The Hierarchy of Psychedelic Effects: Three Systematic Reviews and Meta-Analyses

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Abstract:
Serotonergic psychedelics induce altered states of consciousness and have shown potential in treating a variety of neuropsychiatric disorders, including depression and addiction. Yet their modes of action are currently not fully understood. Here, we provide three systematic reviews and meta-analyses of three hierarchical levels relevant to the effects of psychedelics, i.e., 1) subjective experience (phenomenology), 2) whole-brain neuroimaging and 3) molecular pharmacology. Phenomenologically, medium and high doses of LSD yield significantly higher ratings of visionary restructuralisation than psilocybin on the 5-dimensional Altered States of Consciousness Scale. Our neuroimaging results reveal that psychedelics significantly strengthen between-network functional connectivity (FC) while diminishing within-network FC. Pharmacologically, we found no significant between-drug differences in the selectivity of psychedelics for the 5-HT_{2A}, 5-HT_{2C}, or D_2 receptors, relative to the 5-HT_{1A} receptor, but we did observe that LSD induces significantly more inositol phosphate formation at the 5-HT_{2A} receptor than DMT and psilocin. Our meta-analyses link each of the classic psychedelics – DMT, LSD, and psilocybin – to specific neural fingerprints at each level of the tripartite hierarchy. The results show a highly non-linear relationship between these fingerprints. Overall, the results point to the need for standardising experimental procedures and analysis techniques, as well as for more research on the emergence between different levels of psychedelic effects. Future work could use our tripartite hierarchy framework to investigate the dose-dependent effects of different psychedelics in the same participants.

Keywords:

psychedelics, ayahuasca, LSD, psilocybin, meta-analysis, fMRI, functional connectivity, BOLD activation, pharmacology, receptor affinity, receptor agonism, phenomenology, subjective experience, consciousness

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Section 1. Introduction

Psychedelics have been utilised by early cultures for millennia within diverse sociocultural contexts, as well as spiritual and healing rituals (Garcia & Maia, 2022; Nichols, 2016; Tupper et al., 2015). Western research into psychedelics, having blossomed in the '50s and '60s following the first study of lysergic acid diethylamide (LSD) in 1947 (Stoll, 1947), came to a halt in the late 1960s due to changes in government regulations and the classification of these substances as "drugs of abuse" with "no recognised medical value" (Tupper et al., 2015). Revitalisation of psychedelic research commenced in the 1990s (Hermle et al., 1992; Strassman et al., 1994; Strassman & Qualls, 1994), with three key factors inspiring the current interest: scientific advances, evidence of therapeutic potential, and increased public interest (Aday et al., 2021). Researchers have come to recognise that psychedelics may be effective tools in the treatment of psychiatric disorders such as depression (Muttoni et al., 2019; Nutt et al., 2020) and addiction (Tófoli & de Araujo, 2016).

The effects of psychedelic substances have been examined at several levels. Pharmacological research has measured their interaction with various receptors in the brain (e.g. Glennon et al., 1984; Watts et al., 1995), while other research domains have explored the subjective experience of a psychedelic 'trip'. Neuroimaging research has examined changes in brain activity and functional connectivity under the influence of psychedelics, yet there are still relatively few studies and a plethora of different analysis techniques. Here, we report the findings of a systematic meta-analysis focused on synthesising the evidence from three classic psychedelics: DMT, LSD, and psilocybin. The main aim is to provide an overview and analysis of the literature across three levels of description: (1) phenomenology—to discuss key differences in the states of consciousness induced by these psychedelics; (2) functional neuroimaging—to compare the changes in brain activity, functional connectivity, and entropy that are induced by psychedelics; and (3) pharmacology—to discuss the binding affinities and functional activity of psychedelics with respect to various neural receptors.

Section 1.1. Phenomenology

Psychedelics produce altered states of consciousness that are characterised by ego death, or a breakdown in one's sense of self, and "mystical" experiences (Griffiths et al., 2018; Yaden et al., 2021). Mystical experiences on psychedelics can be defined by four components: a sense of unity and sacredness; transcendence of time and space; positive mood; and ineffability (Barrett et al., 2015; Maclean et al., 2012). Individuals who have taken one of the classic psychedelics are significantly more likely to have had a full mystical experience than people who had other kinds of meaningful experiences (Griffiths et al., 2019).

However, perhaps the strongest predictor of therapeutic outcomes from psychedelic research is so-called 'emotional breakthrough' experiences, as assessed by the emotional breakthrough inventory or EBI (Roseman et al., 2019). Additionally, psychological insight, which includes awareness of previously repressed emotions (Davis et al., 2021; Peill et al., 2022), correlates with the therapeutic effects of psychedelics.

These experiential themes – insight, mystical experiences, and ego dissolution – are all captured by the Altered States of Consciousness (ASC) scale. The 5D-ASC measures altered states of consciousness along five different dimensions: oceanic boundlessness (e.g. a sense of interconnectedness), anxious ego dissolution, visionary restructuralisation (e.g. visual hallucinations), auditory alterations, and reduction of vigilance. Subsequent factor analyses led to the extraction of 11 lower-order dimensions from the 5D-ASC,

resulting in the development of the 11D-ASC: experience of unity, spiritual experience, blissful state, insightfulness, disembodiment, impaired control and cognition, anxiety, elementary imagery, complex imagery, audio-visual synesthesia, and changed meaning of percepts (Studerus et al., 2010). Because the ASC is the most common subjective questionnaire in the literature on the neuroimaging of psychedelics, we performed a meta-analysis on both the 5D- and 11D-ASC scores of DMT, LSD, and psilocybin.

However, the ASC is just one of many scales for rating the subjective effects of psychedelics. The multiplicity of scales makes it difficult to comprehensively evaluate the literature on the phenomenology of psychedelics. To date, only two studies have used a single set of scales to compare the subjective effects of LSD and psilocybin in the same group of participants (Holze et al., 2022; Ley et al., 2023). More recent research has attempted to draw direct comparisons by qualitatively examining larger datasets, such as the Erowid corpus of trip reports (Ballentine et al., 2022; Coyle et al., 2012; Qiu & Minda, 2021; Sanz et al., 2018; Zamberlan et al., 2018). The key findings from these comparative studies are discussed in *Section S3*.

Section 1.2. Neuroimaging

After a long pause in psychedelic research on humans, the pioneering positron emission tomography (PET) scans by Vollenweider and Gouzoulis-Mayfrank in the late 1990s ushered in a new era of research on the human brain under psychedelics (Gouzoulis-Mayfrank et al., 1999; Vollenweider et al., 1997, 1999). Forty to fifty years after the initial spate of electroencephalography (EEG) studies on psychedelics (see Tagliazucchi (2020) for a review), several studies used EEG to measure human brain activity under psychedelics, especially ayahuasca (Hoffmann, 2001; Riba, Anderer, et al., 2002; Riba et al., 2004; Riba, Rodríguez-Fornells, et al., 2002; Stuckey et al., 2005) and psilocybin (Umbricht et al., 2002, 2003). However, many of these studies were predicated on the notion that psychedelics are principally useful as a model for psychosis and schizophrenia. For instance, Vollenweider et al. (1997) considered the feeling of ego dissolution on psychedelics to be a model of psychosis. However, the last decade has seen a huge rise in more explorative, data-driven or hypothesis-free neuroimaging studies on psychedelics, as well as studies on their therapeutic benefits for clinical populations, e.g. patients with depression. The first functional neuroimaging study of psychedelics, published in 2012 (Carhart-Harris, Erritzoe, et al., 2012), was an exploratory analysis of psilocybin-induced changes in cerebral blood flow and BOLD activity in healthy human participants. Since then, dozens of fMRI studies have been performed on human participants under the influence of ayahausca, LSD, psilocybin and DMT, including several studies on depressed patients (Carhart-Harris et al., 2017; Daws et al., 2022; Doss et al., 2021; Mertens et al., 2020; Roseman et al., 2018; Wall et al., 2022). Additionally, in the last decade, two studies collected primary magnetoencephalography (MEG) data on healthy human participants who had been administered LSD and psilocybin (Carhart-Harris et al., 2016; Muthukumaraswamy et al., 2013).

We chose to perform a meta-analysis exclusively on the fMRI data and not on any of the other modalities used to measure brain activity. There were too few primary PET (4), SPECT (4), or MEG (2) datasets to merit a meta-analysis; by comparison, 30 fMRI studies have collected original data. While there are many more primary EEG datasets (25) from the post-1960s era (and even more from the 1950s-1960s era) than PET, SPECT, or MEG, most of the EEG studies do not spatially localise the brain activity recorded at EEG electrodes. Without the raw data, which may be difficult to access when some of the studies are nearly 20 years old, we cannot source-localise the EEG activity ourselves. On the other hand, the published fMRI data on psychedelics tends to report the specific coordinates of brain regions that

become more or less active under psychedelics. In general, EEG has higher temporal resolution than fMRI (Haufe et al., 2018), so a future meta-analysis that focuses on the temporal, rather than spatial, characteristics of brain activity on psychedelics could consider the EEG rather than fMRI data.

The fMRI studies assess three different metrics of brain activity: BOLD activation, connectivity, and entropy. Studies on BOLD activation analyse changes in the trajectory of BOLD timeseries with a rapidly-acting psychedelic, e.g. intravenously-administered psilocybin. Connectivity studies can examine undirected, instantaneous correlations between different regions (a type of functional connectivity) or model the experimental factors that modulate directed connections between regions, using dynamic causal modeling (a tool for measuring effective connectivity). The entropy of spontaneous brain activity is best assessed with MEG and EEG, but efforts to compute entropy on the spontaneous BOLD signal, as well as the entropy rate (Lempel-Ziv complexity) and indices of criticality, have also been attempted (see *Section S1.2* for a full list of citations). While studies on BOLD activation and functional connectivity are common for most subject areas within cognitive neuroscience, entropy is a rather unique feature of the psychedelic neuroimaging literature. The studies on entropy were motivated by Robin Carhart-Harris' influential *Entropic Brain Hypothesis* (EBH) (Carhart-Harris et al., 2014; Carhart-Harris, 2018), which states that psychedelics alter consciousness by elevating the entropy of spontaneous brain activity across time.

We performed a quantitative meta-analysis of the pairwise functional connectivity data using a novel algorithm. We initially attempted to conduct a quantitative meta-analysis of the BOLD activation data with the GingerALE method, which examines common clusters of BOLD activity across studies. However, we found that the data was too heterogeneous for the results to be valid. From the outset, we decided to provide a qualitative discussion of the studies on entropy, due to the wide range of methods in that section of the literature.

