Breathwork-Induced Psychedelic Experiences Modulate Neural Dynamics

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Keywords: Breathwork, Psychedelics, Altered States of Consciousness, Neural Complexity, Neurophenomenology

Abstract

Breathwork is a term for an understudied school of practices that involve the intentional modulation of respiration to induce an altered state of consciousness (ASC). We map here the neural dynamics of mental content during breathwork, using a neurophenomenological approach by combining Temporal Experience Tracing, a quantitative phenomenological methodology that preserves the temporal dynamics of subjective experience, with low-density portable EEG devices for every session. Fourteen novice participants completed a series of up to 28 breathwork sessions - of 20, 40 or 60 minutes - in 28 days, yielding a neurophenomenological dataset of 301 breathwork sessions. Using hypothesis-driven and data-driven approaches, we found that positive 'psychedelic-like' subjective experiences that occurred within the breathwork sessions were associated with increased neural Lempel-Ziv complexity. Further, exploratory analyses showed that the aperiodic exponent of the power spectral density (PSD) - but not oscillatory alpha power - was also associated with these psychedelic-like phenomenological substates. We demonstrate the strength of this neurophenomenological framework, maximising the concurrent data acquisition of brain activity and phenomenological dynamics in multiple experiential dimensions. Non-linear aspects of brain dynamics, like complexity and the aperiodic exponent of the PSD, neurally map both a data-driven complex composite of positive experiences, and hypothesis-driven aspects of psychedelic-like experience states such as high bliss.

1. Introduction

Mapping the relationship between subjective experience and the brain is a primary aim of the neuroscience of consciousness (Koch et al., 2016; Lutz & Thompson, 2003; Varela, 1996). Research over the last two decades has focused on identifying neural signatures associated with the breakdown of consciousness, in states such as dreamless sleep or anaesthesia. One overarching finding is that neural signal diversity, such as Lempel-Ziv (LZ) complexity, decreases in states of reduced consciousness (Schartner et al., 2015; Luppi et al., 2019; King et al., 2013; Pascovich et al., 2022). LZ complexity has also been useful for probing the *contents* of consciousness. For example, neural differentiation (measured by LZ) increases when conscious contents are reported as differentiated (i.e. two contents) rather than integrated (i.e. one content) during auditory and visual bistable perception (Canales-Johnson et al., 2020; 2023). Taking a neuro-centric view within the study of the breakdown of consciousness has demonstrable utility, as highlighted by the usefulness of neural signal diversity as an index of arousal in patients with disorders of consciousness (Casali et al., 2013). However, when mapping the territory within altered states of consciousness (ASCs) that have multi-dimensional and rich subjective experiences, such as the 'psychedelic state' (Bayne & Carter, 2018; Fortier-Davy & Milliere, 2020), the picture becomes more complex. Some studies have ignored the subjective experiences that occur from psychedelics (Barnett et al., 2020; Deco et al., 2018; Petri et al., 2014; Varley et al., 2020a), thus yielding neural signatures that may be broadly related to the *state* of consciousness that occurs, rather than the *contents* of consciousness itself.

To counter this, a group of researchers have recently emphasised the necessity to pair first-person subjective reports with neurophysiological data in the study of phenomenologically rich altered

states of consciousness (ASCs) such as psychedelics, hypnosis, and meditation (Timmermann et al., 2023a). The methodology in question (neurophenomenology; Varela, 1996) is growing within the neuroscience of ASCs (Cardeña et al., 2013; Dor-Ziderman et al., 2013; Dor-Ziderman et al., 2016; Timmermann et al., 2019; Garrison et al., 2013; Berkovich-Ohana et al., 2013). Of note, Timmermann et al. (2019) conducted a neurophenomenological study of the potent and fast-acting psychedelic substance N,N-Dimethyltryptamine (DMT), demonstrating that LZ complexity was related to the subjective intensity of the experience over time. This is in concordance with a growing body of research showing that an increase in neural signal diversity is one of the most robust signatures of the 'psychedelic state' (Schartner et al., 2017; Mediano et al., 2024; Pallavicini et al., 2021)[1], much like a breakdown of consciousness is associated with a reduction in neural signal diversity. From the perspective of the Entropic Brain Theory (EBT; Carhart-Harris et al., 2014; Carhart-Harris, 2018), this increase in neural informational complexity is theoretically associated with the heightened 'richness' of experience cultivated through the administration of psychedelics.

