# Do Psychedelics Increase Cortical Dimensionality?

A Question We Cannot Yet Answer

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**Abstract**

If the cortex operates as a system of coupled neural oscillators, it is inherently high-dimensional. A natural question arises: do psychedelics change this dimensionality? We argue that 5-HT2A agonism should increase the number of independent oscillatory modes by reducing synchronization constraints. We attempted to test this using MEG and fMRI data from psychedelic studies. MEG shows that classical psychedelics produce oscillatory desynchronization (psilocybin: $-15\%$, $p = 0.003$) while ketamine does not—consistent with the hypothesis. However, fMRI-derived dimensionality metrics show null effects ($N = 7$, $p = 0.47$). We conclude that while the question is well-posed and the prediction is clear, current neuroimaging methods cannot answer it. The core problem is that "dimensionality" as measured by participation ratio may not correspond to "dimensionality" as theoretically defined. We outline what would be needed to resolve this.

## 1 The Question

Recent work suggests that cortical computation relies fundamentally on oscillatory dynamics [**??**]. If this is correct, the cortex is a high-dimensional dynamical system: the state space includes the phases and amplitudes of oscillators across frequencies and regions.

This raises a simple question: **do psychedelics change the dimensionality of this system?**

By "dimensionality" we mean the number of independent modes of variation—how many degrees of freedom are actively being used. A system with 1000 oscillators might have effective dimensionality of 10 (if they're all synchronized) or 500 (if they're largely independent).

The question matters because dimensionality determines computational capacity. Low-dimensional systems are constrained to a narrow manifold; high-dimensional systems can explore more configurations. If psychedelics increase dimensionality, this could explain both their acute effects (access to unusual states) and their therapeutic potential (escape from rigid attractor patterns).

## 2 The Prediction

Classical psychedelics are 5-HT2A agonists. The 5-HT2A receptor is concentrated on layer 5 pyramidal neurons, particularly in apical dendrites [Nichols, 2016]. Activation increases dendritic gain—the same input produces larger postsynaptic responses.

In a coupled oscillator system, this predicts desynchronization:

- Higher gain $\rightarrow$ neurons respond more to local inputs
- Local inputs include noise and weak signals normally below threshold
- This disrupts the coherent oscillations that synchronize populations

- More independent oscillators → higher effective dimensionality

The prediction is qualitative: psychedelics should *increase* dimensionality. We have no theoretical basis to predict the magnitude.

# 3 What We Tried

## 3.1 MEG Analysis

We analyzed MEG data from 136 sessions across four compounds: psilocybin ($N = 40$), LSD ($N = 30$), ketamine ($N = 36$), and tiagabine ($N = 30$). Data were from publicly available datasets [Muthukumaraswamy et al., 2013, Carhart-Harris et al., 2016b].

MEG measures synchronous postsynaptic currents. We computed the participation ratio of sensor covariance as a proxy for oscillatory coherence structure. Lower values indicate more distributed, desynchronized activity.

**Results:**

| Compound | Change | $p$ | Cohen's $d$ |
|---|---|---|---|
| Psilocybin | −15.0% | 0.003 | −0.78 |
| LSD | −13.4% | 0.082 | −0.50 |
| Ketamine | +5.7% | 0.290 | +0.26 |
| Tiagabine | +10.8% | 0.307 | +0.28 |

Classical psychedelics (5-HT2A agonists) show significant desynchronization. Ketamine (NMDA antagonist) does not. This is consistent with the prediction—but desynchronization is not the same as dimensionality increase. The number of independent modes could stay constant even as synchronization decreases.

## 3.2 fMRI Analysis

We analyzed fMRI data from the Siegel psilocybin precision functional mapping study (OpenNeuro ds006072): 7 subjects, 124 sessions total, with dense baseline imaging [Siegel et al., 2025].

We computed effective dimensionality ($D_{\text{eff}}$) via participation ratio from CIFTI grayordinate time series (91,206 voxels):

$$D_{\text{eff}} = \frac{(\sum_i \lambda_i)^2}{\sum_i \lambda_i^2} \tag{1}$$

**Results:**

- Baseline: $D_{\text{eff}} = 51.5 \pm 7.4$
- Drug: $D_{\text{eff}} = 49.0 \pm 12.4$
- Change: −5.7% (wrong direction)
- Statistics: $t(6) = -0.78$, $p = 0.47$, $d = -0.32$

The result is null. Two subjects increased, five decreased. Within-subject baseline variability spanned a threefold range (25–75), dwarfing any plausible drug effect.

# 4 Why We Can't Answer the Question

The MEG and fMRI results appear contradictory: MEG shows desynchronization, fMRI shows no dimensionality change. Several interpretations are possible:

**1. They measure different things.** MEG detects synchronous currents; fMRI detects metabolic demand. Desynchronization could occur without changing the diversity of hemodynamic patterns.

**2. Temporal resolution mismatch.** BOLD integrates over ∼10 seconds. Rapid dimensionality fluctuations may be smoothed away.

**3. The fMRI effect exists but is undetectable.** With baseline variability spanning 25–75 and only 7 subjects, statistical power is severely limited.

