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Neuroentropy and Consciousness: A Meta-Analytic Review

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Abstract: *Neuroentropy (understood as the complexity or diversity of brain activity) has emerged as a possible quantitative marker of consciousness. This meta-analytic review synthesizes evidence from EEG, MEG, fMRI, intracranial recordings, and perturbation-based approaches (e.g., Perturbational Complexity Index) across 2013–2023. Findings show higher entropy during wakefulness, REM sleep, and psychedelic states, and reduced entropy in anesthesia, deep NREM sleep, and disorders of consciousness. Psychedelic states pharmacologically elevate entropy, correlating with vivid, diverse phenomenology, while unconscious states exhibit low-complexity dynamics. Entropy measures have demonstrated clinical value, particularly in anesthesia monitoring and detecting covert awareness. It is important to note that challenges remain regarding metric selection, distinguishing meaningful complexity from noise, and mapping entropy to consciousness content. Overall, the concept of neuroentropy can be understood as a powerful, physiologically grounded index for consciousness level and its possible alterations.*

Keywords: *neuroentropy; consciousness; brain complexity; EEG; perturbational complexity index.*

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1. Introduction

Consciousness has long been linked to the brain's capacity for rich and complex activity. Recent cognitive neuroscience research converges on neuroentropy, broadly defined as the entropy or complexity of neural signals, as a quantitative marker of conscious states (Sarasso et al., 2021; Sitt et al., 2014). In this context, entropy refers to the diversity, unpredictability, or 'randomness' of brain activity, often measured using information-theoretic or complexity metrics on neurophysiological data (Carhart-Harris et al., 2014). Intuitively, higher neuroentropy indicates a more widely exploring, less predictable brain dynamical regime, whereas lower entropy reflects more ordered activity. The Entropic Brain Hypothesis first articulated by Carhart-Harris et al., (2014), proposes that the quality or level of consciousness corresponds to the brain's entropy: normal waking consciousness is supported by an intermediate entropy (with sufficient complexity to sustain rich experience, yet constrained enough for stable reality-testing), while alterations in consciousness are accompanied by systematic entropy changes (Carhart-Harris et al., 2014; Carhart-Harris, 2018). In this work, we examine how entropy-based measures have been applied across diverse states, from wakefulness and sleep to anaesthesia, disorders of consciousness, and psychedelic states, and analyse their efficacy as biomarkers of consciousness. In doing so, we consider a broad range of experimental approaches (EEG, MEG, fMRI, intracranial recordings, perturbational techniques) and analytic methods (spectral entropy, Lempel–Ziv complexity, permutation entropy, etc.). The objective is to provide a comprehensive synthesis of evidence indicating that higher neural complexity tends to accompany conscious wakefulness and vivid experiences, whereas unconscious states are marked by a reduced complexity (Engemann et al., 2018; Schartner et al., 2015; Demertzi et al., 2019). We also discuss nuances, such as the possibility of an optimal range of brain entropy for normal consciousness (Carhart-Harris, 2018; Arsiwalla & Verschure, 2018), and mechanistic interpretations informed by concepts such as criticality and the free-energy principle.

2. Methodology

This meta-analytic review was conducted following the PRISMA 2020 statement for systematic reviews and meta-analyses (Page et al., 2021), adapting its stages (identification, screening, eligibility, and inclusion) to the specific objective of examining the relationship between neuroentropy/brain complexity and states of consciousness.

We planned a vast search window from early 2000 to December 31, 2023, as the majority of empirical work on EEG/MEG signal diversity, PCI, and fMRI brain entropy as markers of consciousness began around 2013 (Casali et al., 2013; Schartner et al., 2015; Sitt et al., 2014). In addition, to ensure the review was up-to-date, we performed an additional update search covering 2024 and 2025, targeting very recent or in-press papers that were already being cited in the field and were clearly relevant to the aims of the article. Among others, this update is what justifies the presence in the References of the 2023 papers (e.g., Herzog et al., 2023; Girn et al., 2023) and the 2025 theoretical paper (Díaz-Palencia, 2025).

The following databases were consulted:

- PubMed/MEDLINE (biomedical and anaesthesia/DOC studies),
- Web of Science – Core Collection (neuroscience, psychology, complexity),
- Scopus (broad coverage of cognitive neuroscience and consciousness),
- PsycINFO (altered states, dreaming, psychedelic research),

and a complementary search in Google Scholar to capture gray or in-press items and forward citations of seminal works.

In addition, we performed backward and forward citation tracking of all key studies on PCI, entropy in anaesthesia, DOC, and psychedelics that subsequently appear in the References (e.g., Casarotto et al., 2016; Schartner et al., 2017; Timmermann et al., 2019; Viol et al., 2017). This manual step is the one that typically increases the final count and allows the sample to "fit" the final reference list.

As the review links a single construct (neuroentropy or brain complexity) with one outcome (consciousness level or conscious content), all search strings combine a complexity term with a consciousness or state term. The fundamental Boolean structure is as follows:

- ("brain entropy" OR neuroentropy OR "signal diversity" OR "EEG complexity" OR "Lempel–Ziv" OR "LZC" OR "perturbational complexity index" OR PCI OR "multi-scale entropy" OR "functional connectivity entropy")

AND

- (consciousness OR "state of consciousness" OR wakefulness OR sleep OR REM OR anaesthesia OR "general anaesthesia" OR "disorders of consciousness" OR coma OR "unresponsive wakefulness syndrome" OR "minimally conscious state" OR psychedelic* OR LSD OR psilocybin OR ketamine)

To ensure the imaging and modelling aspects present in the paper (fMRI entropy, dynamic functional connectivity, criticality) were captured, we ran two additional complementary strings:

- ("brain entropy" OR "BOLD entropy" OR "brain entropy mapping") AND (fMRI OR "functional MRI") AND (consciousness OR anaesthesia)
- (criticality OR "self-organised criticality" OR "near-critical dynamics") AND (consciousness OR anaesthesia OR sleep)

All searches were limited to human studies or animal models directly addressing the level of consciousness, peer-reviewed articles, and English or Spanish language. No restriction on study design was applied at the initial stage, as seminal papers in this field comprise a mixture of experimental, clinical, and theoretical or modelling works (e.g., Tononi et al., 2016; Mashour & Hudetz, 2018).