However, as mentioned, despite the increasing adoption of neurophenomenological approaches in consciousness science, we are still yet to fully understand how the specific *contents* of consciousness that arise in ASCs are related to neural signatures. This may be due to (i) under-powered sample sizes in psychedelic studies, (ii) the use of likert scales to quantify the overall intensity of experiential dimensions, thus ignoring the temporal dynamics of phenomenology, and (iii) a 'uni-dimensional' approach to studying the relationship between phenomenology and the brain (Bayne & Carter, 2018; Fortier-Davy & Milliere, 2020).

[1] It is of note that this association may be most robust within high temporal resolution neuroimaging modalities, such as EEG and MEG. A recent study has found conflicting results when investigating the relationship between neural complexity and psychedelics using fMRI (McCulloch et al., 2023).

To counteract the above issues, we present the current study as a novel approach to the study of ASCs. Specifically, we utilise temporal experience tracing (TET; explained in detail in Methods; Jachs et al., 2022; Jachs, 2021), a novel phenomenological methodology to empirically investigate subjective experience dynamics during breathwork, an ASC induced through voluntary changes in respiration (such as depth, breadth, and frequency). Briefly, the breathwork practice within this study involves cyclic hyperventilation in combination with breath retentions in order to induce a hypoxic state (Kox et al., 2014; see Methods for further explanation). Breathwork was investigated as it is a non-pharmacological way to induce an ASC, with purported phenomenological similarities to serotonergic psychedelics such as LSD and psilocybin (Puente et al., 2014; Bahi et al., 2023; Rock et al., 2015; Fincham et al., 2023a). EEG and accelerometer data were collected through low-density portable EEG devices (Arnal et al., 2020).

To address aforementioned issue (i), the study of a non-pharmacological ASC that is accessible to novices (unlike certain meditative states, which often require tens of thousands of hours of practice (Yang et al., 2024)), combined with portable EEG devices used at home, has permitted the collection of this neurophenomenological dataset, which is an order of magnitude larger than comparable psychedelic studies (e.g., Timmermann et al., 2019; 2023b; Schartner et al., 2017). To address issue (ii), the use of TET data supersedes the capability of likert scales in neurophenomenological analyses, as TET produces phenomenological timeseries, which is a more accurate reconstruction of the temporal dynamics of phenomenology. Finally, to address

issue (iii), we use data-driven techniques to reveal multi-dimensional phenomenological clusters (see Methods), which may therefore be associated with neural signatures.

Prior to the analysis of the data, neurophenomenological hypotheses were pre-registered on the Open Science Framework (https://osf.io/ef5j3). Due to the potential phenomenological similarities between breathwork and psychedelics (Puente et al., 2014; Bahi et al., 2023; Rock et al., 2015), and the fact that an increase in signal diversity is associated with the subjective intensity of a psychedelic experience (Schartner et al., 2017; Timmermann et al., 2019; Mediano et al., 2024), we focussed our initial neurophenomenological analyses on LZ complexity (Lempel & Ziv, 1976; Ziv & Lempel, 1978). The data were statistically analysed using Data-Driven (DD), Hypothesis-Driven (HD), and Stimulus-Driven (SD) approaches, in order to elucidate the potential relationships between physiology, phenomenology, and neural complexity during breathwork. Within the DD approach, we broadly hypothesised that there would be a psychedelic-like phenomenological cluster revealed through k-means clustering (Likas et al., 2003), and this phenomenological cluster would significantly differ in LZ complexity compared to the opposing cluster. For the HD approach, we hypothesised that there would be an association between the retrospectively rated intensity of 'bliss' and LZ complexity. This was motivated due to the fact that psychedelics robustly increase the phenomenological dimension of bliss (Hirschfield & Schmidt, 2021; see methods for the definition of bliss and the other phenomenological dimensions used in this study). As bliss may load heavily onto the subjective experiences found within psychedelic experiences (Roseman et al., 2018), we therefore aimed to explore how this related to neural signatures associated with psychedelics. Finally, within the SD approach, it was broadly hypothesised that (proxy) hypoxic states induced through breath

retention would significantly differ in LZ complexity compared to states in which O_2 saturation is comparatively high.