Section 1.3. Pharmacology

Chemically, psychedelics fall into three categories: tryptamines (e.g. DMT, psilocybin, ayahuasca), ergolines (e.g. LSD), and phenethylamines (e.g. mescaline, 2C-B) (Nichols, 2018). The molecular structure of tryptamine psychedelics strongly resembles that of serotonin; in fact, serotonin is itself a tryptamine, as both are synthesised from the same amino acid, tryptophan (Brandt et al., 2004). Ergolines are rigid and more complex analogues of tryptamines (Nichols, 2004), whereas the chemical backbone of phenethylamines is not the same as that of tryptamines; it is instead constituted from the amino acid phenylalanine (Fantegrossi et al., 2008).

Despite their chemical differences, both tryptamines and phenethylamines – indeed, all classic psychedelics – activate serotonin receptors. Phenethylamines are very selective for the serotonin-2 (5-HT_2) receptor subtype, including 5-HT_{2A}, 5-HT_{2B}, and 5-HT_{2C}, whereas tryptamines exhibit a more "promiscuous" binding profile, as they also have affinity for the 5-HT_1 receptor subtype (Araújo et al., 2015). In spite of the broad range of serotonin receptors that psychedelics, especially tryptamines, bind to, their interaction with the 5-HT_{2A} receptor is their primary mechanism of action (González-Maeso et al., 2007; López-Giménez & González-Maeso, 2018). Multiple studies have demonstrated that blocking the 5-HT_{2A} receptor with antagonists such as ketanserin eliminates their subjective effects (Preller et al., 2017; Quednow et al., 2012; Vollenweider et al., 1998). 5-HT_{2A} is expressed postsynaptically in the apical dendrites of layer V pyramidal neurons (Barrett et al., 2020; R. L. Carhart-Harris et al., 2016; Dai et al., 2023; Girn et al., 2022; Lebedev et al., 2015; Madsen et al., 2021; Müller, Dolder, et al., 2018; Müller,

Liechti, et al., 2018; Roseman et al., 2014)(Aleksandrova & Phillips, 2021; Hamada et al., 1998; Jakab & Goldman-Rakic, 1998), which are the primary excitatory neurons in mammalian cortex (Spruston, 2008). Binding to 5-HT_{2A} amplifies the firing rate of pyramidal neurons (Barrett et al., 2020; Dai et al., 2023; Girn et al., 2022; Lebedev et al., 2015; Madsen et al., 2021; Müller, Dolder, et al., 2018; Müller, Liechti, et al., 2018; Roseman et al., 2014)(Barrett et al., 2020; Dai et al., 2023; Girn et al., 2022; Lebedev et al., 2015; Madsen et al., 2021; Müller, Dolder, et al., 2018; Roseman et al., 2014)(Barrett et al., 2020; R. L. Carhart-Harris et al., 2016; Dai et al., 2023; Girn et al., 2022; Lebedev et al., 2015; Madsen et al., 2021; Müller, Dolder, et al., 2018; Roseman et al., 2014)(Barrett et al., 2020; Dai et al., 2023; Girn et al., 2022; Lebedev et al., 2015; Müller, Dolder, et al., 2018)(Puig et al., 2003) and upregulates the release of glutamate by increasing the amplitude and frequency of excitatory postsynaptic potentials (Aghajanian & Marek, 1997, 1999). 5-HT_{2A} expression is profuse in human cortex, with one study finding highest expression in the posterior cing(Barrett et al., 2020; R. L. Carhart-Harris et al., 2016; Dai et al., 2023; Girn et al., 2022; Lebedev et al., 2015; Madsen et al., 2021; Müller, Dolder, et al., 2018; Roseman et al., 2014)ulate cortex and V1 (Barrett et al., 2020; R. L. Carhart-Harris et al., 2016; Dai et al., 2023; Girn et al., 2022; Lebedev et al., 2015; Madsen et al., 2021; Müller, Liechti, et al., 2018; Roseman et al., 2014)(Barrett et al., 2020; R. L. Carhart-Harris et al., 2016; Dai et al., 2023; Girn et al., 2022; Lebedev et al., 2015; Madsen et al., 2021; Müller, Dolder, et al., 2018; Müller, Liechti, et al., 2018; Roseman et al., 2014)(Beliveau et al., 2017). In both humans and monkeys, 86-100% of glutamatergic cells in layers II-V of cortex express mRNA encoding 5-HT_{2A} receptors (de Almeida & Mengod, 2007). 5-HT_{2A} has also been identified in many subcortical regions (Nichols, 2016), though human PET imaging implies lower expression than in the cortex (Beliveau et al., 2017).

Although the consciousness-altering effects of psychedelics do primarily arise from their action at the 5-HT_{2A} receptor, we stress that different psychedelics display different binding profiles. For instance, unlike DMT and psilocybin, LSD has moderate affinity for dopamine receptors (de Vos et al., 2021). Differences in binding affinities could partially account for the distinctive phenomenology of each psychedelic. There is also some evidence that the 5-HT_{1A} and 5-HT_{2C} receptors may mediate the effects of psychedelics (Canal & Murnane, 2017; Pokorny et al., 2016).

However, binding affinity paints an incomplete picture of the pharmacology of psychedelics. Another key aspect is their functional activity at receptors. Serotonin and dopamine receptors are G protein-coupled receptors (GPCRs) (Gurevich et al., 2016; Shah et al., 2020), which perform essential roles in neurophysiological processes like smell, taste, light perception, and more (de Oliveira et al., 2019). GPCRs regulate these processes through G protein signaling pathways, which are initiated when agonists bind to GPCRs and activate G proteins (Tuteja, 2009). Different families of G proteins are selective for particular signaling pathways (Giulietti et al., 2014). In a phenomenon known as biased agonism, agonists can induce certain conformations in GPCRs, which then selectively activates certain pathways and not others (Andresen, 2011). 5-HT_2 receptors couple preferentially to a family of G proteins known as $G\alpha_{q/11}$, which activates the enzyme phospholipase C (PLC). This enzyme then catalyses the synthesis of the secondary messenger inositol triphosphate (IP_3, a species of inositol phosphate [IP]) , which subsequently leads to the release or "mobilisation" of calcium from the endoplasmic reticulum (López-Giménez & González-Maeso, 2018). Psychedelics are also known to recruit β-arrestin proteins (Pottie, Cannaert, et al., 2020; Pottie, Dedecker, et al., 2020; Rodriguiz et al., 2021; Schmitz et al., 2022). These proteins block the interaction between G proteins and the GPCR and remove the GPCR from the cell membrane, while also coupling

GPCRs to signaling proteins without activating G proteins; thus, β-arrestin promotes alternative signaling pathways (Bohn & Schmid, 2010). Functional GPCR assays on psychedelics have tended to focus on the three aspects of GPCR signaling described above: (1) IP formation, (2) calcium mobilisation, and (3) β-arrestin (specifically β-arrestin2) recruitment.

We performed a meta-analysis of the selective affinity of DMT, LSD, and psilocin for the 5-HT_{2A}, 5-HT_{2C}, and D_2 receptors, relative to the 5-HT_{1A} receptor. Additionally, we conducted a meta-analysis of their functional activity at the 5-HT_{2A} receptor, as measured by the three aforementioned assays.

Section 2. Results

We present the results of our meta-analysis of the phenomenology, neuroimaging, and pharmacology of three classical psychedelics: DMT, LSD, and psilocybin. At each level, we measured the alignment between the corresponding results and the Yeo networks, which facilitated comparisons between the three hierarchical levels.

Section 2.1. Phenomenology

We performed a meta-analysis on the 5D- and 11D-ASC scores of DMT, LSD, and psilocybin. Our literature search identified n = 44 phenomenology studies that met the inclusion criteria, including 5 studies on DMT (5D-ASC: n = 3; 11D-ASC: n = 3), 14 studies on LSD (5D-ASC: n = 9; 11D-ASC: n = 12), and 25 studies on psilocybin (5D-ASC: n = 12; 11D-ASC: n = 17). The eleven dimensions of the 11D-ASC are subscales of three dimensions in the 5D-ASC: oceanic boundlessness (OB), anxious ego dissolution (AED), and visionary restructuralisation (VR). Nevertheless, the 11D-ASC questionnaire contains fewer items than the 5D-ASC questionnaire, so 5D-ASC data cannot be directly compared to 11D-ASC data. Hence, we ran separate meta-analyses for the 5D-ASC and 11D-ASC data. In order to account for the measurement of multiple subjective dimensions, sometimes with more than one dose or drug, in individual studies, we performed a multilevel random-effects meta-analysis (Assink & Wibbelink, 2016; Harrer et al., 2021).

DMT was administered intravenously (IV) in the phenomenological studies, whereas LSD and psilocybin were administered orally (we excluded phenomenological studies that used IV LSD and psilocybin). IV administration yields different pharmacokinetics, which are known to influence the subjective experience of the drug (Luan et al., 2023; Vogt et al., 2023). Therefore, while we conducted meta-analyses of all three drugs, we only examined significant between-drug differences for ASC ratings of LSD and psilocybin. Additionally, we only compared similar doses of LSD and psilocybin. We assumed 20 mg psilocybin is equivalent to 0.01 mg LSD (Ley et al., 2023), and we defined low, medium, and high doses based on the literature (Carbonaro et al., 2018; Hasler et al., 2004; Vollenweider et al., 2007).

Pooled 5D-ASC scores for DMT, LSD, and psilocybin are shown in **Figure 1** (numerical data are given in **Table S1**). Between-drug differences for LSD and psilocybin are displayed in the left column of **Figure 1a-c**, and within-drug differences are displayed in the right column. At medium doses (LSD: 0.075-0.109 mg, psilocybin: 15-21 mg), 5D-ASC scores were significantly greater for LSD than psilocybin in the OB dimension (p = 0.0283), which corresponds to feelings of interconnectedness, and the VR dimension (p = 0.0468), which measures the quality and intensity of visual hallucinations. We also observed a significant difference between LSD and psilocybin in the VR dimension (p = 0.0417) at high doses (LSD: ≥0.010 mg,

psilocybin: ≥22 mg). There were no significant differences at low doses (LSD: 0.050-0.074 mg, psilocybin: 8-14 mg).

Within-drug differences between the five subjective dimensions were quite similar. A clear separation can be seen between two groups of subjective categories: (1) OB, VR, RV, and (2) AA and AED. At medium doses, VR and OB scores were significantly higher than both AED and AA scores for both LSD and psilocybin. Intriguingly, RV scored higher than all other dimensions at low doses of psilocybin, but this comparison was not significant. For DMT, there were no significant differences between dimensions at high doses (≥16 mg bolus injection, followed by continuous infusion of 1 mg/min), but for low doses (10-15 mg bolus + 0.6-0.99 mg/min continuous infusion), AED ranked significantly lower than both OB and VR. (Note that only one study measured AA and RV scores for DMT (Vogt et al., 2023), so we did not perform a meta-analysis on these dimensions for DMT.)

