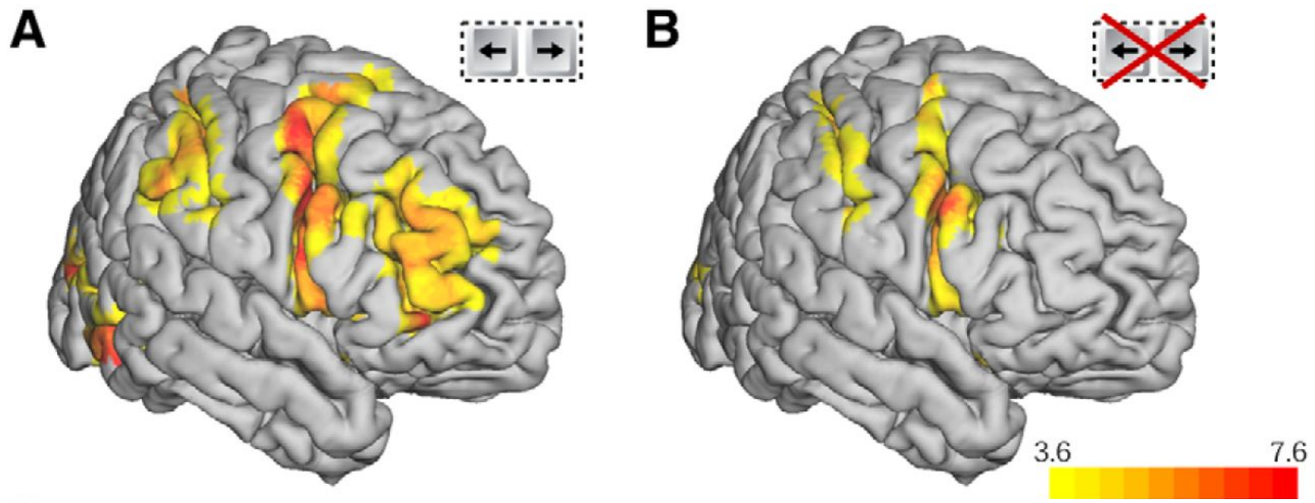
Frässle, S.; Sommer, J.; Janssen, A; Naber, M; Einhäuser, W. *J. Neurosc.* **2014**, *34* (5), 1738.

Binocular Rivalry: frontal activity relates to report, not perception

Blood oxygen level dependent signal (BOLD)



With active report of perception change



Without active report of perception change

Frässle, S.; Sommer, J.; Janssen, A; Naber, M; Einhäuser, W. *J. Neurosc.* **2014**, *34* (5), 1738.

No-report paradigms toward "true" NCC

	Traditional, Report-Based Paradigm	No-Report Paradigm
Possible underestimation of the NCC	Conscious, but forgotten (inattentional amnesia). Conscious, but not reportable (e.g., aphasia, minimally conscious state). Conscious, but below decision criterion. Experience without access.	Some percepts may be experienced only when report is attempted. Contrast of conditions (e.g., not reported percept A vs B) may heavily rely on subsequent memory-based trial categorizations (e.g., later reports of A vs B).
Possible overestimation of the NCC	Inclusion of post-perceptual processes (e.g., executive processes, self-monitoring, report, access). Inclusion of pre-perceptual processes (e.g., prior exposure, attention).	Inclusion of non-conscious processing.
Advantages	Ambiguous stimuli and threshold stimuli can remove stimulus-related confounds.	Can be applied to situations where reports are difficult to obtain (patients, babies, animals, anesthesia, and sleep).

Suchiya, N.; Wilke, M.; Frässle, S.; Lamme, V. *Trends Cogn. Sci.* **2015**, *19* (12), 757.

Outline

Conscious *level*

e.g. vividly awake vs. dreamless sleep

Conscious *content*

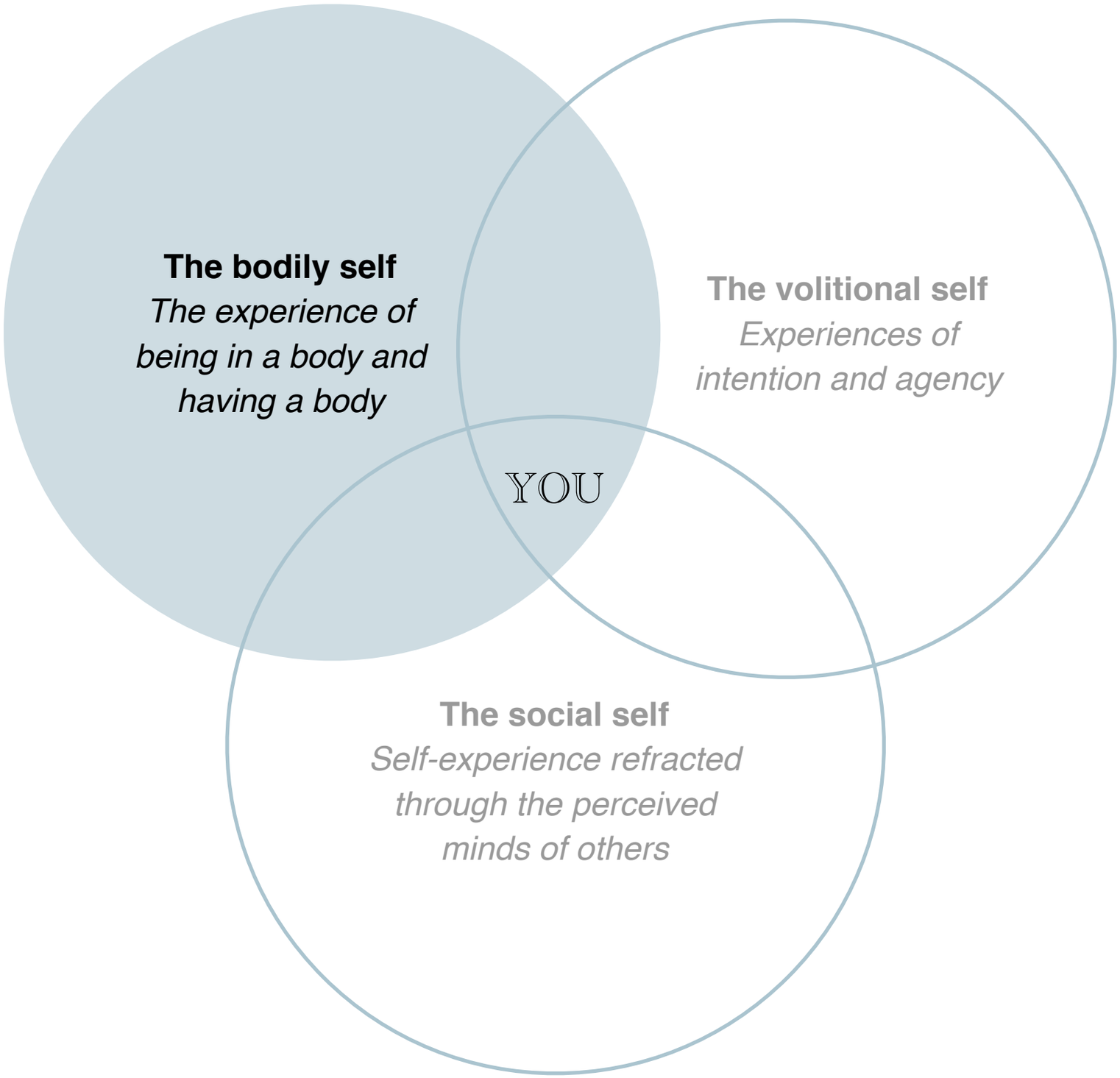
What populates your experience when you are awake