2. Methods

2.1 Temporal Experience Tracing (TET)

TET has previously been used to study the phenomenological dynamics of different styles of meditation (Jachs et al., 2022; Jachs, 2022), is currently being used to study temporal dynamics of stress in autism (Gernert et al., 2023), has been applied to the study of chronic pain (Niedernhuber et al., 2023) and is being applied to two separate studies with the potent and fast-acting psychedelic DMT (publications ongoing). With the methodology of TET, dimensions of subjective experience most relevant to the phenomenon of study are identified. These dimensions are sub-components of the contents of consciousness, relating to affective, attentional, or motivational aspects of experience. After completing a session of the particular phenomenon of study, participants complete a retrospective trace of the intensity of each specific dimension.

At the time of this study, there had been little research conducted on the subjective experiences of breathwork. Therefore, we sought to map out specific dimensions that form the phenomenological foundation of breathwork practices. SOMA Breath, an organisation that provides training and courses in breathwork practices, created a modified and streamlined version of an existing course for this study (under procedure), consisting primarily of breathwork sessions. The first author (ELH) completed this streamlined course. Each dimension was discussed with an experienced breathwork practitioner and with the CEO of SOMA Breath, and

circulated to breathwork teachers for feedback. Fourteen dimensions were chosen as the most phenomenologically relevant for this particular breathwork modality. Five of these dimensions (highlighted in bold) were also used in Jachs (2022). Below is a description of each dimension.

1. **Meta-awareness** is defined as being aware of the current contents of thought (Schooler et al., 2011). This has been highlighted as a fundamental construct in meditation practices, particularly open monitoring (Laukkonen & Slagter, 2021). This dimension was included as it may be a potential measure of the veridicality of the overall phenomenological report.
2. Presence/Distraction is defined as how present or distracted participants were during the breathwork session. An example provided to participants was, "…if you are not focused on putting effort into the breathwork session, then distraction would be particularly high at the moment. However, if you are 'with' the breathwork practice, being at one with your experience as it arises, you are highly present, and thus score low in distraction."
3. Physical Effort refers to the amount of physical exertion participants exhibited during the breathwork experience. The breathwork sessions can be physically demanding, due to an increase in breathing frequency or sustained breath holds. It was therefore deemed a key dimension in the practice of breathwork across participants.
4. **Mental Effort** may be defined as the exertion of attentional resources under increasingly demanding task-conditions (Alnæs et al., 2014). Mental effort has also been contextualised within the terms of the costliness of cognitive control (Shenhav et al., 2017).

5. **Boredom** has received much attention in the scientific literature (Fisherl, 1993; Smith, 1981). The phenomenology of boredom has been characterised by feelings of restlessness, lethargy, lack of concentration, and distorted time perception (Martin et al., 2006). A review study has highlighted that boredom is related to an inability to sustain attentional capacities (Westgate & Steidle, 2020). It may therefore be related to the construct of mental effort.
6. Receptivity/Resistance refers to a state in which a participant is resistant to the experiences that occur within the breathwork practice. Being receptive to the successive experiences is the antonym of resistance, and may be phenomenologically similar to the state of 'surrender', which has been highlighted as a baseline predictor of positive reactions to psychedelic experiences (Aday et al., 2021).
7. **Emotional Intensity** was a dimension related to the intensity of their emotional state, regardless of positive or negative valence. This setup, of retrospectively rating the intensity of emotions in a continuous fashion, was also employed in a study using virtual reality (Hofmann et al., 2021). The researchers found that emotional intensity was associated with parieto-occipital alpha power, which was further confirmed through decoding analysis.
8. **Clarity** refers to the vividness of the contents of consciousness (Lutz et al., 2015). In the case of perceptual clarity, we may refer to visual vividness as analogous to this. In previous studies, endogenous attention has demonstrably increased the perceived contrast of stimuli in a rapid serial visual presentation task (Liu et al., 2009). While visual vividness may be included in the experience of clarity, other aspects of conscious experience are also perceived with a degree of clarity, such as affective tone.