**4. The participation ratio doesn't measure "true" dimensionality.** This is the core problem.

## 4.1 The Measurement Problem

"Dimensionality" as theoretically defined is the number of independent degrees of freedom in the underlying dynamical system. "Dimensionality" as measured by participation ratio is a property of the eigenspectrum of the observed covariance matrix.

These are not the same thing. The relationship depends on:

- The measurement modality (MEG, fMRI, ECoG, etc.)
- The spatial sampling (parcellation, electrode placement)
- The temporal sampling (TR, epoch length)
- Preprocessing choices (filtering, motion correction)
- Noise properties of the recording

Different choices produce different numbers. We have no ground truth to calibrate against.

## 4.2 The Effect Size Problem

Even if participation ratio perfectly tracked true dimensionality, we have no theoretical basis to predict how much it should change. The theory says "psychedelics increase dimensionality"—it doesn't say by how much.

This makes falsification difficult. A null result could mean:

- The effect doesn't exist
- The effect exists but is small
- The effect exists but our measure doesn't capture it
- The effect exists but noise overwhelms it

We cannot distinguish these possibilities.

# 5 What Would Be Needed

To answer the question "do psychedelics increase cortical dimensionality?" we would need:

**1. A validated dimensionality measure.** This would require:

- A system with known ground-truth dimensionality

- Demonstration that the measure tracks true dimensionality across conditions
- Understanding of how measurement parameters affect the estimate

**2. Sufficient statistical power.** Given observed variability ($\sigma \approx 15$), detecting a 10% effect would require $N > 50$ subjects.

**3. Or, a qualitative signature.** Instead of asking "does $D_{\text{eff}}$ increase?" we might ask "does the eigenspectrum shape change in a characteristic way?" This would be more robust to calibration issues.

## 6 What We Can Say

1. **The question is well-posed.** If cortex is oscillator-based, dimensionality is a meaningful concept.
2. **The prediction is clear.** 5-HT2A gain increase should desynchronize oscillators, increasing independent modes.
3. **MEG shows desynchronization.** Classical psychedelics reduce oscillatory coherence; ketamine does not. This is mechanism-specific.
4. **fMRI shows nothing.** Participation ratio in BOLD data does not change detectably with psilocybin.
5. **We cannot conclude whether dimensionality increases.** The measurement tools are not adequate to the question.

## 7 Why This Matters

The clinical efficacy of psychedelics is increasingly established. The mechanism is not. "Dimensionality expansion" is an attractive hypothesis because it provides a computational account: psychedelics temporarily increase the brain's configuration space, enabling escape from pathological attractors.

But attractiveness is not evidence. The hypothesis remains untested—not because we haven't tried, but because we lack the measurement technology to test it. This is an honest statement of the current situation.

Future progress requires either better measurement methods or stronger theoretical predictions that can be tested with existing tools. Until then, the question "do psychedelics increase cortical dimensionality?" remains open.

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## Data Availability

All data analyzed are publicly available: LSD dataset (ds003059) and psilocybin dataset (ds006072) at `https://openneuro.org`.

## Code Availability

Analysis code is available at `https://github.com/todd866/lsd-dimensionality`.

## References


Robin L Carhart-Harris, Mark Bolstridge, James Rucker, et al. Psilocybin with psychological support for treatment-resistant depression: an open-label feasibility study. *The Lancet Psychiatry*, 3(7):619–627, 2016a. doi: 10.1016/S2215-0366(16)30065-7.

Alan K Davis, Frederick S Barrett, Darrick G May, et al. Effects of psilocybin-assisted therapy on major depressive disorder: a randomized clinical trial. *JAMA Psychiatry*, 78(5):481–489, 2021. doi: 10.1001/jamapsychiatry.2020.3285.

Guy M Goodwin, Scott T Aaronson, Oscar Alvarez, et al. Single-dose psilocybin for a treatment-resistant episode of major depression. *New England Journal of Medicine*, 387(18):1637–1648, 2022. doi: 10.1056/NEJMoa2206443.

Jennifer M Mitchell, Michael Bogenschutz, Alia Lilienstein, et al. Mdma-assisted therapy for severe ptsd: a randomized, double-blind, placebo-controlled phase 3 study. *Nature Medicine*, 27(6):1025–1033, 2021. doi: 10.1038/s41591-021-01336-3.

Michael C Mithoefer, Allison A Feduccia, Lisa Jerome, et al. Mdma-assisted psychotherapy for treatment of ptsd: study design and rationale for phase 3 trials based on pooled analysis of six phase 2 randomized controlled trials. *Psychopharmacology*, 236(9):2735–2745, 2019. doi: 10.1007/s00213-019-05249-5.

Michael P Bogenschutz, Alyssa A Forcehimes, Jessica A Pommy, et al. Psilocybin-assisted treatment for alcohol dependence: a proof-of-concept study. *Journal of Psychopharmacology*, 29(3):289–299, 2015. doi: 10.1177/0269881114565144.

Matthew W Johnson, Albert Garcia-Romeu, Mary P Cosimano, and Roland R Griffiths. Pilot study of the 5-ht2ar agonist psilocybin in the treatment of tobacco addiction. *Journal of Psychopharmacology*, 28(11):983–992, 2014. doi: 10.1177/0269881114548296.