- sights, sounds, smells
- emotions, thoughts, beliefs

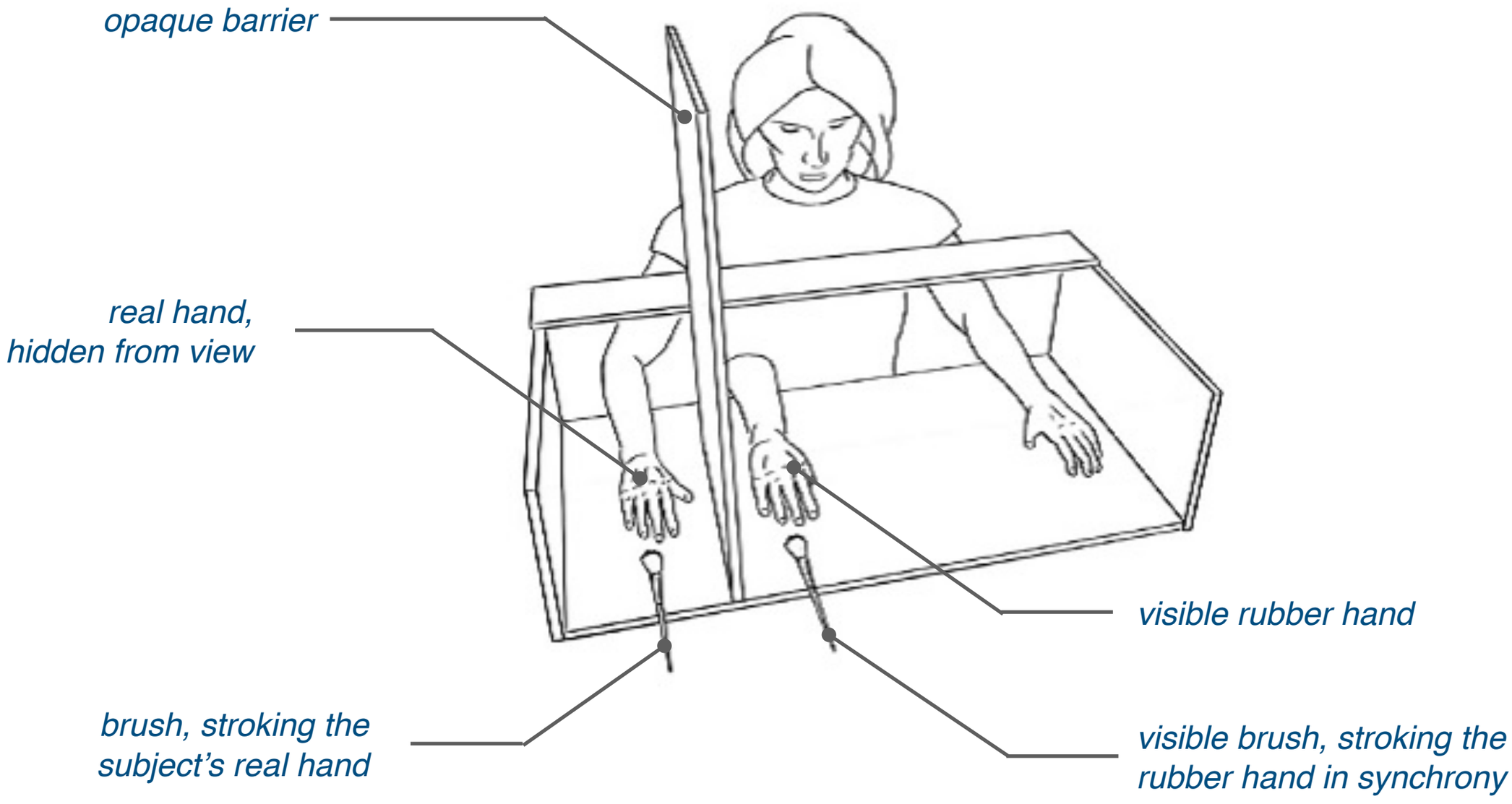
Conscious *self*

specific experiences of *being you*

Different aspects of the conscious self



The “rubber hand illusion” as an example of bodily selfhood

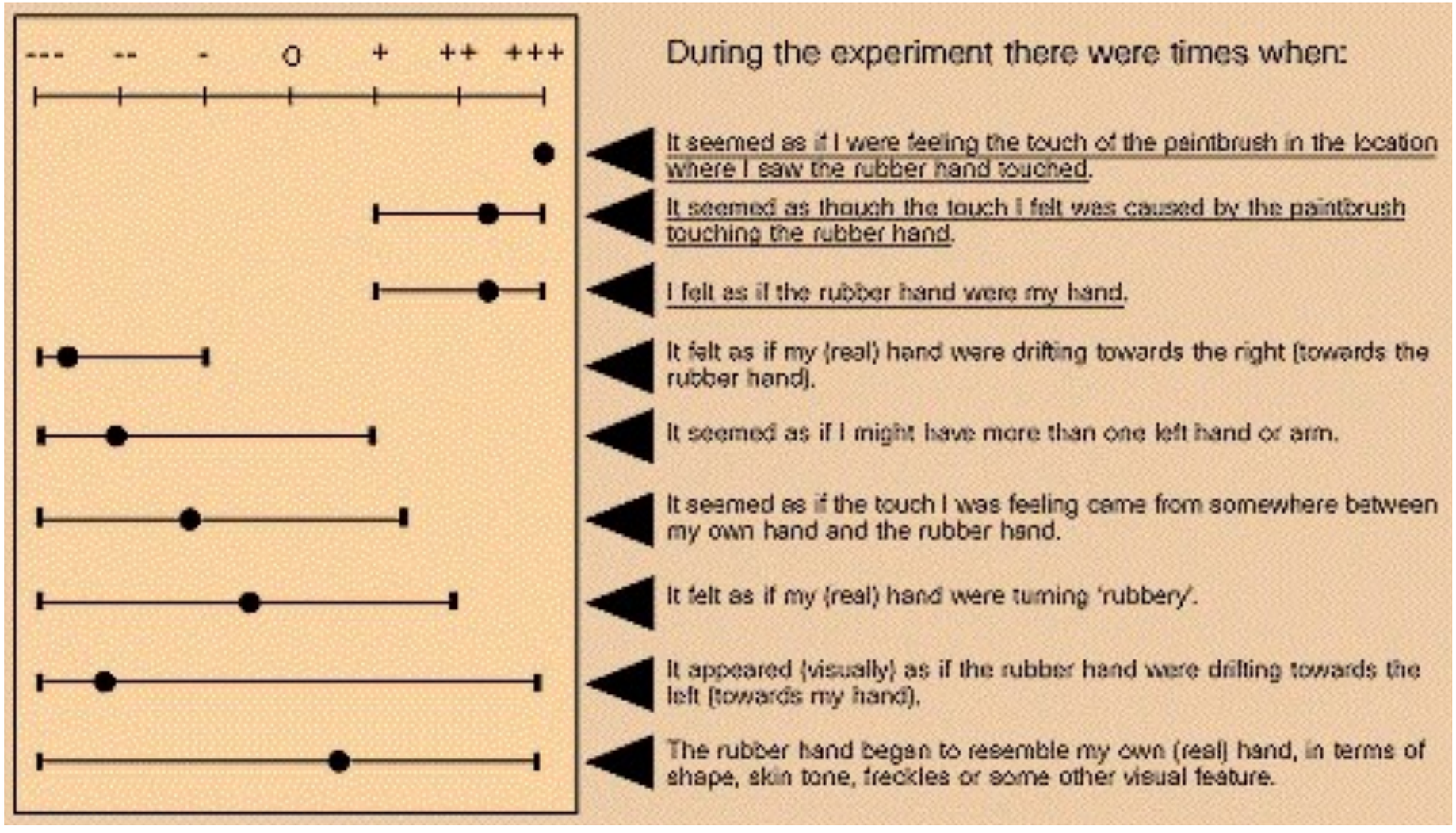


Botvinick, M.; Cohen, J. *Nature* **1998**, *391*, 756.

The “rubber hand illusion” as an example of bodily selfhood

strongly disagree
– – –

strongly agree