9. Release/Tension refers to the amount of either physical, or psychological tension that is experienced. It is hypothesised that high periods of tension may be followed by high periods of release. There may be some overlap with these periods of high intensities of release and "emotional breakthrough" (Roseman et al., 2019), which has its roots in the psychoanalytic concept of catharsis (Breuer & Freud, 1895; Jackson, 1994). Emotional breakthrough may represent a large aspect of the phenomenology of the psychedelic experience (Carhart-Harris et al., 2021), and may be a potential therapeutic mechanism.
10. (Dis)embodiment refers to the experience of not identifying with one's own body (Blanke, 2012). The antonym of this, the feeling of identifying with and normally perceiving one's body, has frequently been investigated and modulated in studies on self-consciousness (Blanke & Metzinger, 2009). Disembodiment forms a specific sub-component of the 11 Dimensions of Altered States of Consciousness questionnaire (11D-ASC; Studerus et al., 2010), and has been modulated through the administration of psychedelics (Bernasconi et al., 2014; Kometer et al., 2012; Kraehenmann et al., 2017). Bahi et al. (2023) found that a conscious connected breathwork session increased feelings of disembodiment similar to a psilocybin dose of 400µg/kg. Within the present study, this dimension was coded so high values denoted a high intensity of embodiment, and low-values denoted a high intensity of disembodiment.
11. Bliss is another sub-component of the 11D-ASC (Studerus et al., 2010). It may be defined as experiencing boundless pleasure, or a profound peace. The empathogen/entactogen 3,4-methylenedioxy-methamphetamine (MDMA) has been found to significantly increase a blissful state (Studerus et al., 2010). Again, Bahi et al. (2023) found that a conscious

connected breathwork session yielded similar ratings of bliss when compared to 400µg/kg of psilocybin.

12. Insightfulness was also taken from the 11D-ASC (Studerus et al., 2010). Within the literature, insight may refer to the experiences of eureka moments. These are characterised as sudden moments of clarity into the solution of a problem (Kounios & Beeman, 2014). Cognitive (neuro)science has attempted to identify the neural correlates of the eureka moment (Aziz-Zadeh et al., 2009; Tik et al., 2018), and assessed the effect of artificially induced eureka moments on metacognition (Laukkonen et al., 2020). However, as eureka moments are temporally localised phenomena, this specific dimension is focussed on assessing the novelty of the stream of consciousness. As above, Bahi et al. (2023) found that retrospective ratings of Insightfulness were similar to 400µg/kg of psilocybin.
13. Anxiety was defined as the experience of dysphoria, characterised by a strong, negatively valenced state. Within studies that evaluated the subjective effects of psychedelic substances, the experience of anxiety has been associated with a lack of response for ketamine-assisted therapy for major depression (Aust et al., 2019). Anxiety also forms a sub-component of the 11D-ASC (Studerus et al., 2010).
14. Spiritual Experience is the final dimension included from the 11D-ASC (Studerus et al., 2010). This dimension is qualitatively similar to peak (Stace, 1960), or mystical (Hood, 1975; Griffiths et al., 2006; Barrett & Griffiths, 2018) experiences, characterised by feelings of intense awe (Hendricks, 2018), and feeling connected to a higher power (Studerus et al., 2010). The mystical experience forms part of psychedelic

phenomenology at higher doses, and may be a predictor of clinical benefits of psychedelics (for a review, see Johnson et al., 2019).

2.2 EEG Headsets

Participants were provided with a portable low-density Dreem EEG headset (Arnal et al., 2020). The EEG headsets collect both neural and accelerometry data. These headsets have seven channels. Each channel is a longitudinal bipolar montage between frontal electrodes (F7, F8, and FPz), or frontal and occipital electrodes (O1 and O2). The sampling rate of the headset was 250Hz, and the resolution of the AD converter was 24 bits. The hardware did not apply any filtering or preprocessing of the data. One channel was re-referenced to provide solely occipital-occipital information.

2.3 Participants

The experimental protocol was approved by the Cambridge Psychology Research Ethics Committee. All participants took the full breathwork course free of charge and were not directly reimbursed for their time.

Participants were recruited via the SOMA Breath advertising channels on social media. The eligibility criteria was the following:

- Between 18-65 years of age
- Participated in two or less sessions of high-ventilation breathwork practices
- Based in the UK and able to complete the whole study
- No chronic mental health, sleep-related or neurological medical problems.

21 participants were originally recruited for this study. One participant withdrew due to pregnancy, three participants withdrew due to unrelated health issues, one participant withdrew due to a bereavement, and one participant withdrew due to a lack of time in the mornings to complete the sessions. Finally, one participant returned the physical TET data in a damaged condition, and thus was excluded from further analysis. Therefore, data is presented from 14 participants (10f, 4m; average age = 40, SD = 9).