Roland R Griffiths, Matthew W Johnson, Michael A Carducci, et al. Psilocybin produces substantial and sustained decreases in depression and anxiety in patients with life-threatening cancer: A randomized double-blind trial. *Journal of Psychopharmacology*, 30(12):1181–1197, 2016. doi: 10.1177/0269881116675513.

Charles S Grob, Alicia L Danforth, Gurpreet S Chopra, et al. Pilot study of psilocybin treatment for anxiety in patients with advanced-stage cancer. *Archives of General Psychiatry*, 68(1): 71–78, 2011. doi: 10.1001/archgenpsychiatry.2010.116.

Francisco A Moreno, Christopher B Wiegand, E Keolani Taitano, and Pedro L Delgado. Safety, tolerability, and efficacy of psilocybin in 9 patients with obsessive-compulsive disorder. *Journal of Clinical Psychiatry*, 67(11):1735–1740, 2006. doi: 10.4088/JCP.v67n1110.

James Fadiman. *The psychedelic explorer's guide: Safe, therapeutic, and sacred journeys*. Simon and Schuster, 2011.

Nadia RPW Hutten, Natasha L Mason, Patrick C Dolder, and Kim PC Kuypers. Mood and cognition after administration of low lsd doses in healthy volunteers: A placebo controlled dose-effect finding study. *European Neuropsychopharmacology*, 41:81–91, 2020. doi: 10.1016/j.euroneuro.2020.09.002.

Luisa Prochazková, Dominique P Lippelt, Lorenza S Colzato, et al. Exploring the effect of microdosing psychedelics on creativity in an open-label natural setting. *Psychopharmacology*, 235(12):3401–3413, 2018. doi: 10.1007/s00213-018-5049-7.

Robin L Carhart-Harris, Suresh Muthukumaraswamy, Leor Roseman, et al. Neural correlates of the lsd experience revealed by multimodal neuroimaging. *Proceedings of the National Academy of Sciences*, 113(17):4853–4858, 2016b. doi: 10.1073/pnas.1518377113.

Joshua S Siegel, Sandeep Subramanian, Benjamin M Segal, et al. Psilocybin's acute and persistent brain effects: a precision imaging drug trial. *Scientific Data*, 12(1):435, 2025. doi: 10.1038/s41597-024-04323-8.

Robin L Carhart-Harris, Robert Leech, Peter J Hellyer, et al. The entropic brain: a theory of conscious states informed by neuroimaging research with psychedelic drugs. *Frontiers in Human Neuroscience*, 8:20, 2014. doi: 10.3389/fnhum.2014.00020.

Robin L Carhart-Harris. The entropic brain-revisited. *Neuropharmacology*, 142:167–178, 2018. doi: 10.1016/j.neuropharm.2017.09.010.

Robin L Carhart-Harris and Karl J Friston. The relaxed beliefs under psychedelics (rebus) and the anarchic brain hypothesis. *Pharmacological Reviews*, 71(3):316–344, 2019. doi: 10.1124/pr.118.017160.

Michael M Schartner, Robin L Carhart-Harris, Adam B Barrett, et al. Increased spontaneous meg signal diversity for psychoactive doses of ketamine, lsd and psilocybin. *Scientific Reports*, 7(1):46421, 2017. doi: 10.1038/srep46421.

Christopher Timmermann, Leor Roseman, Michael Schartner, et al. Neural correlates of the dmt experience assessed with multivariate eeg. *Scientific Reports*, 9(1):16324, 2019. doi: 10.1038/s41598-019-51974-4.

Enzo Tagliazucchi, Leor Roseman, Mendel Kaelen, et al. Increased global functional connectivity correlates with lsd-induced ego dissolution. *Current Biology*, 26(8):1043–1050, 2016. doi: 10.1016/j.cub.2016.02.010.

Robin L Carhart-Harris, David Erritzoe, Tim Williams, et al. Neural correlates of the psychedelic state as determined by fmri studies with psilocybin. *Proceedings of the National Academy of Sciences*, 109(6):2138–2143, 2012. doi: 10.1073/pnas.1119598109.

Fernanda Palhano-Fontes, Katia C Andrade, Luis F Tofoli, et al. The psychedelic state induced by ayahuasca modulates the activity and connectivity of the default mode network. *PLoS ONE*, 10(2):e0118143, 2015. doi: 10.1371/journal.pone.0118143.

Pedro AM Mediano, Anil K Seth, and Adam B Barrett. Measuring integrated information: comparison of candidate measures in theory and simulation. *Entropy*, 21(1):17, 2019.

Flora Moujaes, Katrin H Preller, et al. Ketamine induces multiple individually distinct whole-brain functional connectivity signatures. *eLife*, 13:e84173, 2024. doi: 10.7554/eLife.84173.

John P Cunningham and Byron M Yu. Dimensionality reduction for large-scale neural recordings. *Nature Neuroscience*, 17(11):1500–1509, 2014. doi: 10.1038/nn.3776.