+++



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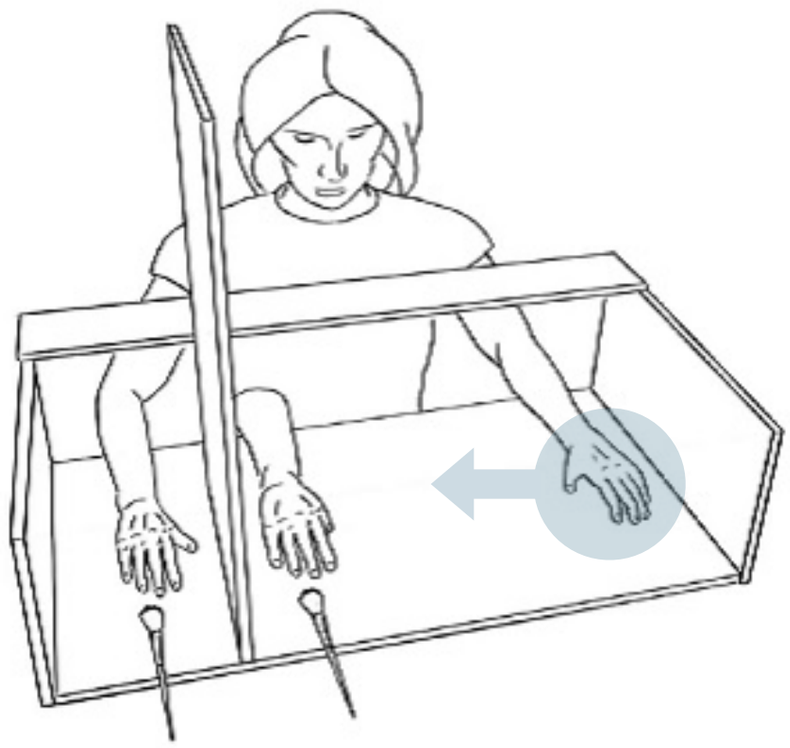
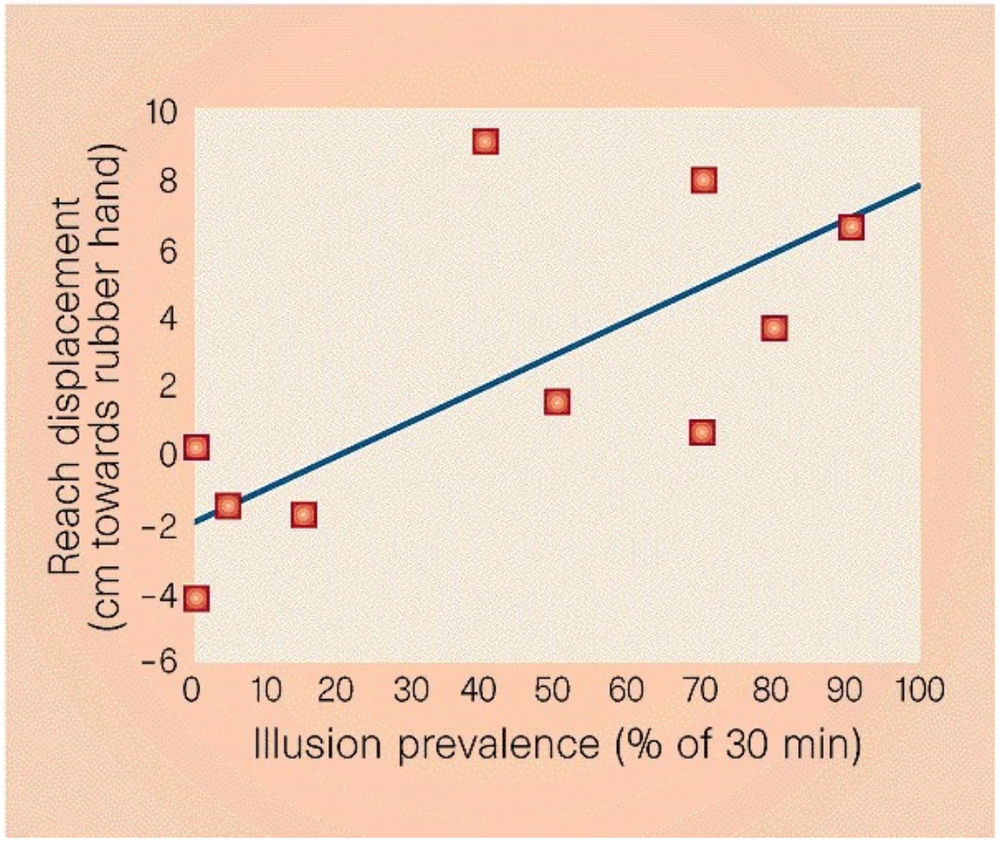


Results



Displacement trends with illusion prevalence

“With eyes closed, the right index finger was drawn along a straight edge below the table until it was **judged to be in alignment** with the index finger of the left hand, which rested on the table in the same position as during the exposure period.”