2.4 Procedure

Participants completed a four-week course delivered online via SOMA Breath. As mentioned, SOMA Breath is a company that provides training and facilitation of breathwork sessions. The four-week course was delivered remotely online. Within this course, participants completed a breathwork session every day for 28 days. The breathwork session is an online audio track, one for each corresponding week of the course. The tracks themselves are composed of breathing instructions, and are accompanied by evocative background music. As the course progressed, the sessions became longer, with more breath holds, inducing a more pronounced acute hypoxic state (Kox et al., 2014).

Prior to the start of the course, participants were provided with a personal low-density EEG device, and either a TET booklet or digital folder of powerpoint presentations. The booklet and powerpoint presentations contained TET graphs for each breathwork session, with markers along the x-axis corresponding to the conditions within the session (see Supplementary Figure S1 for an example). In addition to this, the participants met with the primary researcher to (i) learn how

to perform the tracing method, (ii) learn how to use the portable EEG headset, and (iii) discuss the definition of each phenomenological dimension.

As previously mentioned, the breathwork course was organised into four separate weeks, with the same breathwork session practised each day of the week. For the first and fourth week of the course, the breathwork session was approximately twenty minutes long. For the second week, the session was approximately forty minutes long. For the third week, the session was approximately one hour long. On the first day of each week of the course, the participants met online with the CEO of SOMA Breath, where the breathwork technique was taught, questions could be answered, and the breathwork session for that week was conducted. Succeeding this, each participant was to complete the breathwork sessions daily, yet of their own accord (with recommendation to practise it in the morning). Each session was partitioned into five different instructions (hereby named conditions):

1. **Introduction**: Comprises the first part of the session, where there are no specific instructions and only music is played.
2. **Breath**: Comprises instructions to breathe in a rhythmic and standardised manner. .
3. **Hold**: Within this condition, the participant is instructed to actively hold their breath to induce a state of acute mild hypoxia. In some cases, the participant is instructed when to stop holding the breath, but in the later weeks of the course, there is less explicit instruction as when to conduct this.

4. **Fast**: This section applies to the third and fourth weeks of the course. Within these sections, the participant is instructed to breathe at a rate of one inhalation/exhalation every two seconds.
5. **End**: This represents the end of the session, where there is no instruction given, and only music is played.

Participants were instructed to complete the daily breathwork sessions with eyes closed. Participants wore the EEG headset during these sessions. Succeeding each session, participants completed TET graphs for each of the fourteen phenomenological dimensions. Participants also provided qualitative data regarding subjective experiences during the corresponding breathwork session. They conducted this by using voice-recording software on Microsoft Word, filling in a personalised sheet corresponding to each session. A schematic overview of the course and subsequent analyses can be found in Figure 1.