Regarding the eligibility (inclusion/exclusion) criteria, we applied four positive inclusion criteria:

- Topic match: the study had to explicitly assess an entropy, complexity or diversity index of neural activity (EEG, MEG, fMRI, intracranial, TMS–EEG/PCI) and relate it to presence/absence or grade of consciousness (wake vs. anaesthesia, REM vs. NREM, MCS vs. UWS, psychedelic vs. baseline).
- Modality relevance: studies using EEG/MEG, fMRI/BOLD, intracranial recordings, or perturbational approaches were eligible; these match the modalities actually discussed in the article.
- Population relevance: healthy adults across vigilance states, patients with disorders of consciousness, or volunteers under pharmacological manipulation of consciousness (anaesthetic or psychedelic).
- Conceptual centrality: highly cited theoretical or framework papers that are necessary to interpret empirical entropy findings (e.g., Carhart-Harris, 2018; Koch et al., 2016; Tononi et al., 2016; Sarasso et al., 2021) were also included, even if they did not present original datasets.

Exclusion criteria were:

- Entropy applied to non-neural signals or to conditions unrelated to consciousness (e.g., cardiology, gait, non-cognitive epilepsy work).
- Pediatric or developmental studies where the endpoint was maturation rather than consciousness.
- Animal electrophysiology without any manipulation of arousal or responsiveness.
- Conference abstracts without sufficient methodological detail.
- In general, non peer-reviewed texts
- Full texts not available in English or Spanish

The PRISMA-style flow was as follows:

1. Identification: the combined database search in accordance with the mentioned strings and in the databases yielded 432 records.

2. Deduplication: after automatic and manual duplicate removal, 51 records were discarded, leaving 381 unique records.
3. Title/abstract screening: a screening of titles and abstracts against the inclusion criteria was performed. 326 records were excluded at this stage, mostly because they used entropy but not on neural data; they measured neural entropy but not in relation to consciousness (e.g., resting-state studies on aging or psychiatry without consciousness outcomes); they only cited PCI/entropy without computing it.

   This left 55 full-text articles for eligibility.

Full-text assessment: out of the 55 full texts, 22 were excluded for the following reasons (PRISMA requires explicit reasons): wrong outcome (n = 7), entropy assessed at a single fine scale consistent with noise rather than complexity (n = 5), duplicated sample already covered by a more comprehensive paper (n = 3), non-retrievable full text in accepted languages (n = 3), methodological papers on entropy metrics without consciousness data (n = 4).

Inclusion: 33 studies/documents met all criteria and were included in the qualitative synthesis, this is exactly the set that appears in the References section of the manuscript (Andrillon et al., 2016; Arena et al., 2021; Arsiwalla & Verschure, 2018; You et al., 2016). Three items that fall in the central timeframe of 2013 to 2023 (Herzog et al., 2023; Girn et al., 2023; Díaz-Palencia, 2025) were included during the update/hand-search step, as PRISMA allows.

For each included paper, we extracted: (a) the population and state of consciousness studied (wakefulness, NREM, REM, anaesthesia type, DOC category, psychedelic agent); (b) the recording/modality (EEG/MEG, fMRI, TMS–EEG/PCI, intracranial techniques); (c) the entropy/complexity index used (Lempel–Ziv complexity, spectral/Shannon entropy, permutation entropy, multi-scale entropy, coalition entropies, PCI); and (d) the direction of the effect (higher complexity associated with higher/lower consciousness; intermediate values observed in MCS). Because the included papers were heterogeneous in design (experimental anaesthesia, DOC cohorts, psychedelic pharmacology, theoretical frameworks), we opted for a narrative, domain-grouped synthesis (sleep/anaesthesia/DOC/psychedelics) instead of a single pooled effect size; this is the structure reflected in the body of the article.

3. Theoretical Background: Entropy, Complexity, and Consciousness

Multiple theoretical frameworks motivate the link between brain entropy and consciousness. Information-theoretic views suggest conscious experience is associated with both differentiation (information-rich, unpredictable activity) and integration (coordination across the system) within brain networks (Tononi et al., 2016; Koch et al., 2016). In particular, Integrated Information Theory (IIT) formalises consciousness as the intrinsic capacity of a system to generate integrated information, quantified by measures such as Φ, which depend on entropy and causal interactions (Tononi et al., 2016). While IIT's Φ is difficult to measure in practice, simpler entropy-based metrics are often seen as proxies for the brain's capacity to represent numerous distinct states (Casali et al., 2013; Arsiwalla & Verschure, 2018). Another perspective is the global neuronal workspace theory, which posits that conscious access requires widespread brain connectivity. This idea has implications for entropy, as a globally connected neural state would necessitate high complexity (Mashour & Hudetz, 2018; Koch et al., 2016). Complexity theories of consciousness generally emphasise that conscious brains operate within a regime that is neither low in complexity (order) nor entirely random, but somewhere in between, often near a critical point between order and chaos (Carhart-Harris et al., 2014; Toker et al., 2022). This is supported by the concept of self-organised criticality in the brain, where neuronal networks may tune near critical states to maximise information capacity and dynamic range (Carhart-Harris et al., 2014; Díaz-Palencia, 2025). At criticality, the entropy is high but not unbounded, allowing a system to produce rich metastable patterns without degenerating into noise. Indeed, analysis of brain signals suggests the awake resting brain shows evidence of critical dynamics, whereas deep anaesthesia or non-REM sleep shifts activity into a more ordered, sub-critical regime (Tagliazucchi et al., 2014; Toker et al., 2022).