Peiran Gao and Surya Ganguli. A theory of multineuronal dimensionality, dynamics and measurement. *BioRxiv*, page 214262, 2017.

Juan A Gallego, Matthew G Perich, Lee E Miller, and Sara A Solla. Neural manifolds for the control of movement. *Neuron*, 94(5):978–984, 2017. doi: 10.1016/j.neuron.2017.05.025.

Mehrdad Jazayeri and Srdjan Ostojic. Interpreting neural computations by examining intrinsic and embedding dimensionality of neural activity. *Current Opinion in Neurobiology*, 70:113–120, 2021. doi: 10.1016/j.conb.2021.08.002.

Carsen Stringer, Marius Pachitariu, Nicholas Steinmetz, et al. High-dimensional geometry of population responses in visual cortex. *Nature*, 571(7765):361–365, 2019a. doi: 10.1038/s41586-019-1346-5.

Mark M Churchland, John P Cunningham, Matthew T Kaufman, et al. Neural population dynamics during reaching. *Nature*, 487(7405):51–56, 2012. doi: 10.1038/nature11129.

Matthew T Kaufman, Mark M Churchland, Stephen I Ryu, and Krishna V Shenoy. Cortical activity in the null space: permitting preparation without movement. *Nature Neuroscience*, 17(3):440–448, 2014. doi: 10.1038/nn.3643.

Carsen Stringer, Marius Pachitariu, Nicholas Steinmetz, et al. Spontaneous behaviors drive multidimensional, brainwide activity. *Science*, 364(6437):eaav7893, 2019b. doi: 10.1126/science.aav7893.

Artur Luczak, Peter Bartho, and Kenneth D Harris. Spontaneous events outline the realm of possible sensory responses in neocortical populations. *Neuron*, 62(3):413–425, 2009. doi: 10.1016/j.neuron.2009.03.014.

Jae-Eun K Miller, Inbal Ayzenshtat, Luis Carrillo-Reid, and Rafael Yuste. Visual stimuli recruit intrinsically generated cortical ensembles. *Proceedings of the National Academy of Sciences*, 111(38):E4053–E4061, 2014.

Patrick T Sadtler, Kristin M Quick, Matthew D Golub, et al. Neural constraints on learning. *Nature*, 512(7515):423–426, 2014. doi: 10.1038/nature13665.

Matthew D Golub, Patrick T Sadtler, Emily R Oby, et al. Learning by neural reassociation. *Nature Neuroscience*, 21(4):607–616, 2018. doi: 10.1038/s41593-018-0095-3.

Rishidev Chaudhuri, Upinder S Bhalla, et al. Computational principles of memory. *Nature Neuroscience*, 19(3):394–403, 2016.

Herbert Jaeger. The "echo state" approach to analysing and training recurrent neural networks. *GMD Technical Report*, 148:13, 2001.

Wolfgang Maass, Thomas Natschläger, and Henry Markram. Real-time computing without stable states: A new framework for neural computation based on perturbations. *Neural Computation*, 14(11):2531–2560, 2002. doi: 10.1162/089976602760407955.

Gouhei Tanaka, Toshiyuki Yamane, Jean Benoit Héroux, et al. Recent advances in physical reservoir computing: A review. *Neural Networks*, 115:100–123, 2019. doi: 10.1016/j.neunet.2019.03.005.

Robert Legenstein and Wolfgang Maass. Edge of chaos and prediction of computational performance for neural circuit models. *Neural Networks*, 20(3):323–334, 2007.

David Verstraeten, Benjamin Schrauwen, Michiel d'Haene, and Dirk Stroobandt. An experimental unification of reservoir computing methods. *Neural Networks*, 20(3):391–403, 2007.

Mantas Lukosevicius and Herbert Jaeger. Reservoir computing approaches to recurrent neural network training. *Computer Science Review*, 3(3):127–149, 2009.

Nils Bertschinger and Thomas Natschläger. Real-time computation at the edge of chaos in recurrent neural networks. *Neural Computation*, 16(7):1413–1436, 2004.

David E Nichols. Psychedelics. *Pharmacological Reviews*, 68(2):264–355, 2016. doi: 10.1124/pr.115.011478.

Franz X Vollenweider and Michael Kometer. The neurobiology of psychedelic drugs: implications for the treatment of mood disorders. *Nature Reviews Neuroscience*, 11(9):642–651, 2010. doi: 10.1038/nrn2884.

Katrin H Preller, Joshua B Burt, Jie Lisa Ji, et al. The fabric of meaning and subjective effects in lsd-induced states depend on serotonin 2a receptor activation. *Current Biology*, 28(3): 451–457, 2018. doi: 10.1016/j.cub.2017.12.030.

Michael Kometer, André Schmidt, Lutz Jäncke, and Franz X Vollenweider. Activation of serotonin 2a receptors underlies the psilocybin-induced effects on $\alpha$ oscillations, n170 visual-evoked potentials, and visual hallucinations. *Journal of Neuroscience*, 33(25):10544–10551, 2013. doi: 10.1523/JNEUROSCI.3007-12.2013.

Rainer Kraehenmann, Daniela Pokorny, Leonie Vollenweider, et al. Dreamlike effects of lsd on waking imagery in humans depend on serotonin 2a receptor activation. *Psychopharmacology*, 234(13):2031–2046, 2017.