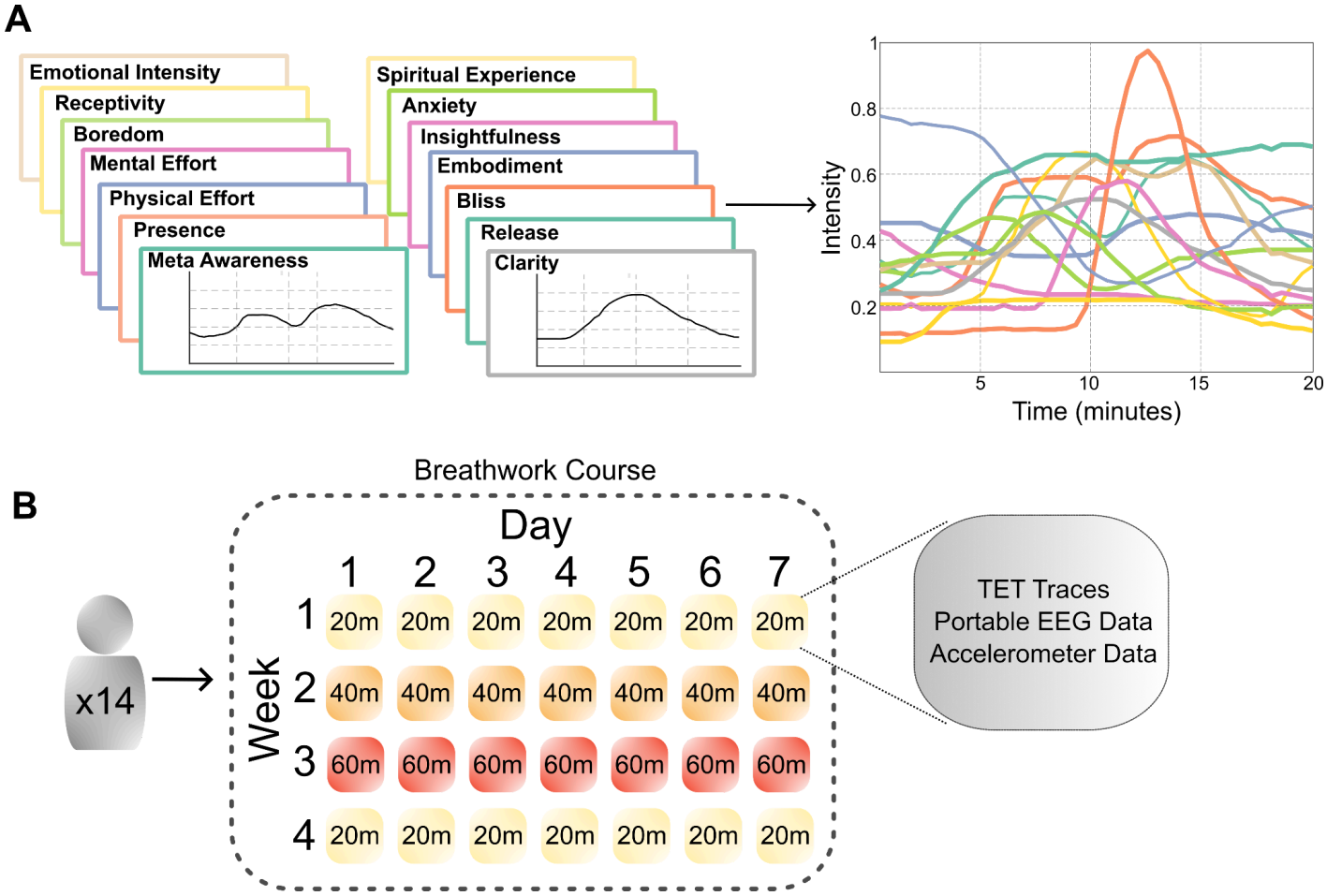


Figure 1: A schematic overview of Temporal Experience Tracing (TET), and the breathwork course. A) After a breathwork session, a participant will retrospectively trace the felt intensity for each distinct phenomenological dimension over time (left). These traces are then digitised into vectors and concatenated, thus forming a 14-dimensional matrix of phenomenological intensity (right). B) 14 participants completed a 28-day breathwork course, organised into four separate weeks. Within each week, the participant conducts the same breathwork session every day for seven days. Between weeks, the sessions become more intense; they increase in length, and comprise more breath holds within the session, allegedly culminating in more intense hypoxic states. During each session, participants recorded EEG and accelerometry data using the Dreem EEG headband (Arnal et al., 2020). After each session, the participants reported the subjective intensity of 14 distinct phenomenological dimensions over time. TET data was preprocessed and organised into experience clusters using k-means. LZ complexity measures were computed on the EEG data, as pre-registered. Exploratory analyses were conducted on the oscillatory power and aperiodic exponent of the EEG signal.

In addition to the above, 7 participants completed a phenomenological interview regarding their subjective experiences of note during the breathwork course. The phenomenological interview lasted up to two hours. These findings are partial and not described in this report.

2.5 Preprocessing

2.5.1 TET Data

TET data was converted to vectors using a semi-automatic custom MATLAB script. The script converted the image coordinates of the TET data to graph coordinates, based on the orientation of the x and y axes. Each phenomenological dimension was manually checked to ensure the vectors were similar to the TET traces themselves. After conversion, each phenomenological dimension was concatenated in a column-wise fashion, creating a 14xN TET matrix for each breathwork session, where N is the corresponding number of data points generated for that session. Each participants' TET data was normalised across all of their sessions for the whole course. Based on the assumptions of previous datasets (Jachs, 2022), each datapoint represented 28 seconds of the breathwork session. Sessions missing one or more dimensions were excluded from further analysis.