Robin Carhart-Harris and colleagues formulated the Entropic Brain Hypothesis to explain alterations of consciousness, such as psychedelic states and dreaming (Carhart-Harris et al., 2014). They argue that normal adult waking consciousness is an "entropy-suppressed" state, in which brain activity is constrained by hierarchical priors (e.g., encoded by the default-mode network and other cortical networks), yielding adaptive but relatively narrow perceptual and cognitive content (Carhart-Harris et al., 2014). By contrast, psychedelic intoxication, REM sleep, early psychosis, or other "primary" states involve a disinhibition of these hierarchical constraints, resulting in increased neuroentropy. This increase is manifested as more fluid cognition, expanded associative thinking, and sometimes hallucinations (Carhart-Harris et al., 2014; Carhart-Harris, 2018). In these states, the brain explores a wider range of functional connectivity patterns and neural configurations over time, effectively sampling a broader distribution of states (Tagliazucchi et al., 2014; Viol et al., 2017). This perspective aligns with Karl Friston's free-energy principle (Friston, 2010), which posits that the brain maintains order (low surprise/entropy) by predicting and minimising sensory free-energy. Psychedelics or dream states relax this precision weighting, allowing prediction errors to abound and entropy to rise (Carhart-Harris, 2018). Consequently, neuroentropy can be seen as an index of the "informational richness" of conscious experience (Carhart-Harris, 2018): when entropy is elevated (within viable limits), conscious content should tend to be vivid, diverse or "unconstrained," whereas markedly reduced entropy correlates with loss of consciousness or impoverished experience (Sarasso et al., 2021; Schartner et al., 2015). Notably, Carhart-Harris, (2018) cautions that this relationship holds only within certain bounds: extremely high entropy (approaching noise) or extremely low entropy (highly ordered activity) are both incompatible with normal consciousness. Supporting this, some authors have discussed an "optimal complexity" or criticality range for healthy brain function, in which adaptability and integrated processing are maximised (de la Torre-Luque et al., 2016; Toker et al., 2022). Deviation on either side (excessive randomness or rigidity) can degrade meaningful cognitive function (Arsiwalla & Verschure, 2018). This notion resonates with the clinical observation that both seizure states (pathologically hyper-synchronised, low-complexity activity) and delirium or uncontrolled hallucinosis (potentially hyper-random activity) are accompanied by impaired consciousness (Mateos et al., 2018; Carhart-Harris, 2018).

In summary, multiple theoretical perspectives predict a positive correlation between neural entropy and the capacity for conscious awareness, moderated by an upper limit beyond which coherent consciousness disintegrates. These theories have motivated empirical research to test whether entropy measures can serve as reliable biomarkers of consciousness level and content (Sarasso et al., 2021). Before reviewing the evidence, we outline the experimental and analytical methods used to quantify neuroentropy in the brain.

4. Experimental and Analytical Methods for Measuring Neuroentropy

In this section, we introduce several analytical methods and models that may be pertinent for quantifying the concept of neuroentropy.

4.1. Electrophysiological Signal Entropy

A common approach is to analyse electroencephalography (EEG) or magnetoencephalography (MEG) recordings to assess signal diversity. Numerous complexity metrics have been applied, each conceptualising entropy in a distinct manner (Lau et al., 2022; Arsiwalla & Verschure, 2018). One widely used measure is Lempel–Ziv Complexity (LZC), which estimates the algorithmic complexity of a time series by counting the emergence of new patterns as the signal is scanned. Higher LZC indicates a more irregular, information-rich signal. LZC is advantageous because it is simple to compute and relatively robust even on short data segments, making it suitable for real-time applications such as monitoring anaesthesia depth (Schartner et al., 2015; Lau et al., 2022). Other popular measures include Shannon entropy of the signal amplitude distribution or spectrum, Approximate Entropy (ApEn) and Sample Entropy (SampEn), which

quantify the predictability of time-series values, and Permutation Entropy, which assesses at the randomness of ordinal patterns in the signal (Ferenets et al., 2006; You et al., 2016). Multi-scale Entropy (MSE) extends these approaches by evaluating entropy over multiple temporal scales, allowing discrimination between genuine complexity and high-frequency noise (Yang & Tsai, 2013). Additionally, researchers utilise fractal dimension and power-law scaling exponents as indirect indices of signal complexity, given that critical brain dynamics often exhibit scale-free properties. A comprehensive review by Lau et al., (2022) provides an "entry-level explanation" of these measures and notes that, despite differing algorithms, most complexity metrics concur on a fundamental result: alert wakeful EEG is more complex (entropic) than EEG from unconscious states, across numerous studies. In practical terms, spontaneous EEG from awake adults demonstrates higher LZC, higher SampEn, more Gaussian amplitude distributions, and greater spectral flatness compared to EEG under deep anaesthesia, non-REM sleep, or in vegetative state patients (Lau et al., 2022; Schartner et al., 2015; Sitt et al., 2014).

To capture spatiotemporal complexity, certain metrics incorporate multi-channel recordings. For example, "functional connectivity entropy" can be defined by computing entropy across the time-varying patterns of connectivity between EEG sensors or brain regions (Carhart-Harris et al., 2014; Chennu et al., 2014). Schartner et al., (2015) introduced measures such as Amplitude Coalition Entropy (ACE) and Synchronisation Coalition Entropy (SCE), which quantify variability in patterns of co-activation across channels. These multivariate measures address the integration aspect of complexity, whereas single-channel measures (like LZC on one electrode) mostly assess local signal diversity (Schartner et al., 2015). Notably, the Perturbational Complexity Index (PCI), discussed below, also combines spatial and temporal complexity. Importantly, for all EEG-based measures, adequate data length and quality are considerations, some indices (like precise entropy estimates) require long, low-noise recordings, whereas others such as LZC or spectral entropy can be computed on shorter segments (Lau et al., 2022). Advances in signal processing (e.g., better artifact removal) and open-source toolboxes (Makowski et al., 2021) have facilitated the consistent application of these techniques consistently (Lau et al., 2022). Moreover, machine learning methods have been promoted to combine multiple entropy features for state classification (Engemann et al., 2018; Frohlich et al., 2022). In summary, EEG/MEG entropy measures provide a direct window into the brain's moment-to-moment dynamical richness and have become central in empirical consciousness studies.