Botvinick, M.; Cohen, J. *Nature* **1998**, *391*, 756.

Volitional selfhood closely related to consciousness

What is voluntary action?

- **neurophysiologically**: arises from internal generation, not external triggering

Voluntary

reaching for a drink

"I want a drink"

Involuntary

recoiling from a burning tea kettle

heat = sensory stimulus

Volitional selfhood closely related to consciousness

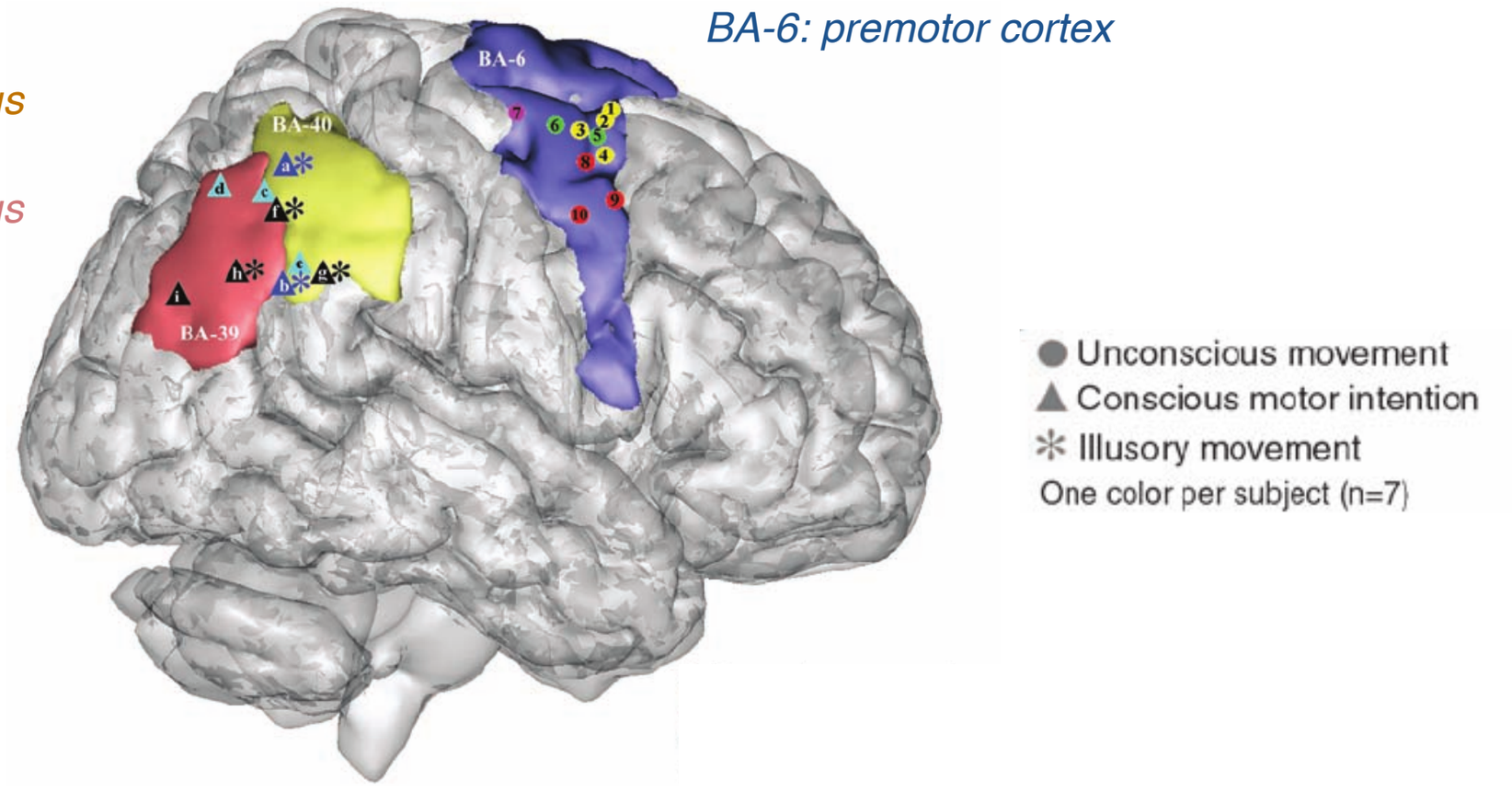
What is voluntary action?

- **neurophysiologically**: arises from internal generation, not external triggering
- **neuroanatomically**: a voluntary motor pathway on the central motor cortex