The results of the 11D-ASC meta-analysis were not very consistent with those of the 5D-ASC meta-analysis (**Figure S3**; **Table S2**). Note that we could not include DMT in the 11D-ASC meta-analysis because two of the three studies on DMT did not report standard errors, which are necessary for pooling the subjective data. At high doses, there were no significant differences between LSD and psilocybin in any of the dimensions, and standard errors were very large for psilocybin in some dimensions, particularly in some OB and VR subscales. At medium doses, where standard errors tended to be lower, we observed that two of the OB subscales (experience of unity and insightfulness), one of the AED subscales (impaired control and cognition), and three of the VR subscales (complex imagery, audio-visual synaesthesia, and changed meaning of percepts) ranked significantly higher for LSD than psilocybin. In line with the 5D-ASC results, we did not find any significant differences between LSD and psilocybin at low doses. However, unlike the 5D-ASC analysis, the 11D-ASC analysis showed that psilocybin rated higher than LSD in most of the dimensions; that being said, standard errors were very high for both LSD and psilocybin, so our estimates are not reliable. For medium doses, within-drug comparisons for the 11D-ASC analysis generally aligned with those of the 5D-ASC analysis.

We did not find any significant relationship between the pooled 5D-ASC scores and three methodological covariates that were defined *a priori*: prior psychedelic use, the time that the questionnaire was administered relative to the administration of the drug, and the presence or absence of a task in the experiment. Residual heterogeneity did not have a significant influence on estimates of pooled 5D- or 11D-ASC scores ($p < 0.0001$ in both cases). Unfortunately, we were unable to obtain reliable estimates of heterogeneity specifically attributable to within-study and between-study differences.

In order to directly compare the phenomenology of psychedelics to their neuroimaging and pharmacological profiles (*Section 2.2* and *Section 2.3*), we sought to determine the "phenomenology profiles" of DMT, LSD, and psilocybin based on the neural correlates of their subjective effects. We performed a separate literature search of studies that measured correlations between ASC ratings and fMRI activity. We determined the Yeo network that contained each brain region that exhibited a significant correlation. The phenomenology profiles were defined by a weighted combination of the mean correlations between each ASC scale and each Yeo network, in which the weights were the pooled ASC ratings of each psychedelic for the corresponding scale.

Because there were few significant differences in the pooled ASC scores, the phenomenology profiles of the psychedelics look very similar (**Figure 2**). However, these profiles may not reflect the true neural correlates of the subjective effects of psychedelics. Many studies performed correlations between ASC ratings and brain regions that were active only in specific tasks, but the tasks varied strongly in the literature.

The ventral attention network (VAN) appears to be more strongly associated with the subjective effects than any of the other Yeo networks, but this result may be an artifact of one study's decision to correlate the ASC ratings with a seed in the VAN. There need to be more studies that link whole-brain fMRI activity to ASC ratings before we can estimate the phenomenology profiles with confidence.

Finally, we also aimed to relate the phenomenology of different psychedelics by qualitatively synthesising the findings of papers that directly compared the subjective experiences of DMT/ayahuasca, LSD, and psilocybin. *Section S3* contains a comprehensive summary of their major aims, analysis approaches and findings.

Section 2.2. Neuroimaging

As stated above, the fMRI studies on psychedelics measure three different characteristics of brain activity: BOLD activation, entropy, and connectivity. We identified n = 17 studies on BOLD activation, including n = 3 studies on ayahuasca or DMT, n = 7 studies on LSD, and n = 4 studies on psilocybin. Initially, we used the GingerALE method to determine common clusters of BOLD activation across studies. We observed that psilocybin was associated with a cluster of activity in visual cortices, whereas LSD tended to affect more frontal areas. However, three of the four studies on psilocybin displayed visual stimuli to participants. Therefore, our results were likely confounded by the tasks that were used in the literature. We chose not to report the results of our GingerALE analysis because they are likely misleading.

The n = 12 fMRI studies on entropy and criticality in the psychedelic literature are very heterogeneous, employing a wide variety of measures on dissimilar variables of interest. A quantitative meta-analysis was extremely challenging, so we opted instead to perform a qualitative review of this literature, which is reported in *Section S4*.

The studies on connectivity were the only segment of the fMRI literature for which we determined that we could conduct a valid meta-analysis. These studies tended to use the same resting-state experimental procedure, and many of them employed similar methods for measuring connectivity. However, one major obstacle was the variety of parcellations in the literature. Since each study defined regions of interest (ROIs) in a different way, it was not possible to simply perform a weighted average of connectivity values across studies. (This weighted average method is essentially the core technique of the phenomenology and pharmacology meta-analyses.) An alternative approach is to "re-reference" the data to a coarse-grained parcellation: the Yeo networks, of which there are only seven in the brain (Thomas Yeo et al., 2011). That is, for every pair of functionally connected ROIs in the literature, we determine the corresponding Yeo networks that contain them. If the connection is positive (it increases under psychedelics), then the aggregate FC between those Yeo networks is incremented; otherwise, it is decremented. Our method for weighting each connection in the literature is described in *Section S2.2.2*. We determined significance by repeatedly applying our method to an independent resting-state fMRI dataset of sober individuals, which resulted in a null distribution (Van Essen et al., 2013).

This method is capable of synthesising studies on *pairwise* FC, such as seed-to-seed, seed-to-voxel, and within- and between-network FC analyses using independent components analysis (see **Table S4** for a full description of the inputs). The algorithm cannot accommodate global, structural metrics of connectivity such as global brain connectivity (GBC) or graph-theoretic modularity. Additionally, the algorithm does not capture any information about the direction of connectivity between regions; therefore, we did not

incorporate studies of effective connectivity or directed FC. (However, the vast majority of FC studies measured undirected FC.)

Many FC studies are secondary analyses of the same primary dataset. For instance, the primary FC data from Carhart-Harris et al. (2016) was re-analysed at least seven times with different methods in subsequent studies. To mitigate bias, we only inputted the most informative analysis of each unique dataset into the meta-analysis algorithm, such that each dataset was only represented once in the meta-analysis. Our method for selecting the most informative analysis is described in *Section S2.2.2*.

Based on these criteria and others, we ultimately identified n = 12 studies on connectivity that were eligible for our meta-analysis, including n = 3 studies on ayahuasca or DMT, n = 3 studies on LSD, and n = 6 studies on psilcoybin. (There are 22 other studies on connectivity that we qualitatively review in *Section S5*.) Our estimates of aggregate FC between Yeo networks, across all psychedelics, are shown in **Figure 3**. Psychedelics significantly strengthened between-network connectivity. Within-network connectivity decreased in all networks except for the frontoparietal network (FPN). However, the increase in the FPN was significant, whereas all the decreases were not, despite the fact that the reduction in within-network FC for the visual network was disproportionately greater than for all other networks.

In addition to aggregating FC across all psychedelics, we performed our analysis separately on each individual psychedelic (**Figure S4**). All three of the psychedelics lowered FC in the visual network and default mode network (DMN) and generally elevated between-network FC. Intriguingly, ayahuasca/DMT disproportionately augmented FC between two "transmodal" or associative networks (FPN and DMN) & the two "unimodal" or sensory networks (visual and somamotor network [SMN]), while strongly reducing FC within and between the two sensory networks. LSD dramatically increased FC between the visual network and all other networks, yet sharply decreased FC within the visual network. Summing across the rows of each aggregate FC matrix, we find that DMT and psilocybin tend to affect the FC of the DMN the most, whereas LSD displays a more uniform profile of changes in FC across the Yeo networks (**Figure 6**).

Finally, there was no significant association between our results and any of the methodological covariates in the literature that we identified *a priori*: the width of the Gaussian kernel used to smooth the data, the use of FSL or SPM, the technique used to regress out white matter, and the presence or absence of scrubbing to correct head motion.

Section 2.3. Pharmacology

We performed two separate meta-analyses on the pharmacology of psychedelics. The first assessed the selective affinity of DMT, LSD, and psilocin for the 5-HT_{2A}, 5-HT_{2C}, and D_2 receptors, relative to 5-HT_{1A}. The second examined the relative functional activity of the psychedelics at the 5-HT_{2A} receptor, as captured in three different assays of GPCR signaling.

Section 2.3.1. Affinity

We first present our meta-analysis of the selective affinity data. Selectivity is defined as the ratio between the K_i of each psychedelic for a receptor of interest, relative to a reference receptor. K_i refers to the inhibition constant, which reflects the concentration of a drug that is needed to inhibit the binding of another ligand, for instance a radioactively-labeled ligand (radioligand), to the receptor of interest; it is inversely related to binding affinity (Sykes et al., 2019). We chose 5-HT_{1A} to be the reference receptor. We

decided to analyse selectivity rather than absolute K_i because the latter is biased by the potency of the drug. Since LSD is much more potent than DMT and psilocin (Rickli et al., 2016), the meta-analysis would have simply revealed that LSD has higher affinity for all receptors if we were to examine the absolute K_i instead.

Our literature search identified n = 14 studies on selectivity, including n = 6 studies on DMT, n = 9 studies on LSD, and n = 5 studies on psilocin. We performed a random-effects meta-analysis with the drugs as covariates. Pooled selectivity values are displayed in **Figure 5a** (numerical data are given in **Table S8**). We found no significant between-drug differences in selectivity for any of the receptors – 5-HT_{2A}, 5-HT_{2C}, and D_2 – relative to the 5-HT_{1A} receptor. Standard errors were very large for all of the pooled selectivity values, and heterogeneity was very high for the 5-HT_{2A} selectivity data (I^2 = 93.69%) and for the 5-HT_{2C} selectivity data (I^2 = 99.14%). Nevertheless, it is clear that all drugs display less selectivity for D_2 than they do for 5-HT_{2C} and 5-HT_{2A}. Each individual drug is more selective for 5-HT_{2A} than 5-HT_{1A}. DMT and psilocin are about as equally selective for 5-HT_{2C} as they are for 5-HT_{1A}, but LSD is much less selective for 5-HT_{2C} than for 5-HT_{1A}.

We constructed another random-effects model in which both the drug and the radioligand for the receptor of interest were included as covariates; we refer to this as the "full" model and the previous one as the "reduced" model. For 5-HT_{2A}, the use of the radioligands [^{3}H]-ketanserin (p = 0.0141) and [^{3}H]-spiperone (p = 0.0271) significantly influenced the pooled selectivity estimates. Use of [^{3}H]-mesulgerine (p = 0.0292), but not [^{3}H]-ketanserin (p = 0.0872), significantly affected our estimates of selectivity for 5-HT_{2C}. According to the corrected Akaike's information criterion, the full model performed significantly better than the reduced model for 5-HT_{2A} selectivity (p < 0.0001), whereas the reverse was true for 5-HT_{2C} selectivity (p = 0.0024).