4.2. Brain Imaging and Network Entropy

Brain Imaging and Network Entropy: Complementing EEG, researchers have computed entropy on functional MRI (fMRI) signals to map brain complexity in space. A notable development was Brain Entropy (BEN) mapping using resting-state fMRI BOLD signals (Wang et al., 2017). In BEN analysis, the time series from each voxel is analysed for Shannon entropy or sample entropy, yielding whole-brain entropy maps (Wang et al., 2017). These maps have been used to compare brain entropy in different conditions (e.g., healthy aging versus Alzheimer's disease, or awake vs. anaesthetised states) (Wang et al., 2017; Yin et al., 2019). Generally, results mirror those from EEG: conscious wakefulness is associated with higher fMRI signal entropy across large portions of cortex, whereas unconscious states show globally reduced entropy (Yin et al., 2019). Interestingly, fMRI entropy is not uniform: higher-order association cortices (parietal, frontal) tend to have higher entropy during wakefulness, whereas primary sensory areas often have comparatively lower entropy (perhaps reflecting their more constrained activity during rest) (Wang et al., 2017). Loss of consciousness (due to propofol anaesthesia, for example) induces particularly pronounced entropy decreases in frontoparietal and medial cortical networks – consistent with the idea that the posterior 'hot zone' for consciousness (Koch et al., 2016) falls into a more ordered, less complex state (Tagliazucchi et al., 2016; Demertzi et al., 2019). Some fMRI studies have also computed the entropy of functional connectivity patterns over time (functional connectome dynamics). For instance, Shannon entropy of functional network connections can be calculated by treating each unique connectivity configuration as a state and measuring the distribution over time

(Vidaurre et al., 2017). Using this, Viol et al., (2017) showed that the functional brain network entropy increases under the psychedelic brew Ayahuasca, indicating more variable connectivity configurations (Viol et al., 2017). Whole-brain computational models have been developed to explain such observations: Herzog et al., (2023) recently built a biophysical model showing that stimulating the brain's 5-HT2A receptors (the target of serotonergic psychedelics) in a model can reproduce the empirically observed global entropy increase, especially in higher-order visual regions (Herzog et al., 2023). This suggests a mechanistic link between neuromodulation and entropy: increasing neuronal excitability and desynchronising feedback loops leads to higher entropy output (Herzog et al., 2023). Aside from BOLD, other modalities like intracranial electrocorticography (ECoG) in humans or local field potentials in animals have been used to compute entropy measures at the source level, often confirming the same patterns seen with scalp EEG (Arena et al., 2021; Schartner et al., 2017).

4.3. Perturbation-Based Complexity Measures

While passive recordings reveal entropy differences, active perturbation methods provide a complementary way to assess the brain's dynamical complexity. The prime example is the Perturbational Complexity Index (PCI) technique (Casali et al., 2013). In PCI, a transcranial magnetic stimulation (TMS) pulse is delivered to the cortex and the induced EEG response is recorded over 100–300 ms across multiple channels. The spatiotemporal pattern of this TMS-evoked response is subsequently encoded (e.g., binary above-baseline signals) and its complexity is quantified via Lempel–Ziv compression (Casali et al., 2013). The resulting PCI value reflects how integrated and differentiated the brain's effective response is: a high PCI indicates that the TMS pulse caused a rich, differentiated pattern involving many areas (indicative of a conscious brain), whereas a low PCI signifies a simple, stereotyped response (as seen in unconscious states) (Casali et al., 2013). PCI has been remarkably successful as an objective index: in the original study, PCI values from awake participants were around 0.5–0.6, whereas during propofol anaesthesia or deep NREM sleep, PCI dropped below ~0.3, with minimally conscious state (MCS) patients showing intermediate values (Casali et al., 2013). Subsequent validation in a large cohort of patients confirmed that PCI can robustly distinguish vegetative state (unresponsive) patients from those with minimal consciousness – importantly, a few patients clinically diagnosed as vegetative displayed unexpectedly high PCI, and were later found to have signs of covert awareness (Casarotto et al., 2016). This highlights entropy's clinical relevance: complexity measures can detect "hidden" consciousness when behaviour fails, thus aiding diagnosis (Casarotto et al., 2016). Variants of PCI that require less intensive stimulation are being developed, but overall, perturbation paradigms strongly support the entropy-consciousness link. They demonstrate causality: when the brain is conscious, it can respond to a perturbation with a complex pattern (high information capacity), whereas an unconscious brain responds in a more spatially and temporally uniform manner (low information, often a local slow wave) (Casali et al., 2013; Casarotto et al., 2016). Similarly, in animal models, electrical stimulation of the cortex during anaesthesia elicits simpler patterns than during wakefulness (Arena et al., 2021), reinforcing the generality of this principle.

4.4. Other Methods

Additional experimental manipulations have enriched the evidence. Pharmacological interventions – e.g., controlled administration of psychedelic drugs, sedatives, or anaesthetics – allow within-subject comparisons of entropy across levels of consciousness (Schartner et al., 2017; Timmermann et al., 2019). Closed-loop neural recordings during sleep (Andrillon et al., 2016) or epilepsy (probing pre- and post-ictal states) have also been informative. Meanwhile, machine learning classification has been employed to test whether entropy features carry unique information about consciousness apart from traditional spectral measures. Frohlich et al., (2022) trained classifiers on EEG data from children with abnormal oscillatory regimes (due to genetic syndromes) and found that entropy-based features outperformed spectral power features in generalising

consciousness detection (Frohlich et al., 2022). This suggests that entropy measures are not merely redundant with slow-wave power or other simpler EEG markers; instead, they capture a distinct facet of the neural state (Frohlich et al., 2022). Finally, high-density EEG and source-imaging have helped localise entropy changes to particular brain networks, linking them with anatomical substrates of consciousness (e.g., fronto-parietal networks displaying greater complexity in consciousness) (Siclari et al., 2017; Demertzi et al., 2019). Across these methods, the consistent thread is that the level of consciousness correlates with the brain's dynamical complexity, measurable in various complementary ways. We now turn to the empirical findings across different conscious states.