BA-40: super marginal gyrus

BA-39: angular gyrus

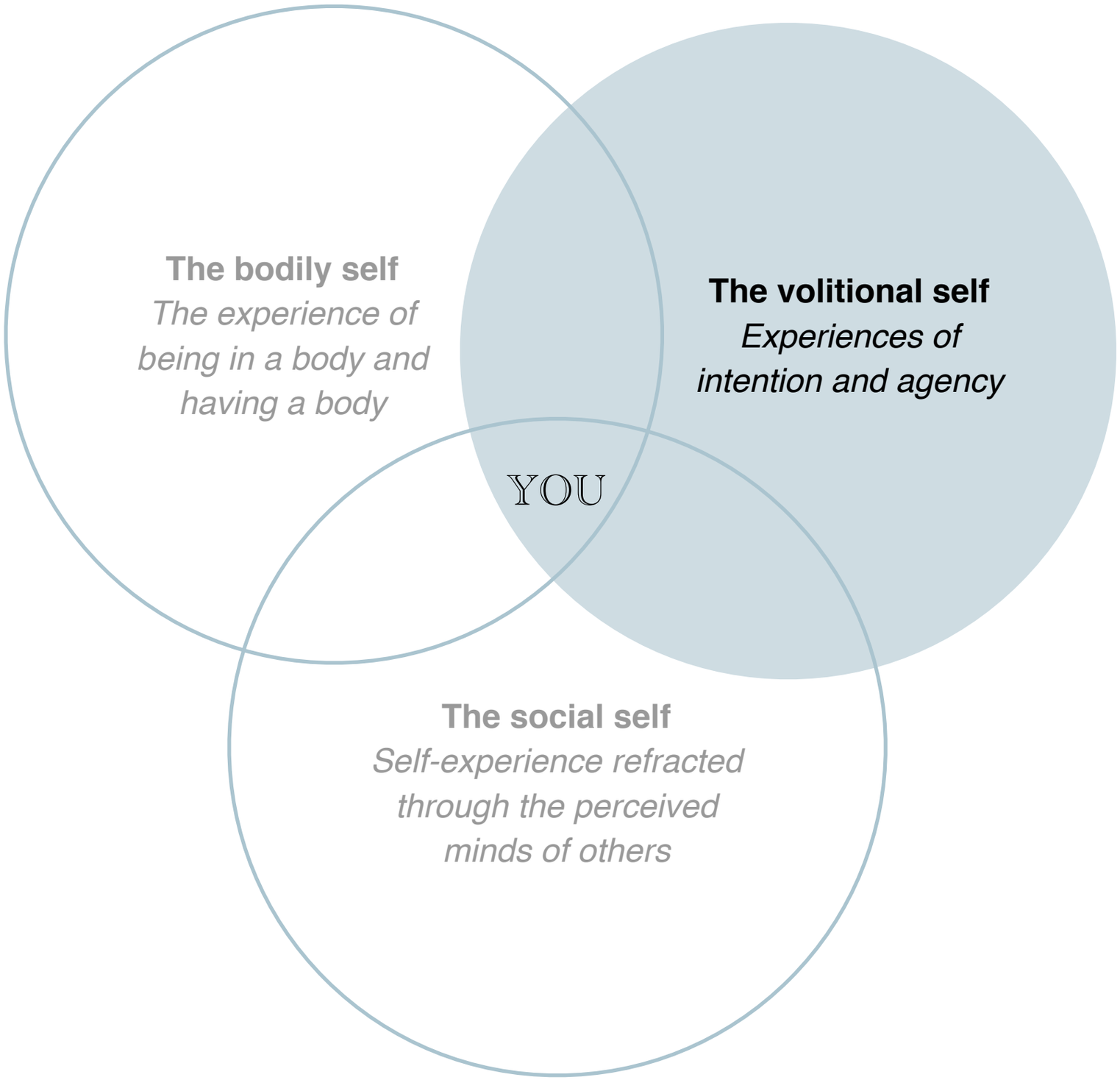
BA-6: premotor cortex



Electrical stimulation to different parts of the brain during awake brain surgery resulted in different voluntary response

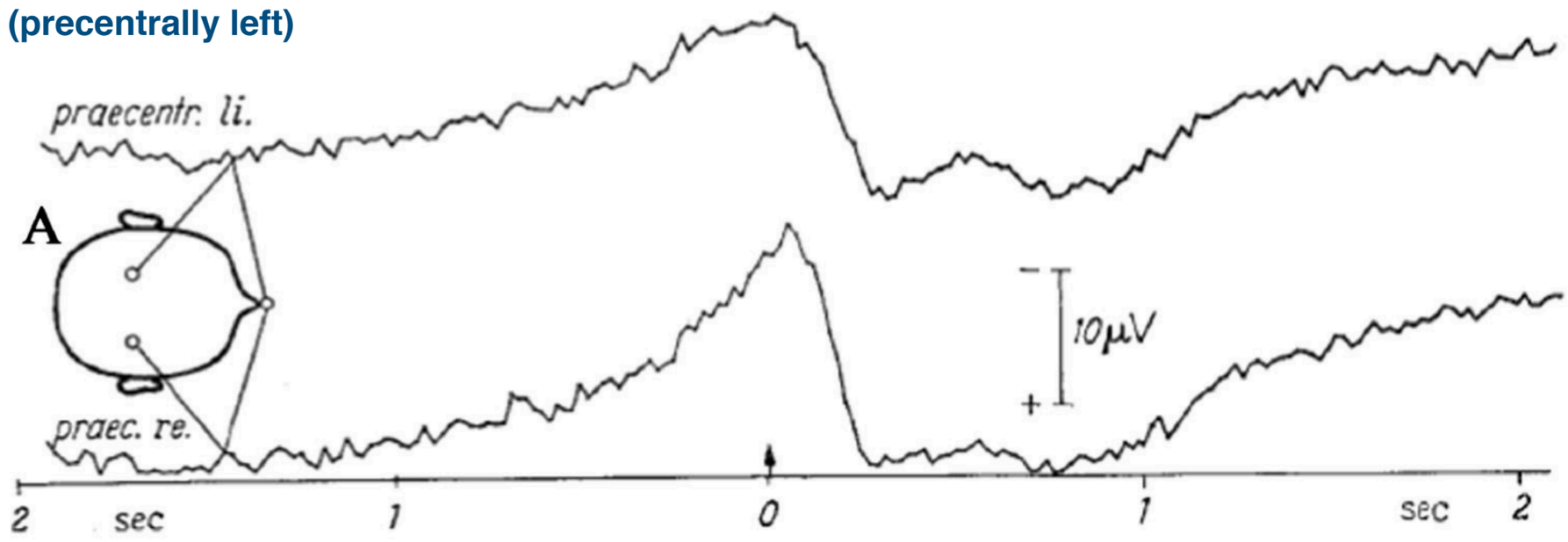
Desmurget, M. *et al. Science* **2009**, *324*, 811.