To relate the selective affinities to the neuroimaging and phenomenology of psychedelics, we first determined the expression of the 5-HT_{2A} and D_2 receptors in the Yeo networks, based on an atlas of PET maps (Hansen et al., 2022) (unfortunately, this did not include maps of the 5-HT_{2C} receptor). Then, we defined the "pharmacology profile" as the weighted combination of the expression patterns, in which the weights were the selectivity of each psychedelic for the corresponding receptor (**Figure 6**). The PET atlas indicates that 5-HT_{2A} receptor density is around two orders of magnitude higher than that of D_2 receptor density, so the pharmacology profile predominantly reflects selectivity for 5-HT_{2A}. Because psilocin's selectivity for 5-HT_{2A} is greater than that of LSD and DMT, psilocin has the "largest" pharmacology profile. 5-HT_{2A} is expressed more in transmodal networks than the visual network; thus, selectivity for 5-HT_{2A} may affect brain activity the most in these networks.

Section 2.3.2. Functional activity

Binding affinity is only one facet of the pharmacology of psychedelics. Another key aspect is their functional activity: the responses that they elicit in receptors after binding to them. While there are many ways to measure functional activity, we focused on GPCR signaling through three different pathways: (1) IP formation, (2) calcium mobilisation, and (3) β-arrestin2 recruitment. We limited our analysis to functional activity at specifically the 5-HT_{2A} receptor, as there was simply much more data about this receptor in humans.

When a drug is a partial, rather than full, agonist at a receptor, estimates of functional activity are affected in a nonlinear manner by the sensitivity of the assay (Kenakin, 2017). The sensitivity of an assay can increase or decrease, for instance, based on whether the cells in the assay overexpress the receptor of

interest or express it at endogenous levels. One solution is to compare the relative activity, defined as $\Delta\log(E_{max}/EC_{50})$ (Kenakin et al., 2011). E_{max} is the maximal response elicited by the drug of interest, relative to a reference ligand, and EC_{50} is the concentration of drug that is needed to bring about 50% of the maximal response. Δ refers to the difference between the activity of the drug of interest and a reference ligand. Because activity is quantified relative to the reference ligand, this measure essentially cancels out differences in assay sensitivity (Kenakin, 2017). Thus, there is no need to include differences between assays, such as the cell line, as covariates in the meta-analysis.

We found $n = 18$ relevant studies on functional activity, including $n = 6$ studies on DMT, $n = 13$ studies on LSD, and $n = 6$ studies on psilocin. We performed a random-effects meta-analysis, with the drugs as covariates. For the IP formation and calcium mobilisation assays, the reference ligand was serotonin; for the β-arrestin2 recruitment assays, the reference ligand was chosen to be mescaline, as this was the only reference ligand used in experiments on all three psychedelics. The pooled relative activity values indicate that LSD induces significantly more IP formation than DMT ($p < 0.0001$) and psilocin ($p = 0.0002$) (**Figure 5b**). Additionally, DMT elicits significantly more IP formation than psilocin ($p = 0.0203$). There were no significant between-drug differences for the other two pathways. Heterogeneity was very high for all three pathways (IP formation: $I^2 = 95.35\%$, calcium mobilisation: $I^2 = 92.66\%$, β-arrestin2 recruitment: $I^2 = 91.05\%$).

Section 3. Discussion

Here we examine the effects of psychedelics at three levels: 1) subjective experience (phenomenology), 2) functional connectivity (neuroimaging), and 3) the interaction of psychedelics with serotonin and dopamine receptors (pharmacology). At each level, we performed a quantitative meta-analysis and computed the alignment between the results and the seven resting-state Yeo networks. The latter network analysis enabled us to directly compare the effects of three psychedelics – ayahuasca/DMT, LSD, and psilocybin – within and between levels. It is worth noting that, while we refer to these three levels of description as a "hierarchy," we do not mean to imply a simple "vertical" causal structure, in which the pharmacology determines the neuroimaging, which in turn decides the phenomenology. Instead, there is a highly complex network of causal relationships between these three levels, with many feedback loops (Block, 1991; Kringelbach et al., 2020).

Section 3.1. Unifying the levels of the hierarchy

For the phenomenology literature, we conducted a meta-analysis of both the 5-dimensional and 11-dimensional versions of the Altered States of Consciousness (ASC) scale, a common questionnaire for measuring changes in subjective experience on psychedelics. At both medium and high doses, LSD ranked significantly higher than psilocybin in "visionary restructuralisation," a dimension capturing the quality and intensity of visual hallucinations. The VAN appears to be correlated with the phenomenology of all three psychedelics, but this result may be spurious due to the small number of studies that measured correlations between ASC ratings and fMRI activity. Nevertheless, there are reasons to think that the VAN may be uniquely implicated in the phenomenology of psychedelics. The VAN is responsible for orienting attention toward surprising objects or events (Vossel et al., 2014), and it is engaged during mismatch negativity (MMN), an event-related potential that is triggered when an unexpected stimulus is shown (Lee et al., 2017). Psychedelics diminish the MMN response while enhancing the neural response to familiar stimuli (Duerler

et al., 2021; Timmermann et al., 2018), perhaps because these drugs engender profound feelings of childlike awe and wonder (Hendricks, 2018). This heightened predisposition towards subjective experiences of novelty may increase activity in the VAN.

The whole-brain neuroimaging data consisted of three subsets of data: BOLD activation, entropy, and FC. We did not report a meta-analysis of the BOLD activation or entropy literature due to the heterogeneity of experimental procedures and analysis methods, respectively; however, we did conduct a qualitative review of the entropy literature (*Section S4*). To perform a meta-analysis on the FC data, we essentially re-parcellated the published data into the Yeo networks and then calculated a weighted sum of the connections between Yeo networks. LSD strongly elevated FC between the visual network and the other networks, whereas ayahuasca/DMT increased FC most between transmodal networks (specifically, the FPN and DMN) and unimodal networks (i.e. SMN and visual).

For pharmacology, we conducted two meta-analyses: one of selectivity and another of relative functional activity. There were no significant differences between psychedelics in selectivity for the 5-HT_{2A}, 5-HT_{2C}, or D_2 receptors relative to the 5-HT_{1A} receptor. Compared to DMT and psilocin, LSD elicited significantly more relative activity in IP formation assays. We did not observe any significant between-drug differences for the calcium mobilisation and β-arrestin2 recruitment assays.

Directly comparing the pharmacology, neuroimaging, and phenomenology profiles of psychedelics (**Figure 7**) reveals a weak one-to-one relationship between the three levels of the hierarchy, which is unsurprising given the highly non-linear, complex, and reciprocal (Kringelbach et al., 2020) interactions between them. However, the results of the meta-analyses at each level may reveal some insights into the nature of these interactions.

On a superficial level, there do appear to be some direct correspondences between the phenomenology, neuroimaging, and pharmacology. Phenomenologically, we only found one significant difference between psychedelics that was consistent across dose levels: LSD induces more visionary restructuralisation than psilocybin does. Neurobiologically, LSD disproportionately enhanced connectivity between the visual network & all other networks, while very strongly reducing connectivity within the visual network. LSD's effect on FC between other networks was much weaker.

The relationship between the pharmacology results and the above findings is more difficult to establish. Our results show that LSD increases IP formation, whereas DMT and psilocin decrease it. IP formation occurs whenever $G\alpha_q$ proteins are recruited to initiate cellular signaling. Furthermore, there is evidence that $G\alpha_q$ activation is necessary for 5-HT_{2A} agonists to bring about hallucinogenic effects. When administered the psychedelic (±)1-(2,5-dimethoxy-4-iodophenyl)-2-aminopropane (DOI), mice that lack the gene for $G\alpha_q$ proteins do not exhibit behaviours (head twitches) that typically indicate hallucinations (Garcia et al., 2007). More recently, activation of $G\alpha_q$ pathways by 5-HT_{2A} agonists has been shown to predict head-twitch behaviour, whereas 5-HT_{2A} agonists that are biased for the β-arrestin2 pathway do not induce head twitches (Wallach et al., 2023). There appears to be a threshold level of $G\alpha_q$ activation that must be surpassed in order for a 5-HT_{2A} agonist to induce hallucinogenic effects (Wallach et al., 2023). Intriguingly, the pro-psychotic properties of drugs can be predicted from the extent to which they increase $G\alpha_q$ activation (relative to a different G-protein pathway) when these drugs interact with a complex formed between the 5-HT_{2A} receptor and a metabotropic glutamate receptor (Fribourg et al., 2011). In other words, the more that a drug upsets the normal balance of $G\alpha_q$ signaling, the more likely it is to engender hallucinations. However, these studies only establish the presence of hallucinations elicited by $G\alpha_q$ signaling. They do not indicate whether $G\alpha_q$ signaling induces *visual* hallucinations in particular. Thus, we can only

speculate that the pharmacology, neuroimaging, and phenomenology literature all convergently indicate that LSD has a uniquely strong effect on visual awareness.

There do not appear to be any tools at the moment for relating the pharmacology of drugs to the precise nature of the subjective experiences that they produce. Methods for examining the relationship between neuroimaging and phenomenology are currently limited to correlations and linear regressions (Burt et al., 2021; R. L. Carhart-Harris et al., 2016), which do not capture causality. There is a need to develop new techniques for elucidating the causal relationships between phenomenology, neuroimaging, and pharmacology.

Section 3.2. Relating the results of the meta-analysis to the literature

Section 3.2.1. Phenomenology

We sought to verify the results of our phenomenology meta-analysis by comparing them to the two studies that measured ASC ratings of LSD and psilocybin in the same group of participants. Holze et al. (2022) gave a medium (15 mg) and a high (30 mg) dose of psilocybin, as well as a medium (0.01 mg) and a high (0.02 mg) dose of LSD, and then compared both 5D- and 11D-ASC scores. It is worth noting that the doses of psilocybin and LSD in this study are not equivalent, since 0.01 mg LSD = 20 mg psilocybin. When comparing 15 mg psilocybin to 0.01 mg LSD, mean 5D-ASC and 11D-ASC scores tended to be higher for LSD than psilocybin. However, the only differences that reached significance were in the OB and VR scales for the 5D-ASC analysis, and in the complex imagery and audio-visual synaesthesia subscales for the 11D-ASC analysis. In our meta-analysis, LSD and psilocybin were significantly different in both OB and VR ratings, and in complex imagery but not audio-visual synaesthesia ratings, at medium doses. Ley et al. (2023) compared the subjective effects of medium doses of LSD (0.01 mg) and psilocybin (20 mg). Here, the doses are equivalent, unlike in the previous study. The study found no significant differences between LSD and psilocybin in any of the dimensions, both in the 5D and 11D analyses. Therefore, the results of our meta-analysis are not entirely supported by studies that conducted direct comparisons between psychedelics.