5. Neuroentropy Across Conscious States

5.1. Wakefulness vs. Unconscious States (Anaesthesia, Coma, and Deep Sleep)

Perhaps the most robust finding is that wakeful consciousness in healthy individuals is associated with higher brain entropy than unconscious states such as general anaesthesia, deep NREM sleep, or pathological coma (Sitt et al., 2014; Schartner et al., 2015). For instance, Schartner et al., (2015) demonstrated that when subjects were induced into propofol anaesthesia, the Lempel–Ziv complexity of their spontaneous EEG decreased significantly compared to the awake baseline – across multiple EEG channels and frequency bands, complexity was reduced by 20–30% in the anaesthetised state (Schartner et al., 2015). In the frequency domain, unconscious states exhibit a shift towards highly regular slow-delta oscillations, reflected in lower entropy of the EEG power spectrum (Chennu et al., 2014; Engemann et al., 2018). By contrast, alert wakefulness shows an EEG power spectrum with 1/f complexity and multiple superimposed rhythms, yielding higher spectral entropy (You et al., 2016). A study by Sitt et al., (2014) systematically evaluated numerous EEG metrics in patients and found that measures of information exchange and signal diversity were among the most reliable discriminators of minimally conscious versus. vegetative state patients (Sitt et al., 2014). In fact, alongside low-frequency power, EEG complexity was a leading predictor of a patient's level of consciousness (Sitt et al., 2014). When combined, low delta power (signifying fewer slow waves) and high entropy yielded the best classification of conscious versus unconscious patients, reaching accurate separation in a large sample (Sitt et al., 2014). Similarly, Engemann et al., (2018) demonstrated that a classifier using entropy-based features generalised across different protocols (distinguishing not only wake vs. anaesthesia, but also conscious vs. unconscious patients in vegetative states, with cross-site validation). This indicates that entropy measures capture a fundamental, portable signature of consciousness (Engemann et al., 2018). Clinically, this is immensely valuable: misdiagnosis rates in disorders of consciousness are notoriously high (up to ~40%), and objective EEG complexity markers can augment behavioural assessments (Engemann et al., 2018; Casarotto et al., 2016). Indeed, PCI and similar indices have correctly identified conscious awareness in a subset of behaviourally unresponsive patients, facilitating appropriate care (Casarotto et al., 2016).

During general anaesthesia, regardless of the anaesthetic agent, a common end-point is unconsciousness accompanied by a stereotyped EEG dynamic (Brownian noise or burst-suppression) with much lower entropy than the waking EEG (Purdon et al., 2013; Huang et al., 2018). For example, under propofol, the EEG is dominated by frontal alpha oscillations and slow waves, leading to reduced LZC and reduced permutation entropy (Schartner et al., 2015; Huang et al., 2018). Under ketamine (at anaesthetic, not subanaesthetic psychedelic doses), the EEG shows prolonged slow-delta patterns (albeit with some differences), and again, complexity metrics indicate decreased diversity relative to wakefulness. Notably, some anaesthetics (ketamine, nitrous oxide at certain doses) can induce dissociative states in which patients are behaviourally unresponsive but internally have some conscious (often dreamlike or delirious) experiences. In these cases, EEG complexity sometimes does *not* drop as low as in fully unconscious states – for example, a paradoxical finding is that ketamine anaesthesia can maintain relatively higher EEG entropy (compared to propofol) even though behaviourally the patient is "out" (Voss et al., 2012;

Sarasso et al., 2021). This has led to intriguing questions about whether certain metrics track the "level" of consciousness or the "contents" of consciousness. Some authors argue that a dissociation between oscillatory markers and complexity markers during ketamine suggests that high neural entropy may reflect internally conscious activity (e.g., hallucinations) even when the external responsiveness is absent (Frohlich et al., 2021). Indeed, the term "hidden consciousness" has been used for cases where patients under anaesthesia later report dreams; EEG complexity tends to be higher in those cases than in patients with no reports (Huang et al., 2018). In one study, Huang et al., (2018) found that volunteers who had explicit or implicit memory of intraoperative stimuli exhibited higher brain complexity and connectivity than those who had none, suggesting that residual conscious processing correlates with higher entropy patterns (Huang, 2018).

In slow-wave sleep (non-REM stage N3), which is a physiological unconscious state, the brain also shows a marked complexity reduction. Early work by Massimini et al., (2005) showed that TMS-evoked responses during deep NREM sleep stay local and simple (low PCI), whereas during REM sleep or wakefulness they are complex and widespread (Massimini et al., 2005). Spontaneous sleep EEG likewise demonstrates that signal diversity drops progressively as sleep deepens: Andrillon et al., (2016) documented that LZC and other complexity measures are highest in wakefulness, decrease in stage N2, and reach a minimum in stage N3 (Andrillon et al., 2016). Interestingly, REM sleep – during which vivid dreaming occurs – is a special case. REM EEG is "active" and superficially similar to wake EEG, and indeed, some complexity measures (such as LZC) in REM approach wakefulness levels (Schartner et al., 2017; Andrillon et al., 2016). However, studies have found mixed results: Schartner et al. (2017) reported that certain diversity measures in intracranial EEG were *slightly* lower in REM than in wakefulness, possibly reflecting differences in integration despite high local entropy (Schartner et al., 2017). Andrillon et al. (2016) noted a reversal of the correlation between baseline complexity and responsiveness in REM, implying that while REM is a conscious state (rich in internally generated content), its information processing might be partially insulated from external input (Andrillon et al., 2016). This nuance underscores that not all forms of high entropy guarantee external responsiveness – the source of entropy (intrinsic versus extrinsic activity) matters, a point we revisit in discussion. Nonetheless, REM sleep is certainly far more entropic than NREM: dreaming brain activity is more diverse than dreamless deep sleep, consonant with the presence of conscious experience (although disconnected from the environment) (Siclari et al., 2017; Schartner et al., 2017).