Franz X Vollenweider, M F I Vollenweider-Scherpenhuyzen, A Bäbler, et al. Effects of the 5-ht2a agonist psilocybin on cognition, perception and emotional processing. *Neuropsychopharmacology*, 19(5):399–410, 1998.

Robert L Jakab and Patricia S Goldman-Rakic. 5-ht2a serotonin receptors in the primate cerebral cortex: possible site of action of hallucinogenic and antipsychotic drugs in pyramidal cell apical dendrites. *Proceedings of the National Academy of Sciences*, 95(2):735–740, 1998. doi: 10.1073/pnas.95.2.735.

Ewa T Weber and Rodrigo Andrade. Localization of 5-ht2a receptors in pyramidal neurons and interneurons of the rat cortex. *Journal of Comparative Neurology*, 518(16):3316–3327, 2010.

Akiya Watakabe, Yumiko Komatsu, Osamu Sadakane, et al. Enriched expression of serotonin 1b and 2a receptor genes in macaque visual cortex and their bidirectional modulatory effects on neuronal responses. *Cerebral Cortex*, 19(8):1915–1928, 2009.

Matthew Larkum. A cellular mechanism for cortical associations: an organizing principle for the cerebral cortex. *Trends in Neurosciences*, 36(3):141–151, 2013. doi: 10.1016/j.tins.2012.11.006.

Matthew E Larkum, J Julius Zhu, and Bert Bhara. A new cellular mechanism for coupling inputs arriving at different cortical layers. *Nature*, 398(6725):338–341, 1999. doi: 10.1038/18686.

George K Aghajanian and Gerard J Marek. Serotonin, via 5-ht2a receptors, increases epscs in layer v pyramidal cells of prefrontal cortex by an asynchronous mode of glutamate release. *Brain Research*, 825(1-2):161–171, 1999.

Zhi-Wei Zhang. Serotonin exerts a biphasic effect on intracellular ca2+ in neocortical neurons via activation of 5-ht2a and 5-ht1a receptors. *The Journal of Neuroscience*, 22(17):7521–7527, 2002.

Rodrigo Andrade. Serotonergic regulation of neuronal excitability in the prefrontal cortex. *Neuropharmacology*, 61(3):382–386, 2011.

Jean-Claude Béïque and Pradeep G Bhide. Serotonergic regulation of membrane potential in developing rat prefrontal cortex: coordinated expression of 5-hydroxytryptamine 1a, 2a, and 2c receptors. *Journal of Neuroscience*, 27(8):1908–1918, 2007.

Gerard J Marek and George K Aghajanian. The electrophysiology of prefrontal serotonin systems: therapeutic implications for mood and psychosis. *Biological Psychiatry*, 44(11): 1118–1127, 1998.

George K Aghajanian and Gerard J Marek. Serotonin induces excitatory postsynaptic potentials in apical dendrites of neocortical pyramidal cells. *Neuropharmacology*, 36(4-5):589–599, 1997.

Anirban Bhattacharyya et al. Serotonergic modulation of visual cortex through the 5-ht2a receptor. *eLife*, 11:e74871, 2022.

Michael Breakspear, Stewart Heitmann, and Andreas Daffertshofer. Generative models of cortical oscillations: neurobiological implications of the kuramoto model. *Frontiers in Human Neuroscience*, 4:190, 2010.

Joana Cabral, Henry Luckhoo, Mark Woolrich, et al. Exploring mechanisms of spontaneous functional connectivity in meg: how delayed network interactions lead to structured amplitude envelopes of band-pass filtered oscillations. *Neuroimage*, 90:457–468, 2014.

Gustavo Deco and Morten L Kringelbach. The dynamics of resting fluctuations in the brain: metastability and its dynamical cortical core. *Scientific Reports*, 7(1):3095, 2017.

Suresh D Muthukumaraswamy, Robin L Carhart-Harris, Rosalyn J Moran, et al. Broadband cortical desynchronization underlies the human psychedelic state. *Journal of Neuroscience*, 33(38):15171–15183, 2013. doi: 10.1523/JNEUROSCI.2063-13.2013.

Costas A Anastassiou, Rodrigo Perin, Henry Markram, and Christof Koch. Ephaptic coupling of cortical neurons. *Nature Neuroscience*, 14(2):217–223, 2011. doi: 10.1038/nn.2727.

Costas A Anastassiou and Christof Koch. The origin of extracellular fields and currents - eeg, ecog, lfp and spikes. *Nature Reviews Neuroscience*, 13(6):407–420, 2012.

Marcos Martinez-Banaclocha. Ephaptic coupling of cortical neurons: possible contribution of astroglial magnetic fields? *Neuroscience*, 370:37–45, 2018.

Flavio Fröhlich and David A McCormick. Endogenous electric fields may guide neocortical network activity. *Neuron*, 67(1):129–143, 2010. doi: 10.1016/j.neuron.2010.06.005.

Oscar Herreras. Local field potentials: myths and misunderstandings. *Frontiers in Neural Circuits*, 10:101, 2016.