Section 3.2.2. Neuroimaging

One major finding in the neuroimaging literature is that psychedelics desegregate and disintegrate brain networks. Segregation is defined as the lack of FC *between* brain regions, while integration denotes FC *within* a network. Carhart-Harris et al. (2016) found that LSD led to disintegration and desegregation for most RSNs. This finding has been independently confirmed in several other studies (Barrett, Doss, et al., 2020; Dai et al., 2023; Girn et al., 2022; Lebedev et al., 2015; Madsen et al., 2021; F. Müller, Dolder, et al., 2018; Roseman et al., 2014). In a review of three studies, Müller, Liechti, et al. (2018) found good convergence in reports of desegregation.

Our meta-analysis corroborates the desegregation and disintegration hypothesis. FC significantly increased between all non-identical pairs of brain networks. Within-network FC decreased for all networks except for the FPN. However, all reductions in within-network FC were insignificant. In this meta-analysis, we determined statistical significance by comparing the psychedelic literature to resting-state FC data

collected by the Human Connectome Project in sober human participants. However, the HCP data does not reflect the heterogeneity of analysis methods in the psychedelic literature. Whereas we used a whole-brain seed-to-seed FC analysis of the HCP data, many of the studies in the psychedelic literature isolated specific seeds rather than examining the entire brain. Additionally, we applied a single parcellation (DK-80) to the HCP data, whereas multiple parcellations were used in the psychedelic literature. Thus, the insignificant result may reflect inconsistencies between our methods and the literature. Nevertheless, it does raise the intriguing possibility that reductions in within-network FC can sometimes be greater in sober resting-state than on psychedelics.

While there is a correlation between desegregation/disintegration and the subjective experience of ego dissolution (Tagliazucchi et al., 2016), there is no evidence for a *causal* link. There appear to be parallels between the conscious experience of interconnectedness and the "interconnectedness" of the brain on psychedelics, but further research is needed to demonstrate that the connection between the two is more than merely semantic.

Another common finding is that psychedelics decrease activity and connectivity within the default mode network (DMN), a region that is generally implicated in self-awareness, self-reflection, and other self-referential cognitive processes (Davey et al., 2016; Davey & Harrison, 2018; Molnar-Szakacs & Uddin, 2013; Moran et al., 2013). This popular 'meme' likely has its origin in the first resting-state fMRI study of a psychedelic, where decreased blood flow and BOLD signal were observed in a pattern of regions resembling the DMN (Carhart-Harris et al., 2012). Eleven years later, evidence continues to indicate that psychedelics potently affect the regularity of population brain activity in DMN regions (Timmermann et al., 2023). Since a commonly reported experience on psychedelics is the dissolution of the self, a phenomenon known as "ego death" (Moreton et al., 2020; Nour et al., 2016; Pahnke, 1969), it would superficially make sense that psychedelics dysregulate the DMN. Many studies have found significant correlations between subjective ratings of ego dissolution and DMN disintegration (Atasoy et al., 2017; Barrett, Krimmel, et al., 2020; Luppi et al., 2021; Madsen et al., 2021; Palhano-Fontes et al., 2015; Pasquini et al., 2020; Roseman et al., 2014; Smigielski et al., 2019; Tagliazucchi et al., 2014, 2016), though other analyses did not find evidence for a relationship between the two (Lebedev et al., 2015; F. Müller, Dolder, et al., 2018).

However, claims of "de-activation" or worse, "shutting-off" of the DMN as signatures of psychedelic action are wrong and misleading. Other neuroimaging studies by Carhart-Harris et al. (2012, 2013, 2016) and Roseman et al. (2014) discovered that psychedelics affect the *connectivity* of the DMN, decreasing within-DMN FC ("disintegration") while increasing DMN coupling with other resting-state networks (RSNs) ("desegregation"). Our neuroimaging meta-analysis confirms that psychedelics decrease connectivity within the DMN while elevating its connectivity with other networks. Our phenomenology meta-analysis also revealed that all psychedelics induced positive experiences of depersonalisation and derealisation, as captured by the oceanic boundlessness dimension of the 5D-ASC scale.

Nevertheless, there are many cases in which within-DMN connectivity may decrease without giving rise to the subjective effects that characterise psychedelics. Several other drugs such as amphetamines and alcohol, as well as drug addiction in general, reduce within-DMN connectivity in humans (Schrantee et al., 2016; Weber et al., 2014; Zhang & Volkow, 2019), even though they typically do not lead to ego dissolution (Doss et al., 2020). Certain psychological states that exacerbate self-rumination, such as maladaptive self-focused attention, are *not* associated with hyperconnectivity in the DMN (Fang et al., 2022), and one study found that some tasks requiring self-related judgments were associated with a

suppression of within-DMN connectivity (van Buuren et al., 2010). That being said, a recent meta-analysis of 14 studies did endorse an association between rumination and the DMN (Zhou et al., 2020).

Section 3.2.3. Pharmacology

The results of our affinity meta-analysis aligned well with studies that performed direct comparisons of selectivity between different psychedelics (Eshleman et al., 2014; Janowsky et al., 2014; Kozell et al., 2023; Pierce & Peroutka, 1989; Rickli et al., 2016). In line with our findings, all of these studies showed that LSD is more selective than DMT for 5-HT_{2A}, relative to 5-HT_{1A}. Two studies also observed that psilocin is more selective than LSD for 5-HT_{2A} (Kozell et al., 2023; Rickli et al., 2016). Our meta-analysis demonstrated that DMT is more selective than LSD for 5-HT_{2C}, a conclusion that is supported by three of four studies (Eshleman et al., 2014; Janowsky et al., 2014; Kozell et al., 2023).

Our findings about functional activity were also congruent with studies that measured the effect of multiple psychedelics on IP formation at the 5-HT_{2A} receptor (Braden & Nichols, 2007; Eshleman et al., 2014; Janowsky et al., 2014; Kozell et al., 2023). We found that LSD's relative activity at this pathway was significantly greater than that of psilocin, which was in turn significantly larger than that of DMT. All four studies showed that LSD had higher relative activity at this pathway than DMT. Two studies also reported that psilocin's relative activity was lower than that of LSD, but larger than that of DMT (Braden & Nichols, 2007; Kozell et al., 2023).

Section 3.3. Sources of heterogeneity and recommendations for future research

Our systematic review of the literature has revealed several knowledge gaps in the field of psychedelic neuroscience. Firstly, some areas are lacking data. There are only three studies on the phenomenology of DMT, as evaluated with the 5D-ASC scale. In the neuroimaging literature, there are relatively few primary datasets but many secondary analyses. Of the 58 studies that we included in the neuroimaging meta-analysis, fewer than half (22) collected original data, and over a third are secondary analyses of the same two primary datasets (Carhart-Harris, Erritzoe, et al., 2012; Carhart-Harris et al., 2016) (**Figure S2a**). While the secondary analyses have offered new and compelling perspectives on brain activity under psychedelics, there need to be more replication studies in order to verify the findings from the primary datasets. Ten of the 12 studies on entropy analyse data from these primary datasets, so it is not surprising that all of them conclude that psychedelics increase entropy. If the studies had measured entropy on different primary datasets, then the results may have been different. We acknowledge this bias in our qualitative review of the entropy literature, and we also account for it in our quantitative meta-analysis of the functional connectivity (FC) literature, where we only included one study on each unique dataset.

Secondly, there are inconsistencies in experimental procedures and analysis methods. In the phenomenology literature, studies tended to administer different doses of LSD and psilocybin, such that exactly dose-equivalent comparisons of the two drugs were rare. We could not perform a meta-analysis of the BOLD activation studies because of the considerable variability in the tasks that they administered to participants. Our attempt to synthesise the FC data was hindered by the wide range of parcellations in the literature. Our meta-analysis of selective affinity in the pharmacology literature was confounded by the use of many different radioligands for labeling receptors of interest.

Our neuroimaging meta-analysis was limited by the fact that it assessed the published data rather than the raw data. It is prohibitive, time-consuming, and sometimes impossible to obtain raw data; institutions are limited by data confidentiality agreements, have lost access to old data, or are unwilling to share data for other reasons. We urge future researchers to make data publicly available, pool together raw data on psychedelics from different institutions, preprocess and parcellate it identically, and then re-apply our meta-analysis pipeline. The subsequent findings would not be confounded by different methodological choices made by different labs and would more accurately reflect the common effects of psychedelics on brain activity.

Finally, we encourage researchers to develop tools for modelling the nonlinear relationships between the pharmacology, neuroimaging, and phenomenology of psychedelics, the three hierarchical levels of analysis that are at the heart of this meta-analysis. While some researchers have attempted to examine the associations between each level (Ballentine et al., 2022; Lawn et al., 2022), their techniques are model-free and only measure *correlations* between the effects of psychedelics, rather than elucidating the *causal mechanisms* that underpin them.

Recent whole-brain models have made significant advances in discovering these causal mechanisms (see Kringelbach & Deco (2020) for a general review). Whole-brain models consist of nodes that approximate local or mesoscopic neuronal dynamics through mean field models of coupled excitatory-inhibitory interactions (Deco et al., 2014; Honey et al., 2007) or Hopf models of bifurcations into and out of sustained oscillatory activity (Deco et al., 2017; Freyer et al., 2012), respectively. Crucially, whole-brain models have enabled researchers to identify the specific regions that should be stimulated in order to force transitions between different states of consciousness, such as from sleep to wakefulness (Deco et al., 2019). Whole-brain models have also been applied to psychedelics; in particular, the 5-HT_{2A} receptor density in each area of the brain was used to fit a mean field model of fMRI data on LSD, capturing the nonlinear interactions between connectivity and the distribution of 5-HT_{2A} receptors (Deco et al., 2018). This model was recently extended to determine the associations between global brain connectivity on LSD and categories of subjective experience (Burt et al., 2021). The model has also been applied to the relationship between neurotransmitters (namely, serotonin) and neuronal regions on psilocybin; in particular, Kringelbach et al. (2020) coupled a mean field model of each neuronal region to the release-and-reuptake dynamics of serotonin concentration. Importantly, this coupled neuronal-neurotransmitter model exhibited a better fit to the empirical FC than a model of solely the neuronal activity. Overall, whole-brain models display great promise for linking neurotransmitter release, which is partly determined by pharmacology, to the brain regions that causally mediate, rather than merely correlate with, the effects of psychedelics. Most recently, whole-brain models have also been combined with another cutting-edge method, turbulence, to determine the susceptibility of the brain to external stimuli under psychedelics (Cruzat et al., 2022).