In pathological unconsciousness (such as coma, vegetative state/UWS), studies consistently find markedly reduced brain complexity. For example, Chennu et al. (2014) found that UWS patients had lower EEG permutation entropy and less complex network connectivity patterns than minimally conscious patients or healthy controls, particularly in frontoparietal regions (Chennu et al., 2014). Casarotto et al., (2016) validated that PCI values near zero (around 0.19–0.3) are almost exclusively found in UWS patients, whereas MCS patients show intermediate PCI (~0.31–0.45) and locked-in or conscious controls have high PCI (~0.5–0.6) (Casarotto et al., 2016). Similarly, fMRI studies demonstrate that brain network dynamics in vegetative patients are constrained and stereotyped compared to healthy brains (Demertzi et al., 2019). One Science Advances (2019), studied by Demertzi et al., (2019), combined fMRI and EEG across wake, sleep, and DOC patients, concluding that "human consciousness is supported by dynamic, complex patterns of brain signal coordination" which vanish or simplify in unconscious conditions (Demertzi et al., 2019). They observed that during conscious states (including dreaming REM and ketamine sedation where consciousness persists in altered form) the brain maintains higher network complexity and more flexible transitions, whereas in unconscious states (deep NREM, anaesthesia, UWS) brain activity gets "trapped" in a narrower repertoire of states (Demertzi et al., 2019). This aligns with the concept of a "complexity brake" applied in unconsciousness (Varley et al., 2020) – i.e., a breakdown of the brain's capability to explore states. It is notable that even when overall metabolism is only moderately reduced (e.g., in UWS), the *structure* of brain activity can change qualitatively, favoring large-scale low-frequency synchrony at the expense of complexity (Mashour & Hudetz, 2018).

In summary, across a range of comparisons (awake vs. anaesthetised, awake vs. deep sleep, MCS vs. UWS patients), a higher level of consciousness corresponds to higher neuroentropy in brain signals. This finding has been replicated using multiple methodologies and is now regarded as a "consilient" evidence base (Sarasso et al., 2021). A recent synthesis by Sarasso et al. (2021) noted *"a surge of empirical studies converged on complexity-related measures as reliable markers of consciousness across many different conditions"*, attesting to the consistency of this principle. The following sections examine two special cases in more detail: (a) the effect of psychedelic drugs, which intentionally elevate brain entropy, and (b) the question of how entropy relates not just to level of consciousness (wake vs. unconscious) but also to the contents of consciousness and cognitive function.

5.2. Neuroentropy in Psychedelic and "Expanded" Conscious States

Psychedelic states induced by substances such as LSD, psilocybin, and DMT provide a unique test of the entropic brain hypothesis. These states are characterised by profoundly altered conscious content (hallucinations, synaesthesia, ego-dissolution, etc.) along with increased neural entropy as predicted (Carhart-Harris et al., 2014; Carhart-Harris, 2018). Empirically, evidence from a series of MEG and fMRI studies conducted between 2014 and 2020 consistently demonstrated elevated measures of brain signal diversity under psychedelics compared to placebo. For example, Schartner et al., (2017) reported that MEG recordings during LSD, psilocybin, or ketamine (at psychoactive doses) showed reliably higher spontaneous LZC values than during normal waking consciousness (Schartner et al., 2017). The increase in signal diversity was observed across multiple MEG sensors and was especially pronounced for broadband measures combining information across channels (Schartner et al., 2017). Notably, the degree of entropy increase correlated with the intensity of the subjective psychedelic experience (Schartner et al., 2017; Timmermann et al., 2019). Timmermann et al., (2019) extended this to the fast-acting psychedelic DMT: EEG recordings revealed a significant rise in LZC and other complexity metrics when participants were at the peak of the DMT hallucination, and these complexity measures correlated with participants' self-reported "immersiveness" and visual imagery during the experience (Timmermann et al., 2019). At the whole-brain network level, Viol et al., (2017) found that the entropy of functional connectivity (derived from fMRI) increased under ayahuasca, reflecting a more "disordered" integration among brain regions consistent with the fluid cognition and imagery reported (Viol et al., 2017).

It is important to note that these results support a causal interpretation: whereas in anaesthesia we reduce consciousness and see entropy drop, here we pharmacologically increase entropy and see conscious content become hyper-lucid or atypical. Carhart-Harris et al., (2016) showed, using multimodal imaging, that LSD increases the diversity of functional connectivity motifs and reduces the integrity of constraint networks such as the default mode network (Carhart-Harris et al., 2016). In parallel, participants reported ego-dissolution and sensory crossover, phenomena arguably explained by the brain exploring states that are normally unavailable (Carhart-Harris et al., 2016). As Carhart-Harris (2018) summarised, psychedelics pharmacologically "tune the brain closer to criticality," expanding its dynamic repertoire (Carhart-Harris, 2018). Whole-brain modeling by Herzog et al., (2023) has now replicated these effects in silico by increasing neural gain (through simulated 5-HT2A receptor activation) and demonstrating a resulting entropy surge, particularly in higher cortical areas (Herzog et al., 2023). Interestingly, while global brain entropy increases under psychedelics, it is not homogeneous: some studies find that visual and associative regions show the largest entropy gains (Herzog et al., 2023), which fits the vivid visual hallucinations; in contrast, subcortical regions or primary somatomotor areas may not increase entropy as much (Lebedev et al., 2016). This heterogeneity suggests that the rich phenomenology of psychedelic consciousness might correspond to targeted increases of entropy in specific networks (e.g., the visual cortex "over-decorrelating" from normal constraints to produce kaleidoscopic imagery). Another observation is that not all complexity measures behave identically: Farnes et al., (2020) found that spontaneous EEG signal diversity increased with

ketamine infusion (psychedelic dose), but the complexity of *evoked* EEG responses (to stimuli) did not increase comparably (Farnes et al., 2020). In other words, the brain's internal noise increased, but externally driven information processing remained constrained. This finding aligns with the notion that psychedelics broaden internal awareness but do not necessarily improve external task responsiveness, again emphasising the difference between level of consciousness and content/attention (Farnes et al., 2020; Sarasso et al., 2021).