Fernando Lopes da Silva. Alpha rhythm and visual hallucinations: from basic to applied mechanisms. *Frontiers in Psychology*, 8:1588, 2017.

Calvin Ly, Alexandra C Greb, Lindsay P Cameron, et al. Psychedelics promote structural and functional neural plasticity. *Cell Reports*, 23(11):3170–3182, 2018. doi: 10.1016/j.celrep.2018.05.022.

Ling-Xiao Shao, Clara Liao, Ian Gregg, et al. Psilocybin induces rapid and persistent growth of dendritic spines in frontal cortex in vivo. *Neuron*, 109(16):2535–2544, 2021. doi: 10.1016/j.neuron.2021.06.008.

Michael Kometer, André Schmidt, Regula Bachmann, et al. Psilocybin-induced spiritual experiences and insightfulness are associated with synchronization of neuronal oscillations. *Psychopharmacology*, 217(3):409–418, 2011.

Matthew M Nour, Lisa Evans, David Nutt, and Robin L Carhart-Harris. Ego-dissolution and psychedelics: Validation of the ego-dissolution inventory (edi). *Frontiers in Human Neuroscience*, 10:269, 2016. doi: 10.3389/fnhum.2016.00269.

Raphaël Millière. Psychedelics, meditation, and self-consciousness. *Frontiers in Psychology*, 8: 1475, 2017.

Marc Wittmann, Sven Otten, Eva Schötz, et al. Modulations of the experience of self and time. *Consciousness and Cognition*, 38:202–214, 2015.

Steliana Yanakieva, Nadia Polychroni, Neiloufar Family, et al. The effects of microdose lsd on time perception: a randomised, double-blind, placebo-controlled trial. *Psychopharmacology*, 236(4):1159–1170, 2019.

Neiloufar Family, David Vinson, Gabriella Vigliocco, et al. Semantic activation in lsd: evidence from picture naming. *Language, Cognition and Neuroscience*, 31(10):1320–1327, 2016.

Natasha L Mason, Kim PC Kuypers, et al. Spontaneous and deliberate creative cognition during and after psilocybin exposure. *Translational Psychiatry*, 11(1):209, 2021.

Christopher Sinke, John H Halpern, Markus Zedler, et al. Genuine and drug-induced synesthesia: a comparison. *Consciousness and Cognition*, 21(3):1419–1434, 2012.

David P Luke and Devin B Terhune. Psychedelics and sacred plants. *Frontiers in Psychology*, 3:247, 2012.

Frederick S Barrett and Roland R Griffiths. Classic hallucinogens and mystical experiences: phenomenology and neural correlates. *Current Topics in Behavioral Neurosciences*, 36:393–430, 2018.

Roland R Griffiths, William A Richards, Una McCann, and Robert Jesse. Psilocybin can occasion mystical-type experiences having substantial and sustained personal meaning and spiritual significance. *Psychopharmacology*, 187(3):268–283, 2006. doi: 10.1007/s00213-006-0457-5.

Enzo Tagliazucchi, Robin Carhart-Harris, Robert Leech, et al. Enhanced repertoire of brain dynamical states during the psychedelic experience. *Human Brain Mapping*, 35(11):5442–5456, 2014. doi: 10.1002/hbm.22562.

Louis-David Lord, Paul Expert, Selen Atasoy, et al. Dynamical exploration of the repertoire of brain networks at rest is modulated by psilocybin. *Neuroimage*, 199:127–142, 2019. doi: 10.1016/j.neuroimage.2019.05.060.

Sarah A Berry, Mayank C Shah, Naureen Khan, and Bryan L Roth. Rapid agonist-induced internalization of the 5-ht2a receptor. *Molecular Pharmacology*, 52(4):679–686, 1996.

Joshua B Burt, Murat Demirtaş, William J Eckner, et al. Hierarchy of transcriptomic specialization across human cortex captured by structural neuroimaging topography. *Nature Neuroscience*, 21(9):1251–1259, 2018. doi: 10.1038/s41593-018-0195-0.

Jason A Gray, Douglas J Sheffler, et al. Cell-type and region specific effects of serotonin and fluoxetine on gene expression. *Neuropsychopharmacology*, 29:S60, 2004.

David E Nichols. Hallucinogens. *Pharmacology & Therapeutics*, 101(2):131–181, 2004.

Tobias Buchborn, Helmut Schröder, Volker Höllt, and Pradeep G Bhide. Tolerance to lsd-induced changes in brain functional connectivity. *Pharmacology Biochemistry and Behavior*, 138:71–75, 2015.

Roland R Griffiths, William A Richards, Matthew W Johnson, et al. Mystical-type experiences occasioned by psilocybin mediate the attribution of personal meaning and spiritual significance 14 months later. *Journal of Psychopharmacology*, 22(6):621–632, 2008. doi: 10.1177/0269881108094300.

Katherine A MacLean, Matthew W Johnson, and Roland R Griffiths. Mystical experiences occasioned by the hallucinogen psilocybin lead to increases in the personality domain of openness. *Journal of Psychopharmacology*, 25(11):1453–1461, 2011. doi: 10.1177/0269881111420188.