Section 4. Conclusion

This is the first meta-analysis of the literature on the phenomenology, neuroimaging, and pharmacology of psychedelics. We assess and compare these three hierarchical levels of analysis across three different classical psychedelics: DMT, LSD, and psilocybin. Thus, we performed comparisons not only between psychedelics, but also between the levels of the hierarchy.

We found that the different levels of the hierarchy exhibited a weak one-to-one correspondence with one another. This is not surprising, as the interactions between phenomenology, neuroimaging, and

pharmacology are highly non-linear and complex. We encourage future research to develop tools for modelling these relationships in order to improve our scientific understanding of psychedelics.

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Code Availability
Code is available upon request by emailing the corresponding author: kenneth.shinozuka@psych.ox.ac.uk

Competing Interests Statement
The authors have no conflicts of interest to declare.

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Figures

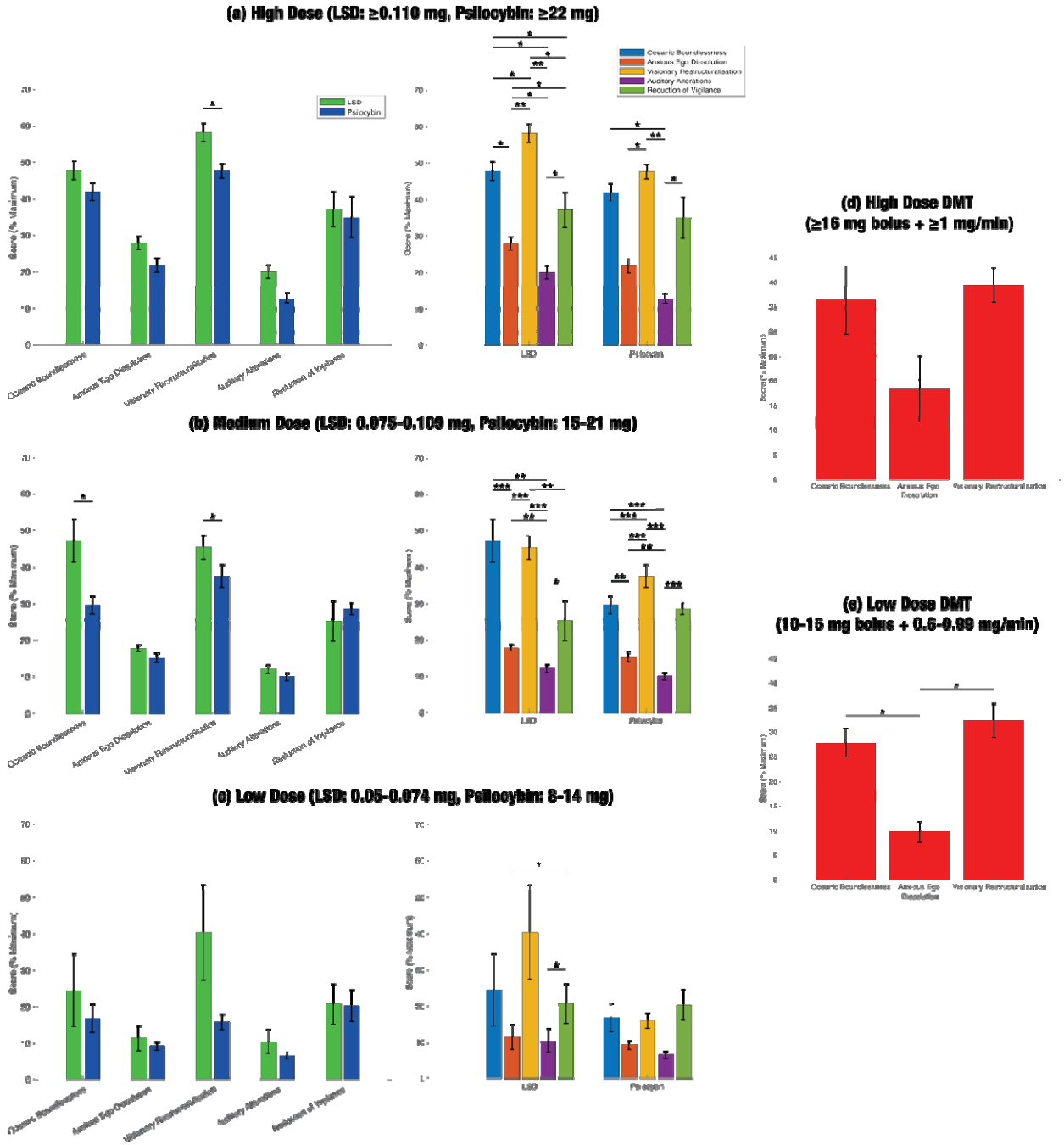


Figure 1. Meta-analysis of the 5-Dimensional Altered States of Consciousness (5D-ASC) data reveals only one significant difference between psychedelics, but many more significant differences within psychedelics. *The 5D-ASC is one of the most commonly used scales for subjective reports of psychedelic experiences. It measures altered states of consciousness along five different dimensions: oceanic boundlessness (OB; a feeling of interconnectedness), anxious ego dissolution (AED), visionary restructuralisation (VR; the quality and intensity of visual hallucinations), auditory alterations (AA), and reduction of vigilance (RV). Our literature search identified 23 studies*

that reported 5D-ASC data. We performed a three-level random-effects meta-analysis, where the third level consisted of studies that reported multiple data points corresponding to different doses given to the same group of participants; this analysis thereby accounted for the lack of statistical independence among the inputs. Within-study and between-study heterogeneity were estimated with the restricted maximum likelihood procedure. Using a Correlated and Hierarchical Effects model to account for within-study correlations in sampling error, we performed meta-regressions to analyse the effect of dose and drug (DMT, LSD, or psilocybin) on pooled 5D-ASC scores. DMT was administered intravenously in phenomenological studies, whereas LSD and psilocybin were administered orally. Thus, DMT has different pharmacokinetics from LSD and psilocybin, which impacts the subjective experience, so we only compared significant between-drug differences for LSD and psilocybin. We only compared the two drugs for similar doses, assuming that 0.1 mg LSD = 20 mg psilocybin (Ley et al., 2023). (a-c, left column) Between-drug comparisons of pooled 5D-ASC scores for LSD and psilocybin. LSD almost always ranked higher than psilocybin, but differences only reached significance in the VR dimension for high and medium doses and in the OB dimension for medium dose. (a-c, right column) Within-drug comparisons for LSD and psilocybin. VR, OB, and RV received much higher scores than AED and AA. (d-e) Within-drug comparisons for DMT. At low doses, OB and VR ranked significantly higher than AED. Only one study measured ASC scores for the AA and RV dimensions on DMT, so we did not perform a meta-analysis on these dimensions for DMT. Numerical data for the above figure are given in ***Table S1****. We also conducted a meta-analysis of the 11-dimensional ASC scale, which is also widely used in the literature; the results are displayed in* ***Figure S3*** *and* ***Table S2****. * < 0.05, ** < 0.01, *** < 0.001.*

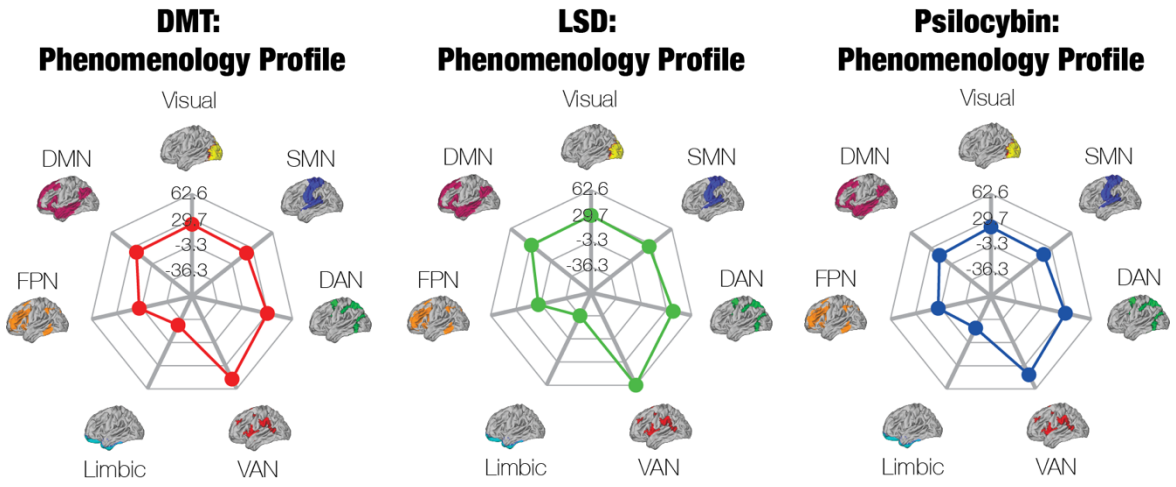


Figure 2. Phenomenology profiles of the psychedelics demonstrate broad similarity between the neural correlates of their phenomenology. *We identified 14 studies that measured correlations between ASC ratings and fMRI activity or pairwise connectivity, including three studies on ketamine. We determined the Yeo network that contained each brain region that exhibited a significant correlation, and then we averaged across the correlations associated with each Yeo network, resulting in the mean correlation between each Yeo network and each ASC scale. The phenomenology profiles were defined by a weighted combination of the mean correlations for each ASC scale, in which the weights were the pooled ASC ratings of each psychedelic for the corresponding scale. Because the pooled ASC ratings are similar across psychedelics, the phenomenology profiles are very alike one another as well. However, the lack of data on the neural correlates of the ASC ratings limits our confidence in the validity of these profiles.*