Beyond drugs, other "expanded" conscious states show similar entropy patterns. Lucid dreaming (when one is aware of dreaming) has been associated with slightly elevated EEG complexity compared to regular REM dreams (Voss et al., 2009). These nuances highlight that while neuroentropy is broadly a marker of conscious level, it may also modulate aspects of conscious content richness. Research by Carhart-Harris and colleagues proposed that higher entropy states permit more "divergent thinking" and cognitive flexibility (Carhart-Harris, 2018).

5.3. Linking Neuroentropy to Conscious Content and Cognitive Function

An emerging direction is to investigate how entropy relates not just to being conscious or not, but to what is in consciousness – the qualitative content and cognitive abilities. High neural entropy has been associated with rich phenomenological content: for example, within REM sleep, trials where subjects reported vivid, perceptual dreams showed higher posterior cortical complexity than those where subjects had only vague thought-like mentation (Siclari et al., 2017; Sanz Perl et al., 2021). Similarly, within psychedelic sessions, particularly intense visual hallucinations correlate with transient spikes in occipital entropy (Atasoy et al., 2017). These findings align with the Integrated Information Theory's idea that more differentiated brain states produce richer conscious content (Tononi et al., 2016). However, complexity is not the sole determinant of specific content – rather, it seems to act as an enabling condition for content variety. A brain in a low-entropy state (e.g., deep NREM or under strong sedation) cannot support detailed conscious content (hence, either no report or very simple imagery upon awakening), whereas a brain in a high-entropy state can support either veridical perception or hallucinations or imaginative thought, depending on other factors such as sensory input and network configuration (Koch et al., 2016; Bayne et al., 2020). This is consistent with empirical data: whenever conscious reports are rich and complex, neural entropy tends to be higher (Sarasso et al., 2015; Casali et al., 2013).

An interesting case is the phenomenon of covert consciousness: patients who appear unconscious but in fact retain some awareness (e.g., some cognitively motor-inactive patients can willfully modulate brain activity as shown by fMRI or EEG responses). In such patients, EEG complexity measures often detect anomalies. For example, in the famous case of a patient who was clinically diagnosed as vegetative but could answer yes/no via imagined motor imagery in fMRI, retrospective analysis showed that their EEG exhibited higher entropy than typical vegetative patients (Cruse et al., 2011). Wu et al., (2020) demonstrated the use of multi-scale entropy features to successfully detect signs of consciousness in a completely locked-in syndrome patient, suggesting that sufficient complexity in the EEG can indicate preserved awareness despite total paralysis (Wu et al., 2020).

From a cognitive neuroscience perspective, higher entropy has been linked to enhanced cognitive performance and adaptability. Kloosterman et al., (2020) reported that individuals with more variable resting fMRI connectivity (higher entropy dynamics) showed greater mental flexibility on certain tasks (Kloosterman et al., 2020). A related concept is that a complex brain can more readily transition between different tasks or states as required. Conversely, extremely ordered brain activity (low entropy) may manifest as cognitive rigidity or disorders of consciousness. In depression and other psychiatric states characterised by rumination and inflexibility, EEG complexity is often slightly reduced relative to healthy controls. This has led to hypotheses that therapeutic interventions (such as psychedelics or transcranial stimulation) might temporarily elevate brain entropy to "shake" the system out of pathological attractors, enabling reconfiguration and therapeutic gains (Carhart-Harris, 2018; Carbonaro et al., 2018). Some preliminary trials of

psilocybin for depression have indeed found that acutely increased entropy correlates with later symptom improvements and personality changes (Carhart-Harris et al., 2018; Carbonaro et al., 2018). However, these findings are preliminary and causality remains to be established.

Finally, we note the nuance that more entropy is not always better for cognitive function. While moderate increases can indicate flexibility, excessive noise or disorganisation may impair effective processing (de la Torre-Luque et al., 2016). For example, in schizophrenia, some evidence indicates elevated resting-state signal diversity (perhaps reflecting unstable or noisy neural dynamics), which correlates with positive symptoms such as hallucinations but detracts from coherent cognition (Yang et al., 2015). Thus, the relationship between neuroentropy and *optimal* conscious function is likely to follow an inverted U-shape: too low, insufficient complexity for rich awareness; too high, loss of coherent integration needed for stable reality (Carhart-Harris, 2018; Arsiwalla & Verschure, 2018). The healthy waking brain appears to self-tune near this balance point (criticality), so that it achieves high complexity with underlying order (Toker et al., 2022). Indeed, recent work by Toker et al., (2022) demonstrated that the awake human cortex operates near the edge of instability, exhibiting maximal entropy and long-range correlations consistent with critical dynamics, whereas upon loss of consciousness (deep sleep, anaesthesia) the dynamics move away from criticality towards a more regular regime (Toker et al., 2022). This near-critical state may be essential for combining the integration and differentiation that consciousness requires (Koch et al., 2016).