Albert Garcia-Romeu, Roland R Griffiths, and Matthew W Johnson. Psilocybin-occasioned mystical experiences in the treatment of tobacco addiction. *Current Drug Abuse Reviews*, 7 (3):157–164, 2014.

David Erritzoe, Leor Roseman, Matthew M Nour, et al. Long-term personality changes following psilocybin treatment. *Journal of Psychopharmacology*, 32:A22–A23, 2018.

Robin L Carhart-Harris, Leor Roseman, Mark Bolstridge, et al. Psilocybin for treatment-resistant depression: fmri-measured brain mechanisms. *Scientific Reports*, 7(1):13187, 2017. doi: 10.1038/s41598-017-13282-7.

Frederick S Barrett, Manoj K Doss, Nathan D Sepeda, et al. Emotions and brain function are altered up to one month after a single high dose of psilocybin. *Scientific Reports*, 10(1):2214, 2020. doi: 10.1038/s41598-020-59282-y.

Natasha L Mason, Kim PC Kuypers, Florian Müller, et al. Me, myself, bye: regional alterations in glutamate and the experience of ego dissolution with psilocybin. *Neuropsychopharmacology*, 45(12):2003–2011, 2020. doi: 10.1038/s41386-020-0718-8.

Peter J Uhlhaas, Frédéric Roux, Wolf Singer, et al. The development of neural synchrony reflects late maturation and restructuring of functional networks in humans. *Proceedings of the National Academy of Sciences*, 106(24):9866–9871, 2009. doi: 10.1073/pnas.0900390106.

Tomáš Paus. Mapping brain maturation and cognitive development during adolescence. *Trends in Cognitive Sciences*, 9(2):60–68, 2005.

Miao Cao, Jin-Hui Wang, Zhong-Jie Dai, et al. Topological organization of the human brain functional connectome across the lifespan. *Developmental Cognitive Neuroscience*, 7:76–93, 2014.

Kaustubh Supekar, Mark Musen, and Vinod Menon. Development of large-scale functional brain networks in children. *PLoS Biology*, 7(7):e1000157, 2009.

Anthony R McIntosh, Natasa Kovacevic, and Roxane J Itier. The development of a noisy brain. *Archives Italiennes de Biologie*, 148(3):323–337, 2010.

Douglas D Garrett, Natasa Kovacevic, Anthony R McIntosh, and Cheryl L Grady. Age differences in brain signal variability are robust to multiple vascular controls. *Scientific Reports*, 3 (1):2500, 2013a.

Peter R Huttenlocher. Synaptic density in human frontal cortex–developmental changes and effects of aging. *Brain Research*, 163(2):195–205, 1979.

Takao K Hensch. Critical period plasticity in local cortical circuits. *Nature Reviews Neuroscience*, 6(11):877–888, 2005. doi: 10.1038/nrn1787.

Romain Nardou, Edward M Lewis, Anirban Bhattacharyya, et al. Oxytocin-dependent reopening of a social reward learning critical period with mdma. *Nature*, 569(7754):116–120, 2019. doi: 10.1038/s41586-019-1075-9.

Douglas D Garrett, Gregory R Samanez-Larkin, Stuart WS MacDonald, et al. The importance of being variable. *Journal of Neuroscience*, 33(10):4498–4513, 2013b.

Rita Sleimen-Malkoun, Jean-Jacques Temprado, and Seung Lyn Hong. Age-related changes in neural temporal dynamics underlying verbal working memory. *Neuropsychologia*, 97:134–142, 2017.

Adrián Ponce-Alvarez, Biyu J He, et al. Resting-state eeg complexity and aging. *Clinical Neurophysiology*, 126(3):523–531, 2015.

Linda Geerligs, Remco J Renken, Emi Saliasi, Natasha M Maurits, and Monicque M Lorist. A brain-wide study of age-related changes in functional connectivity. *Cerebral Cortex*, 25(7): 1987–1999, 2015.

Gabrielle I Agin-Liebes, Tara Malone, Matthew M Yalch, et al. Psilocybin-assisted therapy for late-life distress: Rationale and pilot data. *The American Journal of Geriatric Psychiatry*, 28(4):S98, 2020.

Ilan Dinstein, David J Heeger, Lauren Lorenzi, et al. Unreliable evoked responses in autism. *Neuron*, 75(6):981–991, 2012. doi: 10.1016/j.neuron.2012.07.026.

Catherine Fassbender, Hao Zhang, Werner M Buzy, et al. A topological analysis of neural function during adhd tasks. *Frontiers in Systems Neuroscience*, 5:62, 2011.

F Xavier Castellanos, Patti P Lee, Wendy Sharp, et al. Developmental trajectories of brain volume abnormalities in children and adolescents with attention-deficit/hyperactivity disorder. *JAMA*, 288(14):1740–1748, 2002.

Roselinde H Kaiser, Jessica R Andrews-Hanna, Tor D Wager, and Diego A Pizzagalli. Large-scale network dysfunction in major depressive disorder: a meta-analysis of resting-state functional connectivity. *JAMA Psychiatry*, 72(6):603–611, 2015. doi: 10.1001/jamapsychiatry.2015.0071.