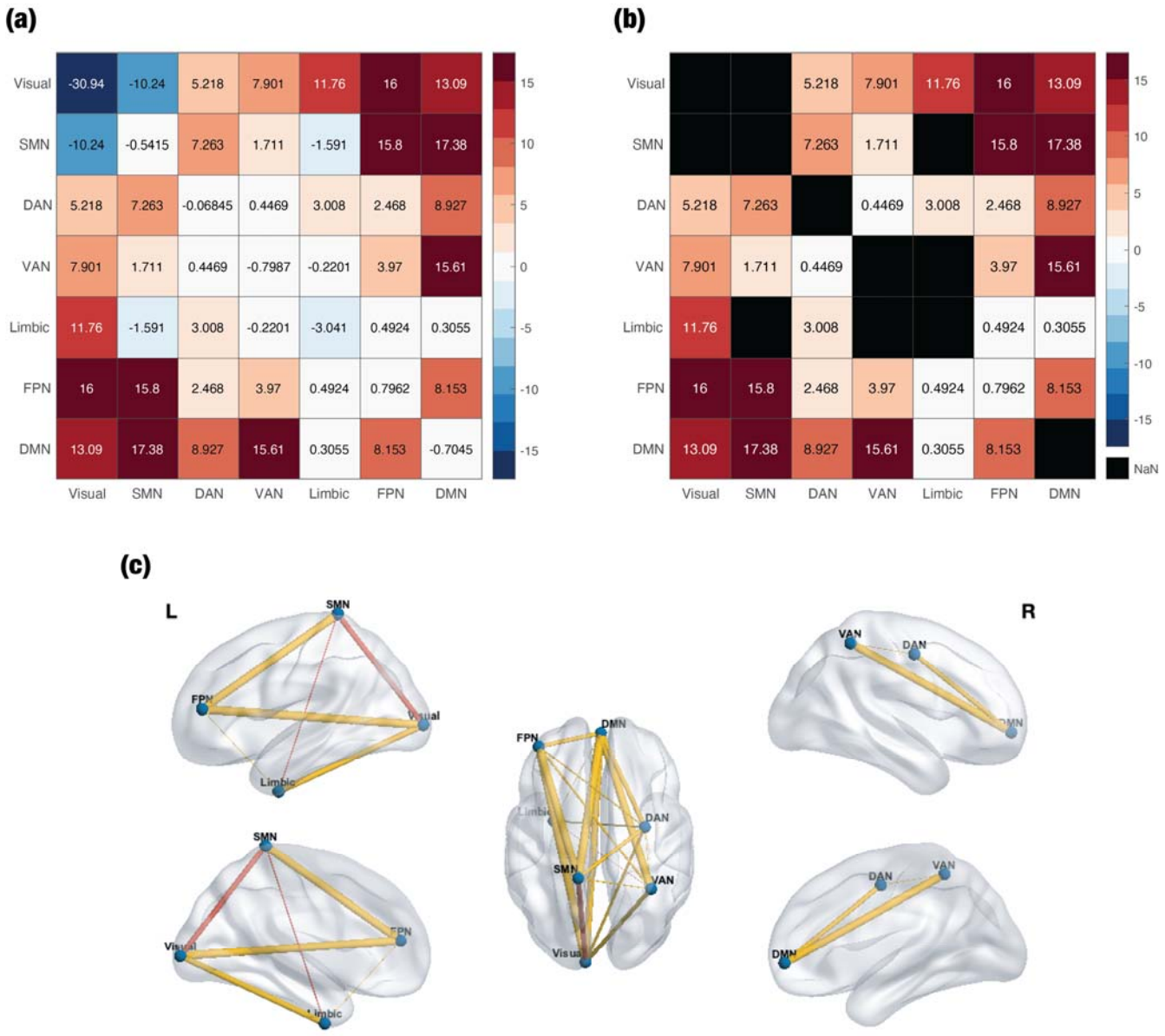


Figure 3. Meta-analysis of the functional connectivity (FC) data indicates increases in between-network connectivity and decreases in within-network connectivity. *To perform a meta-analysis on the FC data, we determined the Yeo networks that contained each pair of functionally connected regions of interest (ROIs) in the literature and then performed a weighted sum of the number of significant connections between Yeo networks. We included n = 12 studies in this meta-analysis, after excluding studies that did not measure pairwise FC and secondary analyses of identical datasets. (a) Aggregate FC matrix, in which each entry contains the overall connectivity between a pair of Yeo networks. (b) Blacked-out values are statistically insignificant (p > 0.05) with respect to a null distribution formed from resting-state Human Connectome Project data. (c) A rendering of the statistically significant FC scores on the surface of the brain. Insignificant edges are red, and significant edges are yellow. Images produced through the BrainNet Viewer (Xia et al., 2013).*

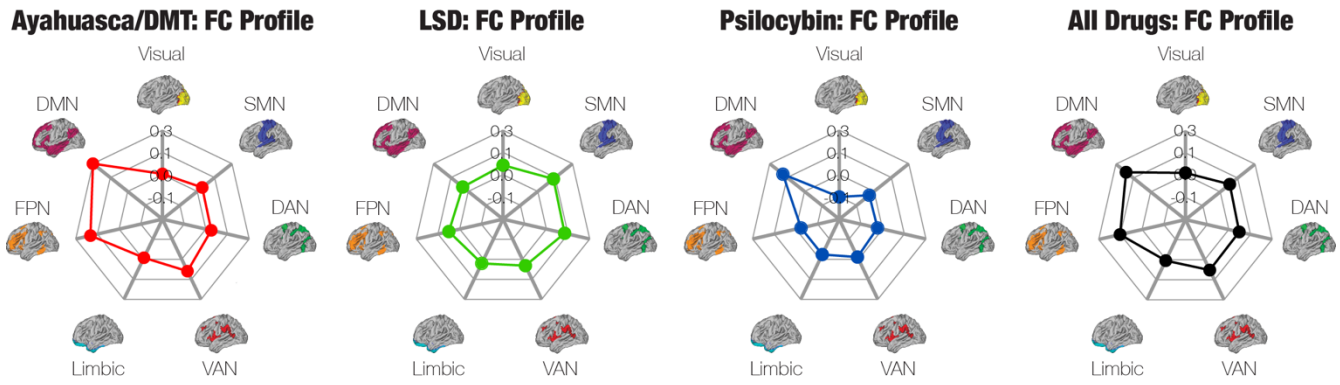
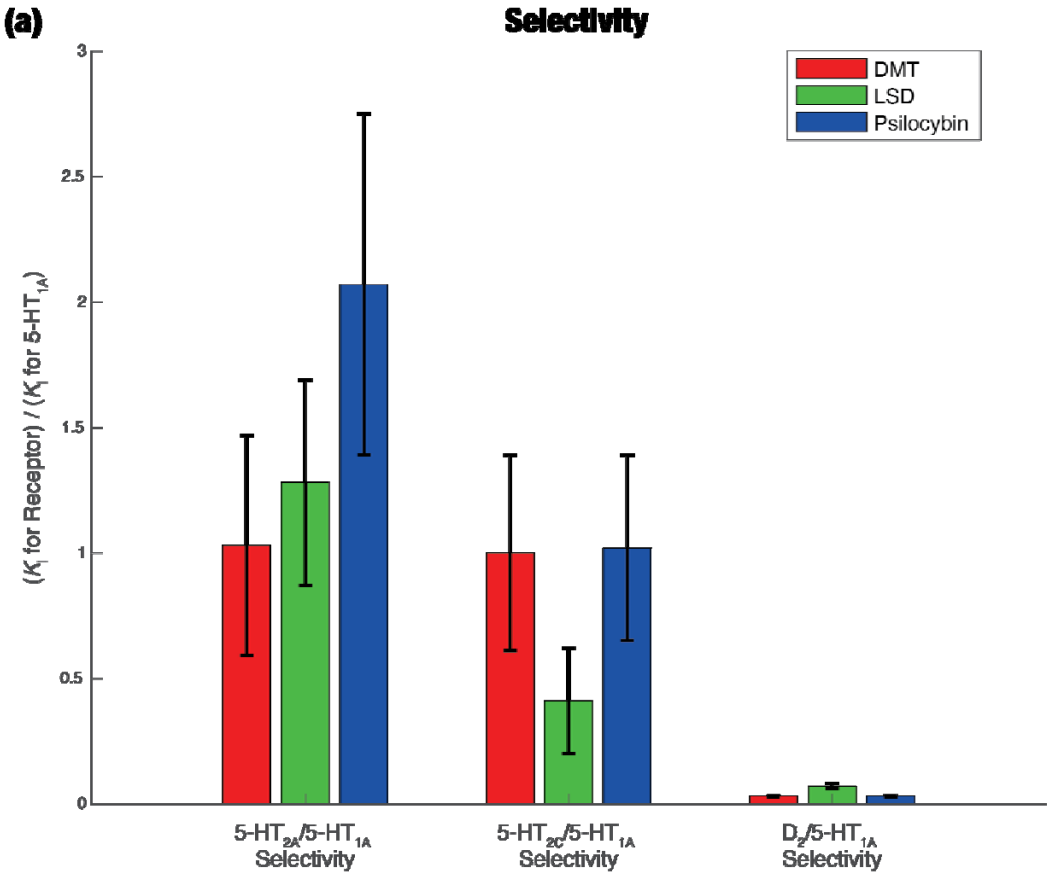


Figure 4. Functional connectivity (FC) profiles show unique FC patterns for each psychedelic. *Out of the n = 12 studies that we examined in our quantitative FC meta-analysis, n = 3 were studies on ayahuasca/DMT (ayahuasca: n = 2; DMT: n = 1), n = 3 on LSD, and n = 6 on psilocybin. Each FC profile contains the total FC of each network, which was obtained by taking the normalised sum of the rows of the corresponding aggregate FC matrices, including insignificant values. (The units of the profiles are arbitrary.) The psychedelics display distinct FC profiles; for instance, ayahuasca and DMT increase total FC for the DMN more strongly than for other networks, whereas LSD elevates FC more for the SMN and DAN than for other networks.*


(a)
Selectivity
DMT
LSD
Psilocybin
(Ki for Receptor) / (Ki for 5-HT1A)
3
2.5
2
1.5
1
0.5
0
5-HT2A/5-HT1A Selectivity
5-HT2C/5-HT1A Selectivity
D2/5-HT1A Selectivity

