Your brain produces more entropy while you are awake

By analysing brain scans of asleep and awake people, researchers have found that the amount of entropy our brains produce varies with consciousness

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By **Karmela Padavic-Callaghan**

Electrical signals in our brains produce entropy as part of processing information
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Our brains produce more entropy when we are awake than when we are asleep. The finding could lead to better ways to measure the consciousness of people in comas.

Entropy is a measure of disorder and in our universe, everything tends to move from less disorder to more over time. For instance, breaking a coffee cup increases entropy. While this breaking can happen in many ways, you never see a broken cup spontaneously re-assemble itself and therefore decrease its entropy.

Electrical signals in our brains can also produce entropy as part of processing and transmitting information, such as the visual signals from our eyes. Rodrigo Cofré at the

Paris-Saclay University in France and his colleagues wanted to determine whether our brains produce more entropy when we are awake or when we are asleep.

The researchers used functional magnetic resonance imaging (fMRI) to scan the brains of 15 people in different states of consciousness: while each person was awake and in three stages of sleep, from light to very deep.

To calculate entropy, the team used a model that was previously developed from studying the pathways that electrical signals can follow inside of the brain. The different routes help reveal the different processes they can carry out, and each of those processes produces different amounts of entropy. From this, the researchers calculated entropy production for each person in each state of consciousness. They found that it decreased as people fell deeper into sleep. In the state of deepest sleep, people's brains, on average, produced 25 per cent less entropy than when they were awake.

Cofré says that this gives researchers a way to quantify consciousness – a person whose brain shows the same amount of entropy production in an fMRI study as someone who is deeply asleep is likely to have the same types of processes happening in their brain and to be at a similar level of consciousness, he says. The new method could then potentially be used to quantify the consciousness of people in comas or eventually help to diagnose people with locked-in syndrome, who are conscious but unable to communicate with the external world, says Cofré.

Previous research has linked consciousness to entropy. Some fMRI studies, for example, have indicated that states of very altered consciousness, such as those induced by psychedelic substances like psilocybin, result in an increase in entropy of the brain itself – meaning that it is harder to predict its overall electrical state – and not just the entropy different signals produce.

Dan Lloyd at Trinity College in Connecticut says that understanding the state of awareness of people that are minimally conscious has long been an area of study. However, it is not yet clear that entropy production is an unambiguous mark of consciousness.

For example, dreams can happen in deep sleep – a time of low entropy – but they reflect "a high level of consciousness", says Lloyd. As such, dreams could actually increase entropy production in the brain, but the study didn't consider this, he says.

Reference: arxiv.org/abs/2207.05197

More on these topics: NEUROSCIENCE MRI CONSCIOUSNESS

Gmail

Comment for New Scientist?

From: Arvid Lundervold <Arvid.Lundervold@uib.no>
Sent: Monday, February 6, 2023 8:01 AM
To: Karmela Padavic-Callaghan <K.Padaviccallaghan@newscientist.com>
Cc: Arvid Lundervold <Arvid.Lundervold@uib.no>
Subject: Re: Comment for New Scientist?

Dear Karmela Padavic-Callaghan,

Thanks for the opportunity to comment on the paper "*Entropy production of Multivariate Ornstein-Uhlenbeck processes correlates with consciousness levels in the human brain*" by Matthieu Gilson, Enzo Tagliazucchi, and Rodrigo Cofré. (https://arxiv.org/pdf/2207.05197.pdf). "In the paper, authors calculate entropy production in a multivariate Ornstein-Uhlenbeck process fitted to fMRI brain activity recordings of the transition from being awake to being asleep. Their analysis identifies a monotonous relationship between entropy production computed in this way and the level of consciousness."

Q: What may we already know about detecting consciousness with fMRI ?
A: Detecting consciousness with fMRI has a relatively long tradition in the otherwise short history of functional brain MR imaging using intrinsic Blood Oxygenation Level Dependent (BOLD) contrast (Ogawa et al., 1990). This BOLD contrast, being hampered by noise of various origin is caused by a cascade of processes: activity patterns in populations of neurons connected in hierarchical networks, neuro-vascular coupling mechanisms characterised by hemodynamic response functions, and changing regional blood concentrations of oxy- and deoxy-hemoglobin in capillaries and small veins supporting the neurons. Since de-oxygenated hemoglobin is strongly paramagnetic and oxyhemoglobin is weakly diamagnetic they will have differential effect on local magnetic fields giving raise to BOLD signals in space and time being picked up by the MR receiving coils and analysed as 3D+time images. Such contrast can be captured by serial T2* image acquisitions of the brain in the resting state (RS-fMRI) at a temporal resolution of 1-2 s for completion of each volume acquisition, and at spatial resolution (voxel size) of 10-20 mm^3. Fifteen years ago, close to the current situation for which the fMRI dataset in Gilson (2023) was recorded, a typical fMRI voxel volume was 3x3x6 mm^3. According to Logothetis (2008), such a voxel, covering a part of the cerebral cortex, say, will contain 5.5 x 10^6 neurons, $2.2–5.5 \times 10^{10}$ synapses, 22 km of dendrites, and 220 km of axons, and also capillaries, glia cells and more -components with their dynamics collectively assumed to represent the substrate or neural correlates of consciousness in man and animal. Today, however, fast (subsecond), high resolution (submillimeter), high field (7 Tesla) recordings, and also layer-fMRI, distinguishing the different cytoarchitectural lamina of our 1-4 mm thick cortical sheet are available with corresponding open software for analysis (https://github.com/layerfMRI/LAYNII). Regarding characterisation and detection of consciousness, such technologies will likely put fMRI-based experimental approaches to a new level of spatio-temporal granularity, modelling opportunities, and insights.