Different aspects of the conscious self



Bereitschaftpotential (BP), or readiness potential

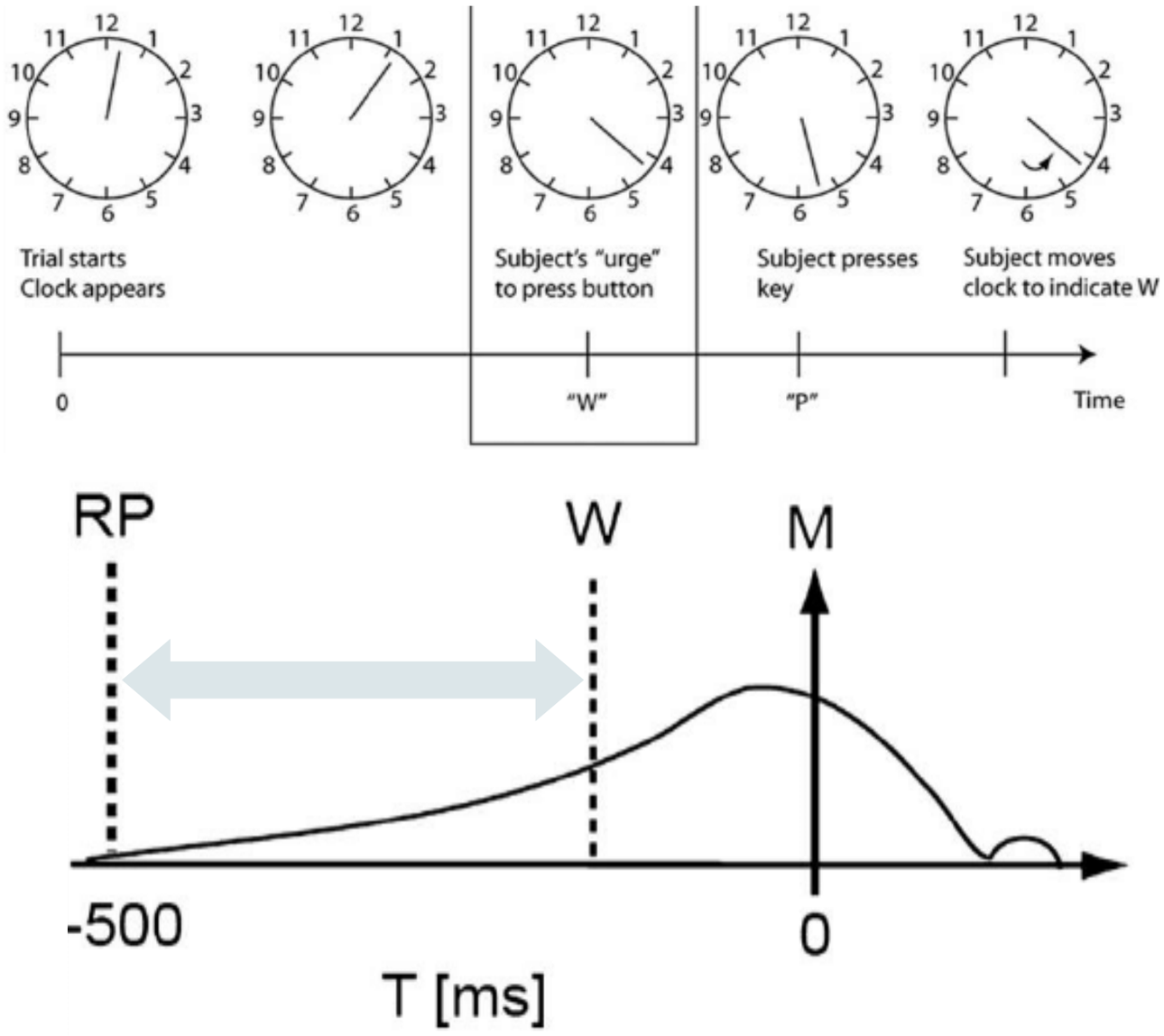
*“**Readiness potential”:** a brain signal linked to voluntary movement*



slowly increasing surface-negative cortical potential of 10–15 μV

Kornhuber, H.H.; Deeke, L. *Pflugers Arch*. **1965**, *284*, 1.

A notorious argument against free will



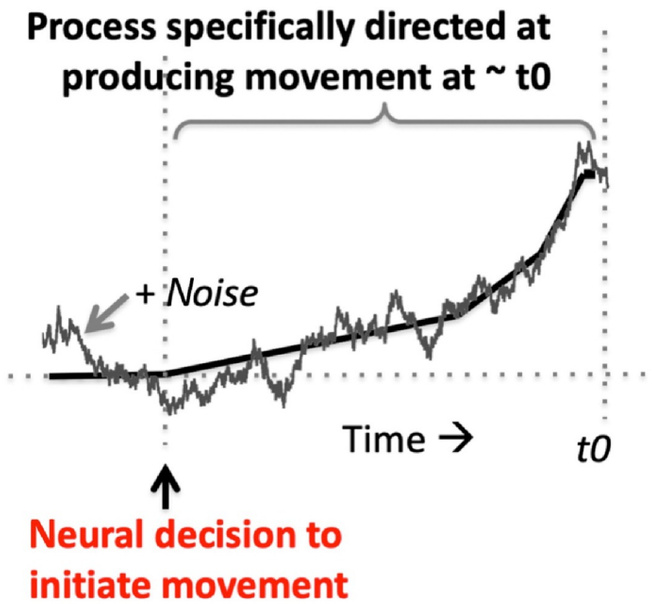
Measurement precision
is ±50 ms

readiness potential preceding W-time ("urge to act") indicates that decision for action was initiated before subject is aware

Libet B. *et al. Brain* **1983**, *106*, 623.

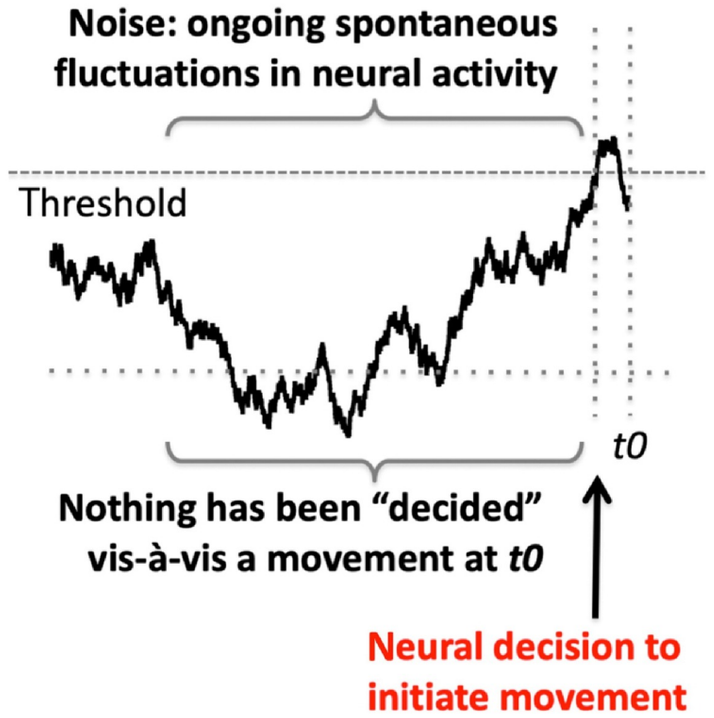
Non-classical interpretation of readiness potential

Early decision account



V.S.