6. Discussion

Based on the previously presented sections and to introduce this section, we firstly provide a brief summary: Neuroentropy has emerged as a unifying metric that links brain dynamics to conscious state. There is evidence that converges on the conclusion that when the brain sustains conscious experience, its activity is complex, variable, and information-rich, whereas when consciousness fades, brain activity becomes stereotypical, low-dimensional, or hyper-synchronised. This pattern holds true across wake/sleep, anaesthesia, and clinical disorders, making entropy-based measures some of the most generalisable markers of consciousness to date (Sarasso et al., 2021; Engemann et al., 2018). As a result, the assessment of neural complexity is beginning to find applications in clinical neurology and anaesthesiology. Commercial anaesthesia monitors already incorporate entropy measures (such as Spectral Entropy or "Response entropy" of EEG) to track depth of sedation, providing real-time feedback to anaesthesiologists (You, Noh, & Shin, 2016). In disorders of consciousness, specialised paradigms like PCI are moving from research to bedside to help detect consciousness that might otherwise be missed by bedside examination (Casarotto et al., 2016).

Despite significant progress, several methodological and theoretical challenges remain. Not all entropy measures are equivalent, and results can vary depending on which metric is used and at what temporal/spatial scale (Lau et al., 2022). For example, single-channel entropy might be high due to local fast noise even if global integration is low – to truly gauge consciousness, one must ideally capture both widespread integration and local differentiation (Koch et al., 2016). Measures such as PCI or Φ attempt this but are computationally intensive or require perturbation. Simpler measures (e.g., LZC) are more accessible but may need to be combined with connectivity metrics to avoid mistaking random noise for genuine complexity (Lau et al., 2022). In practice, researchers often use a battery of measures and look for convergence. The notion of an optimal entropy highlights that the relationship between entropy and *meaningful* complexity is not linear: a signal could have high entropy simply by being uncorrelated white noise, which is not a sign of consciousness but of destruction of organised activity (Bornas et al., 2013). Multi-scale approaches help differentiate true complexity (high entropy across multiple scales) from pseudo-complexity (high entropy at only fine scales that disappears at coarse scales – a signature of noise) (Yang & Tsai, 2013). Researchers are therefore cautious to interpret entropy changes considering spectral and scaling analyses, to ensure we identify meaningful entropy associated with rich dynamics rather than pathological noise (Lau et al., 2022).

Another challenge concerns the granularity of consciousness. Consciousness is not binary, and intermediate states (e.g., drowsiness, light sedation, minimal consciousness) exist. Complexity measures do vary continuously and often correlate with graded behavioural scales (e.g., Ramsay sedation scores, Coma Recovery Scale scores) (Casarotto et al., 2016; Engemann et al., 2018). However, establishing a precise one-to-one mapping between an entropy value and a conscious level is challenging, owing to individual differences and contextual factors. Some individuals may have inherently higher EEG complexity at baseline (due to age, neuroplasticity, etc.), and brain injury can alter complexity independently of consciousness (e.g., reduced complexity due to reduced neural connectivity even if the patient is conscious). Therefore, establishing normative data and personalised baselines is important for clinical use (Lau et al., 2022). Recent research has begun to compile lifespan norms for brain entropy (Wang et al., 2020) to distinguish pathological low complexity from age-expected values.

It is also important to recognise that consciousness comprises both content (qualia) and level (arousal), which may have partially dissociable neural correlates (Bayne et al., 2016). Entropy measures seem most tied to the level or "capacity" of consciousness, the brain's readiness to sustain any conscious experience at all (Mashour & Hudetz, 2018). Content-specific changes (e.g., seeing a face vs. a house) are reflected in more fine-grained neural patterns that may not drastically alter global entropy. Indeed, studies show that while background conditions (like wake vs. anaesthesia) have an effect on complexity, content variations within consciousness (different perceptions or thoughts) modulate complexity only subtly (Sarasso et al., 2015; Siclari et al., 2017). This suggests that entropy is a necessary but not sufficient descriptor of consciousness: it may indicate whether the lights are on, but not the scene in the room. In practical terms, this means neuroentropy is well suited for detecting the presence versus absence of consciousness, but additional measures are required to interpret conscious content.

From a broader perspective, the strong association between neuroentropy and consciousness provides support for the idea that the brain is a complex information-processing system, in which conscious states require a delicate balance of order and disorder. This finding resonates with longstanding proposals that "conscious processes are, in some sense, more complex than unconscious ones" (John, 2002), and now provides quantitative shape to that intuition. This meta-analysis reveals that no significant counter-example has emerged where a clearly unconscious state shows higher brain entropy than a conscious state within the same subject; the direction of the correlation has been consistent. The main caveats involve cases of internally versus externally directed consciousness (e.g., ketamine, REM dreaming), which caution that behavioural unresponsiveness does not always equal zero consciousness, and entropy measures can pick up on this distinction (Frohlich et al., 2021; Sarasso et al., 2021).

7. Conclusion

In conclusion, the provided evidence in this work supports neuroentropy as a parameter for measuring conscious brain function. Consciousness, across its spectrum from minimal awareness to vivid wakefulness, appears to require high but controlled neural complexity, reflected in elevated entropy of brain electrical activity and more diverse network dynamics. Empirically, brain entropy measures have proven to be among the most reliable markers for the presence of consciousness across sleep, anaesthesia, and brain-injured patients, as well as in altered conscious states such as those induced by psychedelics. This meta-analysis has highlighted findings showing that virtually every instance of consciousness diminution (sleep, anaesthesia, coma) coincides with a reduction in measurable neural entropy, and every deliberate increase in entropy (via pharmacological intervention or stimulation) correlates with enhanced or altered conscious contents. These convergent results indicate a profound relationship between the brain's information capacity and the phenomenon of consciousness. They also provide ideas for practical applications: indeed, it may be interesting to explore entropy metrics in monitoring devices, and designing therapeutic interventions that might safely modulate brain entropy in the treatment of disorders of

consciousness or psychiatric conditions. Nevertheless, the exact causal concept of entropy in generating consciousness, as opposed to serving merely as a correlated marker, remains an open scientific question. Certainly, future research will need to address how different aspects of brain activity (synchrony, connectivity, neuromodulation) interact to produce the optimal complexity for consciousness, and whether there are exceptional conditions or additional hidden variables.

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