To the best of my knowledge the first experimental report on "Functional MRI and the study of human consciousness" was published more than 20 years ago (Dan Lloyd, Journal of Cognitive Neuroscience 2002;(14):6:818–831). The author, using four preprocessed datasets (27 subjects) from the National fMRI Data Center and building on philosophical phenomenology, i.e. phenomenal intentionality, phenomenal superposition, and experienced temporality, considered the patterns of all voxels as potential multivariate encodings of phenomenal information. Interestingly, Dan Lloyd, a professor of philosophy did all the 3D+time data analysis himself using MATLAB and a couple of libraries (SPM96, PLS toolbox, and read_analyze from Colin Humphries) available at the time. Moreover, the author in his exploratory analysis of consciousness (coined "neurophenomenology" by Varela, 1996) also applied artificial neural networks to detect a more explicit prediction from the phenomenology in the sense that present experience contains and is inflected by past states of awareness and anticipated events.

The present paper by Gilson et al. (2023) has many similarities to Lloyd (2002), both regarding the use of fMRI data from (“open”) repositories and in the aim of their study: model-guided exploration and measures of “consciousness”, that be entropy production or prediction from phenomenology. In Gilson et al (2023) they employ existing, preprocessed EGG-fMRI data, denoted the “Frankfurt data set”, being studied in several publications, and initially reported by Tagliazucchi and Lauf (2014) in their Neuron paper “Decoding wakefulness levels from typical fMRI resting-state data reveals reliable drifts between wakefulness and sleep”. Such imaging data, in this case “EEG-fMRI of 71 subjects instructed to lie still in the scanner with eyes closed and scanned for 52 min with experiments starting at 7:00 p.m.” and similar large scale fMRI data sets, are provided by e.g. the 1000 Functional Connectomes Project (http://fcon_1000.projects.nitrc.org) and OpenNeuro (https://openneuro.org), where the rationale for their design and curation can be described according to Tagliazucchi and Lauf (2014) as “ … not driven by specific hypotheses, this data-centered approach can open exciting new avenues of discovery science of brain function - provided careful and correct execution”. Even more resources are available to the community such as BrainLife (https://brainlife.io) a community-driven free and secure reproducible neuroscience analysis platform for storage and compute where its public-funding model (NFS, DoD, Kavli Foundation and NIH awards) enables collaboration between publicly funded projects at no additional cost.

Since the early studies of Dan Lloyd there has been a broad range of conceptual and modelling approaches to “computational consciousness” informed by fMRI recordings. Some early speculations regarding consciousness, resting state fMRI, neurodynamics and stochastic resonance was conveyed in Lundervold (2010). The most impactful contributions over the last two decades using fMRI, partly related to sleep and minimally conscious states, has been provided by (among others) Giulio Tononi in Wisconsin (https://centerforsleepandconsciousness.psychiatry.wisc.edu) and his Integrated Information Theory of consciousness (http://integratedinformationtheory.org); Gustavo Deco in Barcelona (https://www.upf.edu/web/cns / https://github.com/decolab); Stanislas Dehaene in Paris (https://www.unicog.org); Enzo Tagliazucchi in Buenos Aires (https://www.cocucolab.org); Karl Friston in London (https://www.fil.ion.ucl.ac.uk/~karl) and the late Allan Hobson, Harvard Medical School.

Some further thoughts. The MR imaging-informed study of “consciousness” (Gilson et al. 2023), fitting a stochastic thermodynamic model to spatio-temporal fMRI data can also be seen in parallel with the new avenue of imaging-based brain tumour research, combining computational neuro-oncology models and advanced MR image acquisitions in space and time cfr. the recent Dagstuhl seminar on Inverse biophysical modelling and machine learning in personalized oncology (https://www.dagstuhl.de/23022). In this context, the emergence and growth patterns of brain tumours, typically malignant diffuse glioblastomas, can be studied in the living brain using inverse mathematical modelling incorporating e.g. reaction diffusion PDE models with patient-specific parameterization of the biological processes (obtained from the imaging data) together with machine learning approaches such as physics-informed neural networks (PINNs) for data-driven solutions of the nonlinear partial differential equations. [PINNs: “are a type of universal function approximators that can embed the knowledge of any physical laws that govern a given data-set in the learning process, and can be described by PDEs” (wikipedia)].
By such means, complex biological processes can be decoded and put into actionable clinical information (e.g. forecasting and treatment plans in neuro-oncology) or provide person-specific characterisation and detection of consciousness, in the resting state or under different experimental conditions.

Kind regards,
Arvid Lundervold

From: Karmela Padavic-Callaghan <K.Padaviccallaghan@newscientist.com>
Date: Friday, 3 February 2023 at 15:44
To: Arvid Lundervold <Arvid.Lundervold@uib.no>
Subject: Re: Comment for New Scientist?

Hi Prof. Lundervold,

Thank you for the quick reply! Any brief comment you may be able to send by Monday would be great.

I appreciate your time,

Karmela Padavic-Callaghan, PhD (she/they)
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lronmely/status/1524570439934222336