Late decision account

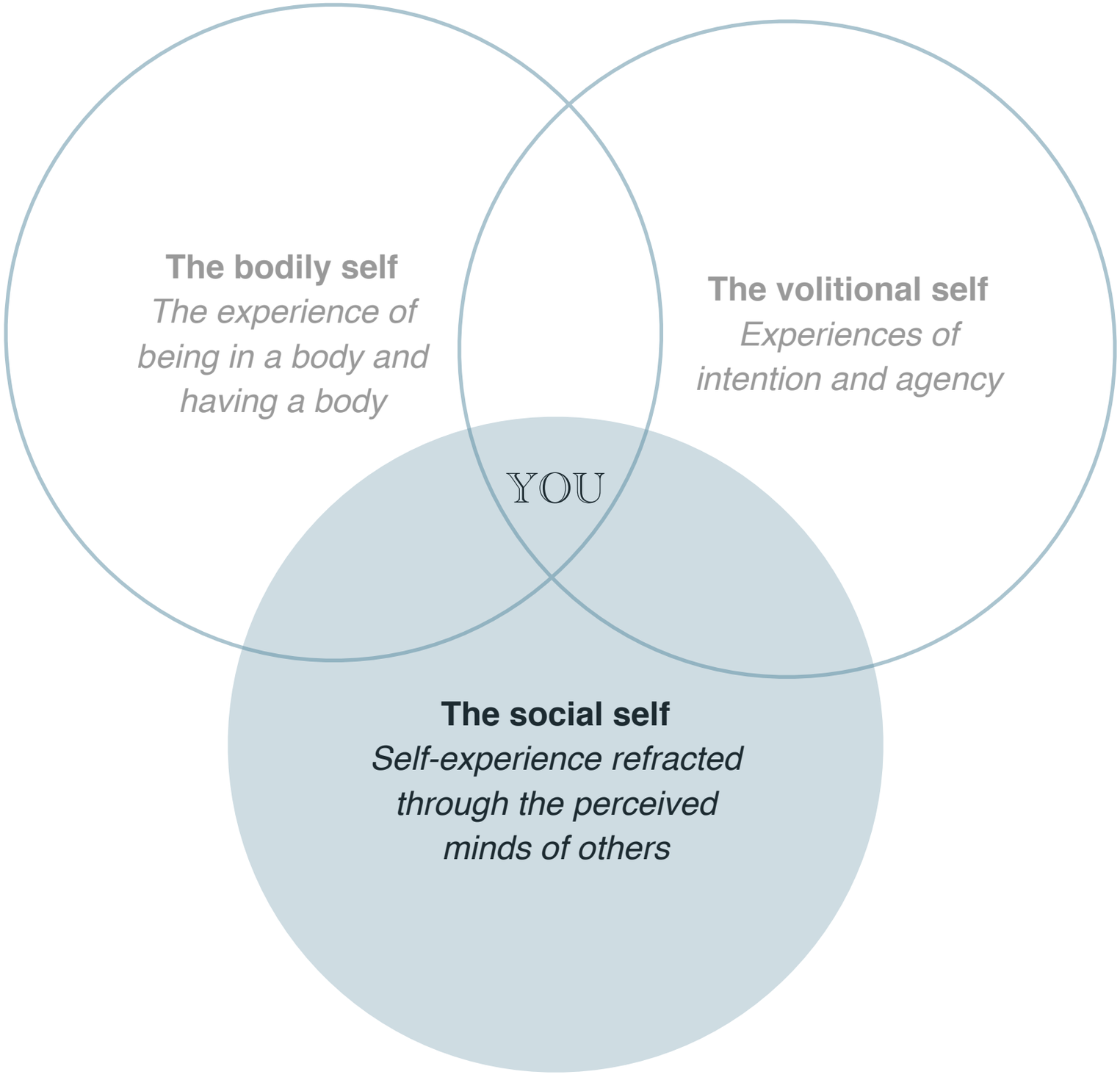


Late decision account: RP reflects neural activity *antecedent* to the decision to move, rather than the outcome of a decision to move.

Schurger, A.; Hu, P.B.; Pak, J.; Roskies, A.L. *Trends Cogn. Sci.* **2021**, *25* (7), 558.

Schurger, A.; Sitt, J.D.; Dehaene, S. *Proc. Natl. Acad. Sci. U.S.A.* **2012**, *109* (42), E2904.

Different aspects of the conscious self



Many neuromechanisms underly social interactions

Learning through observing others

- Reward learning
- Gaze following
- Mirroring

Learning about other minds

- Taking account of others
- Reputation and gossip effects
- Tracking false beliefs

Metacognition ("thinking about thinking")

- Reflective discussions
- Justification of action changes behavior

Frith, C.D.; Frith, U. *Annu. Rev. Psych.* **2012**, *63*, 287.

Gaze-following

- *ubiquitous in typical human social development*
- *failure to respond to gaze cues is associated with pathological social development*

Klein, J.T.; Shepherd, S.V.; Platt, M.L. *Curr. Biol.* **2009**, *19*, R958.

Neuromechanisms of gaze-following in social interactions

Healthy subjects were asked to identify angry, neutral, or happy faces with direct or averted gazes while in a fMRI machine