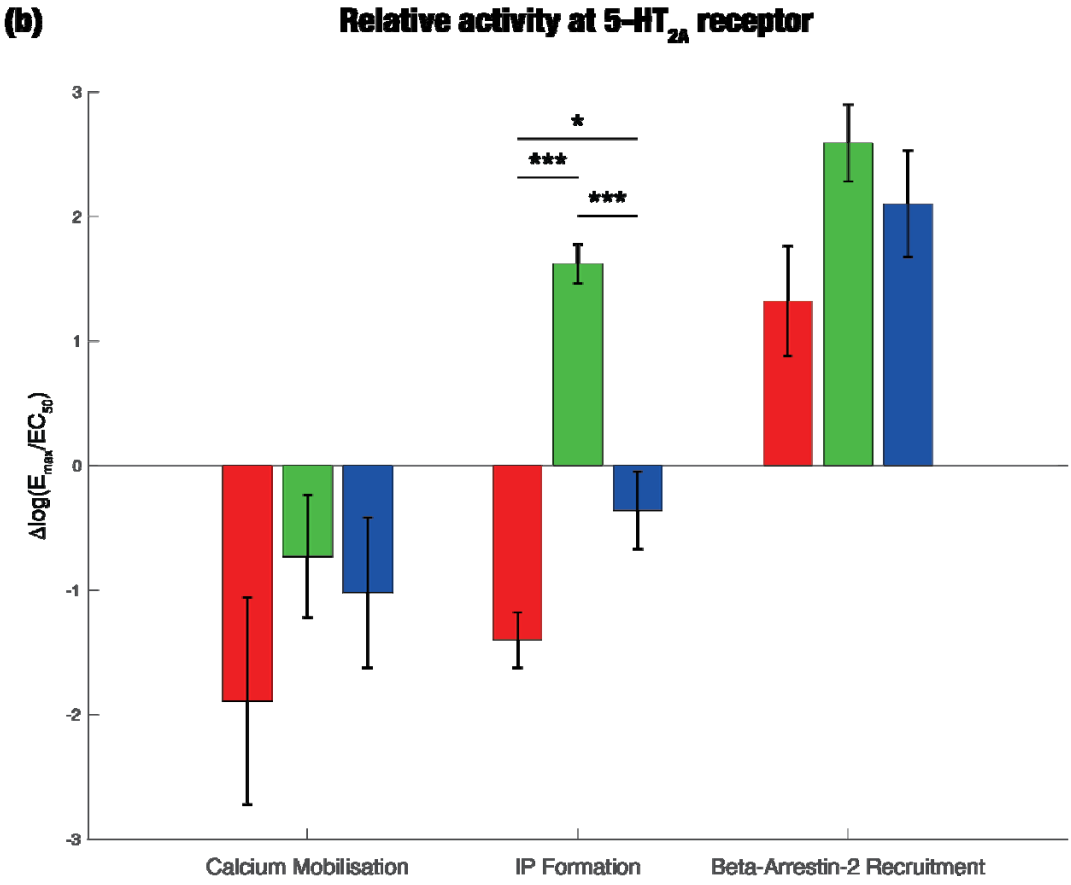

(b)
Relative activity at 5-HT2A receptor
Δlog(Emax/EC50)
3
2
1
0
-1
-2
-3
*
***
***
Calcium Mobilisation
IP Formation
Beta-Arrestin-2 Recruitment

Figure 5. Pharmacology meta-analysis reveals that there are no significant differences in selectivity between psychedelics and that LSD induces significantly higher relative activity at the inositol phosphate (IP) formation pathway. *For both the selectivity and relative activity data, we created random-effects models that modeled between-study variance, with drugs included as covariates. (a) Selectivity is the ratio between the binding affinity (measured as* K_i*) for a receptor of interest and the affinity for a reference receptor. We measured selectivity for three different receptors,* $5\text{-}HT_{2A}$*,* $5\text{-}HT_{2C}$*, and* D_2*, relative to* $5\text{-}HT_{1A}$*. Our literature search identified n = 14 studies on selectivity, including n = 6 studies on DMT, n = 9 studies on LSD, and n = 5 studies on psilocin. We did not find any significant between-drug differences in selectivity for any of the three receptors. (b) Relative activity is* $\Delta\log(E_{max}/EC_{50})$*, where* E_{max} *is the maximal effect of the drug relative to a reference ligand and* EC_{50} *is the concentration needed to elicit 50% of the maximal response. The log of the ratio is measured for both the drug and the reference ligand, and then the difference is taken (Kenakin, 2017). We found n = 18 studies on functional activity, including n = 6 studies on DMT, n = 13 studies on LSD, and n = 6 studies on psilocin. We measured relative activity at three different signaling pathways: calcium mobilisation, IP formation, and β-arrestin2 recruitment. IP formation was the only pathway that exhibited any significant between-drug differences; LSD elicited significantly higher activity than both DMT and psilocin.*

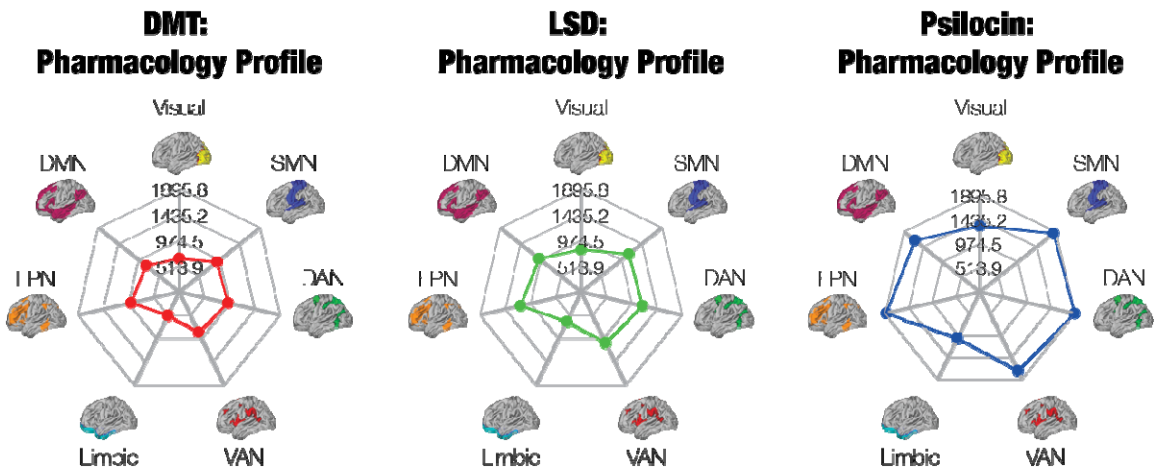


Figure 6. Pharmacology profiles reveal that psilocin binds with (insignificantly) higher specificity to the 5-HT$_{2A}$ receptor than DMT and LSD do. *Based on an available PET atlas of the 5-HT$_{2A}$ and D$_2$ receptors (Hansen et al., 2022), we created the pharmacology profile of each psychedelic. The profiles show the expression of those two receptors in the Yeo networks, weighted by the specificity of the corresponding psychedelics. The PET atlas reveals that the 5-HT$_{2A}$ receptor is expressed much more in the human brain than the D$_2$ receptor. Therefore, the profiles are dominated by 5-HT$_{2A}$ receptor expression. Since psilocin has the most specificity for 5-HT$_{2A}$ (relative to 5-HT$_{1A}$), followed by LSD, psilocin's pharmacology profile is the most extensive.*

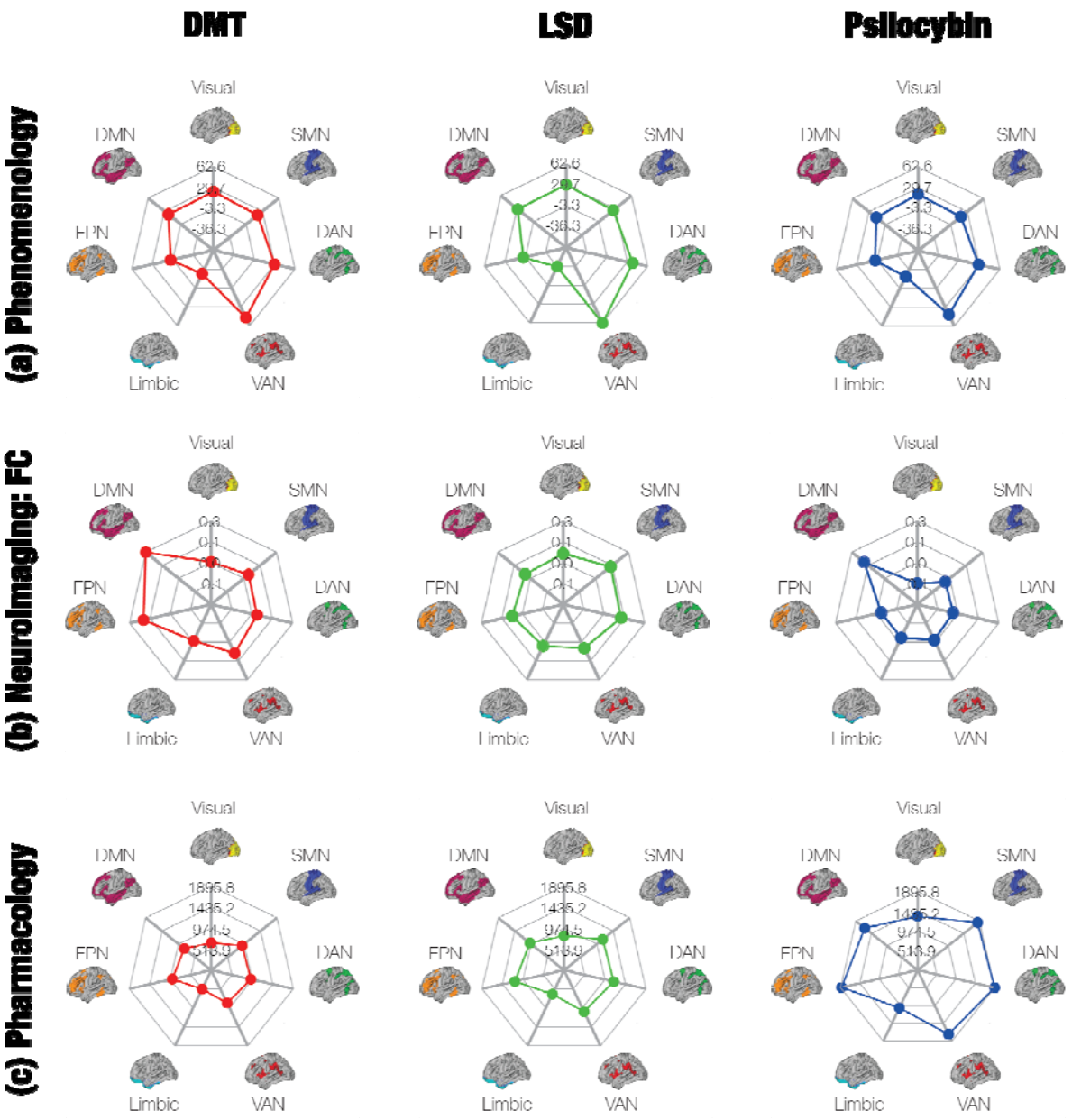


Figure 7. The hierarchy of psychedelic effects highlights the nonlinear relationship between pharmacology, neuroimaging, and phenomenology. *The effects of psychedelics form a tripartite hierarchy, consisting of subjective experience (a, phenomenology), functional connectivity (b, neuroimaging), and their selective affinity for receptors (c, pharmacology). Here, we show the neural correlates of each level of the hierarchy in the seven Yeo networks. In brief, each profile was derived from (a) neural correlates of the subjective dimensions of the ASC scale, (b) summing the aggregate FC between each network and other networks, and (c) multiplying the affinities with each receptor's density in each Yeo network. Clearly, there is a very weak correspondence between the different levels of the hierarchy, revealing the highly non-linear relationship between phenomenology, neuroimaging, and pharmacology. Note: we analysed data on DMT in our phenomenology and pharmacology meta-analyses and data on both DMT and ayahuasca in our FC meta-analysis. We examined data on psilocin in our pharmacology meta-analysis and on psilocybin in both of the other meta-analyses.*