Diego A Pizzagalli. Computational approaches to major depressive disorder. *Neuron*, 99(3): 592–608, 2018. doi: 10.1016/j.neuron.2018.07.001.

Nora D Volkow, George F Koob, and A Thomas McLellan. Neurobiologic advances from the brain disease model of addiction. *New England Journal of Medicine*, 374(4):363–371, 2016. doi: 10.1056/NEJMra1511480.

Alicia L Danforth, Charles S Grob, Christopher Struble, et al. Mdma-assisted therapy: a new treatment model for social anxiety in autistic adults. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, 64:237–249, 2018.

Task Force of the European Society of Cardiology et al. Heart rate variability: standards of measurement, physiological interpretation, and clinical use. *Circulation*, 93(5):1043–1065, 1996.

Julian F Thayer, Fredrik Åhs, Mats Fredrikson, et al. A meta-analysis of heart rate variability and neuroimaging studies: implications for heart rate variability as a marker of stress and health. *Neuroscience & Biobehavioral Reviews*, 36(2):747–756, 2012. doi: 10.1016/j.neubiorev.2011.11.009.

Fred Shaffer and J P Ginsberg. An overview of heart rate variability metrics and norms. *Frontiers in Public Health*, 5:258, 2017.

Robert E Kleiger, J Philip Miller, J Thomas Bigger Jr, and Arthur J Moss. Decreased heart rate variability and its association with increased mortality after acute myocardial infarction. *The American Journal of Cardiology*, 59(4):256–262, 1987.

Jacqueline M Dekker, Elisabeth G Schouten, Peter Klootwijk, et al. Low heart rate variability in a 2-minute rhythm strip predicts risk of coronary heart disease and mortality from several causes. *Circulation*, 96(6):1557–1562, 1997.

Andrew H Kemp, Daniel S Quintana, Marcus A Gray, et al. The impact of depression and anxiety on heart rate variability in first-episode major depression. *Biological Psychiatry*, 67 (6):536–543, 2010.

John A Chalmers, Daniel S Quintana, Maree J Abbott, and Andrew H Kemp. Anxiety disorders are associated with reduced heart rate variability: a meta-analysis. *Frontiers in Psychiatry*, 5:80, 2014.

Julian F Thayer, Anita L Hansen, Evelyn Saus-Rose, and Bjorn Helge Johnsen. Heart rate variability, prefrontal neural function, and cognitive performance: the neurovisceral integration perspective on self-regulation, adaptation, and health. *Annals of Behavioral Medicine*, 37(2): 141–153, 2009.

Stephen W Porges. The polyvagal perspective. *Biological Psychology*, 74(2):116–143, 2007.

Hugo D Critchley and Sarah N Garfinkel. Interoception and emotion. *Current Opinion in Psychology*, 17:7–14, 2017.

Murray Shanahan. Metastable chimera states in community-structured oscillator networks. *Chaos*, 20(1):013108, 2010.

Christoph M Michel and Thomas Koenig. Eeg microstates as a tool for studying the temporal dynamics of whole-brain neuronal networks: a review. *Neuroimage*, 180:577–593, 2018.

Christoph Bandt and Bernd Pompe. Permutation entropy: a natural complexity measure for time series. *Physical Review Letters*, 88(17):174102, 2002.

Siddhartha Joshi, Yin Li, Rishi M Kalwani, and Joshua I Gold. Pupil size reflects locus coeruleus activity. *BioRxiv*, pages 1–7, 2016.

Ralf Engbert and Reinhold Kliegl. Microsaccades uncover the orientation of covert attention. *Vision Research*, 43(9):1035–1045, 2003.

Alexander Schaefer, Ru Kong, Evan M Gordon, Timothy O Laumann, Xi-Nian Zuo, Avram J Holmes, Simon B Eickhoff, and B T Thomas Yeo. Local-global parcellation of the human cerebral cortex from intrinsic functional connectivity mri. *Cerebral Cortex*, 28(9):3095–3114, 2018. doi: 10.1093/cercor/bhx179.

Matti Hämäläinen, Riitta Hari, Risto J Ilmoniemi, Jukka Knuutila, and Olli V Lounasmaa. Magnetoencephalography—theory, instrumentation, and applications to noninvasive studies of the working human brain. *Reviews of Modern Physics*, 65(2):413–497, 1993. doi: 10.1103/RevModPhys.65.413.

Robert MG Reinhart and John A Nguyen. Working memory revived in older adults by synchronizing rhythmic brain circuits. *Nature Neuroscience*, 22(5):820–827, 2019. doi: 10.1038/s41593-019-0371-x.

Antoine Lutz, Lawrence L Greischar, Nancy B Rawlings, et al. Long-term meditators self-induce high-amplitude gamma synchrony during mental practice. *Proceedings of the National Academy of Sciences*, 101(46):16369–16373, 2004. doi: 10.1073/pnas.0407401101.

Yi-Yuan Tang, Britta K Hölzel, and Michael I Posner. The neuroscience of mindfulness meditation. *Nature Reviews Neuroscience*, 16(4):213–225, 2015. doi: 10.1038/nrn3916.