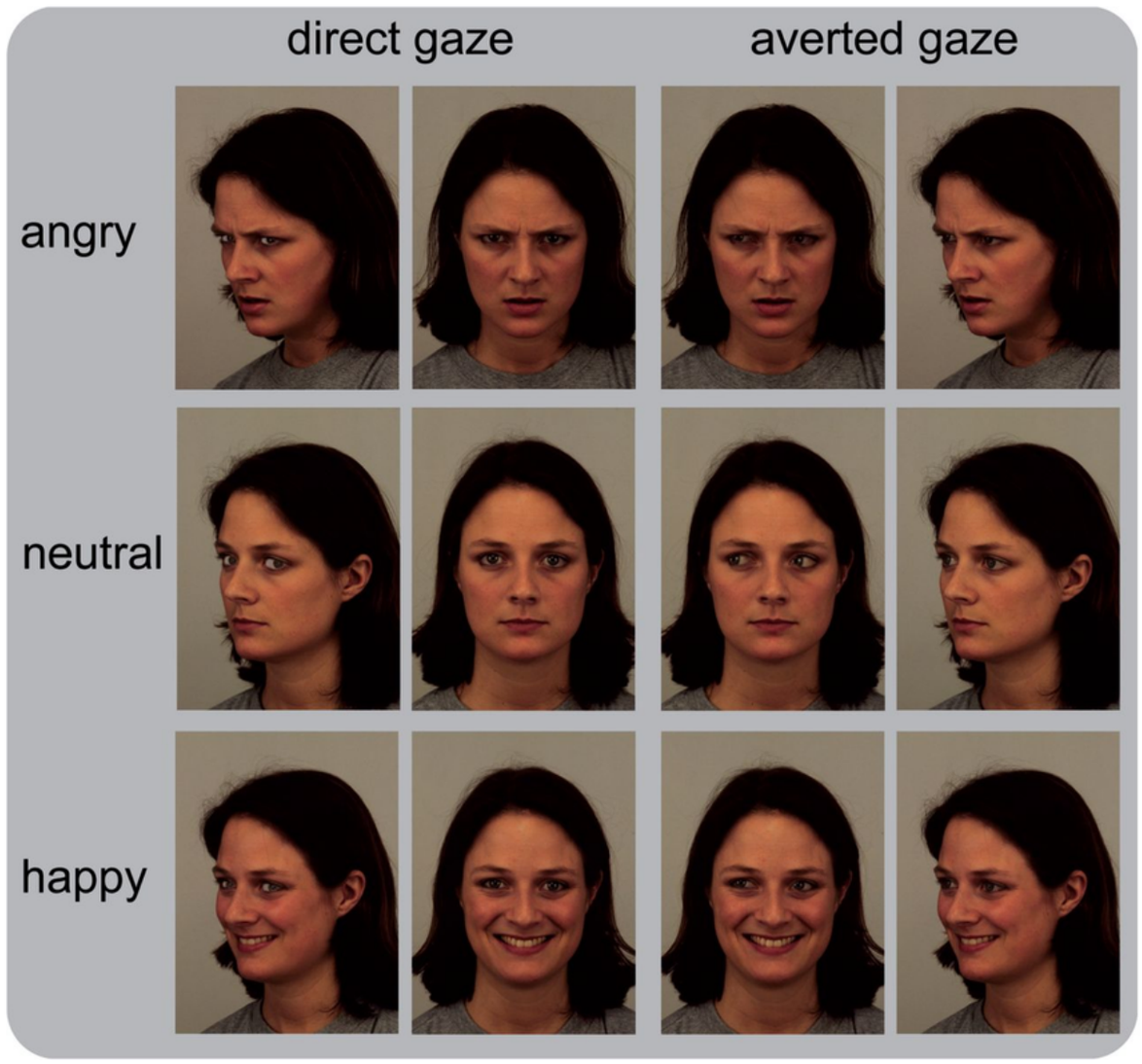
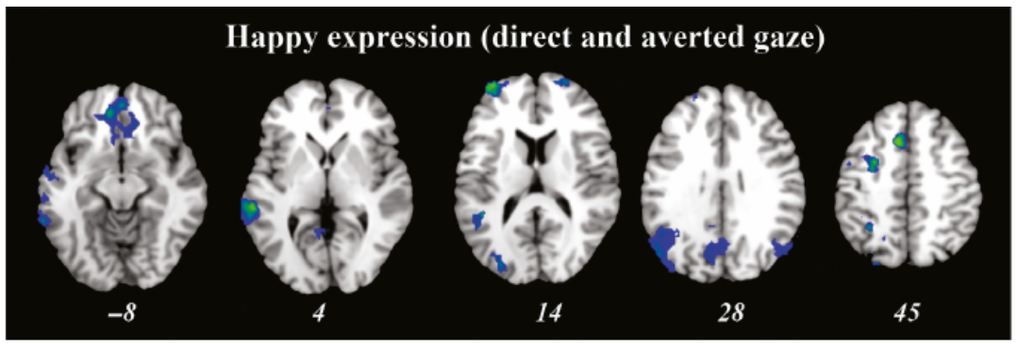


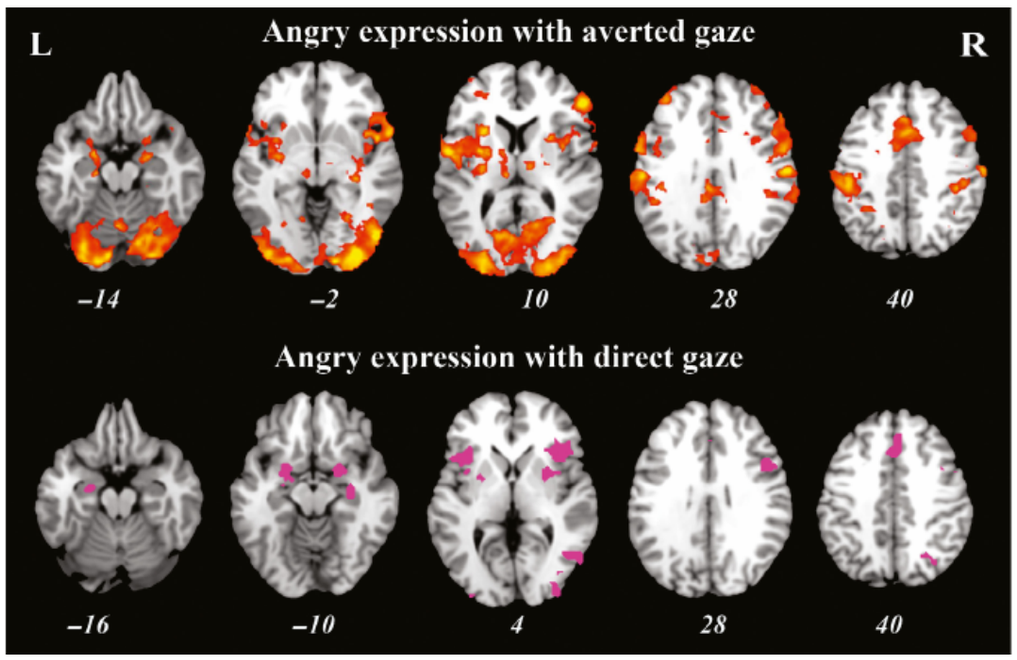
Photo credit: *Soc. Cogn. Affect Neurosci.* **2014,** *9* (8), 1246.
Ziaei, M.; Ebner, N.C; Burianova, H. *Eur. J. Neurosci.* **2017**, *45*, 312.

Neuromechanisms of gaze-following in social interactions

Happy expression: identical brain activity between averted and direct gaze



Angry expression: different brain activity between averted and direct gaze



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e.g. vividly awake vs. dreamless sleep

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What populates your experience when you are awake

- sights, sounds, smells
- emotions, thoughts, beliefs

Conscious *self*

specific experiences of *being you*

Final thoughts

The boundaries of human consciousness is continuously morphed

Conscious *level*

e.g. vividly awake vs. dreamless sleep

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"Only concepts can be defined, others have history" – Nietzsche