2.5.2 Neural Data

Low-pass filtered (35Hz) neural data was downloaded from the Dreem server after the session was automatically uploaded. Neural data was high-pass filtered at 1Hz, and cut into four-second epochs. Within the course, participants were instructed to tap on the headset three times at the

beginning of each breathwork session. Each dataset was manually scanned to identify this within the signal, and the session was cut to this corresponding starting point. Each epoch was labelled according to one of the five aforementioned conditions (i.e. according to 'Introduction', 'Breath', 'Hold', 'Fast', or 'End') based on the instructions of that session. The data was cleaned using a custom script designed to automatically reject epochs exceeding ±300μv. For the hypothesis-driven approach, using association metrics between the intensity of bliss and neural complexity, sessions with more than 50% of the neural epochs rejected were excluded. For the data-driven approach, and the stimulus-driven approach, sessions with over 80% of the neural epochs rejected were excluded.

Further to this, consistent noisy channels at the participant level which led to the rejection of all epochs were excluded in order to keep these sessions for further analysis. Subjects 11 and 19 had two noisy frontal paired channels, which were excluded from further analysis.

2.5.3 Accelerometer Data

For each session, breathing frequency was extracted from the z-axis of the accelerometer on the EEG headband. The data was bandpass filtered between 0.02 and 0.2Hz and detrended.

2.6 Analyses

2.6.1 Lempel-Ziv Complexity

We focused our preregistered hypotheses on LZ complexity measures, as it is a relatively simple method that has been robustly applied to cognitive neuroscientific work on consciousness (Casali et al., 2013, Frohlich et al., 2022; Pascovich et al., 2022; Schartner et al., 2015; 2017; Timmermann et al., 2019). Briefly, LZ complexity is computed through the binarization of the signal around its median, where all values above the signal are 1, and all values below the signal are 0. The signal is then algorithmically scanned sequentially for novel patterns within the signal (Kaspar & Schuster, 1987), creating a 'dictionary' of binary sequences for each timeseries. The length of this dictionary is a measure of the complexity of the signal, which can then be standardised through the division of this by the computed complexity of the same data that is randomly shuffled.

For the current study, LZ complexity was computed in two forms: concatenated LZ (LZc) and summed LZ (LZSum). In the first form (LZc), the timeseries from all channels are concatenated together to form one timeseries, with the computations above applied to the single concatenated signal. In the second form, the LZ computation above can be applied to each channel separately, with the results averaged. We applied these two computations to investigate whether different results would be yielded, as has been observed in previous research (Schartner et al., 2015).

The above computations are a measure of global signal complexity. However, both LZSum and LZc were computed on the separate channel pairing groups (frontal with frontal, frontal with occipital, and occipital with occipital), in order to investigate spatial contributions to complexity

changes within the varying hypotheses. The variations in the computation of LZ complexity, based on spatial contribution and LZSum/LZc, are hereby referred to as complexity types.

2.6.2 Phenomenological Clustering

In order to elucidate metastable clusters of subjective experience that occurred throughout the breathwork course, we applied k-means clustering (Likas et al., 2023) to the TET data, using squared Euclidean distance as the distance metric. This is a data-driven approach to the analysis of the phenomenological (and neural) data, as the clustering algorithm receives no *a priori* information regarding the structure of the phenomenological data, or about which subject, week, or session, the phenomenological data occurs within.

The optimal clustering solution was found through the Calinski-Harabasz criterion (Calinski & Harabasz, 1974). Furthermore, due to the fact that the clustering solution depends on the initiation point of the centroids, the algorithm was replicated 1000 times with randomly chosen initiation points. The resulting clusters with the lowest sum of squared distances were subsequently chosen.

2.6.3 Stimulus-Driven Analyses

The z-axis accelerometer data was extracted from the Dreem EEG device. The data was filtered between 0.02 and 0.2Hz, detrended, and normalised to have zero mean and a standard deviation of one. The data was cut to the length of the session, and the sections of the session in which the

participants were holding their breath were identified. Within these specific windows, the *findchangepts* function in MATLAB was used to identify the most abrupt change in the signal. This timepoint was an approximation of when the participant took their first inhale after holding their breath for a certain amount of time. The LZ complexity of this neural epoch (at the temporal scale of 28s) was compared to the neural epoch prior to the start of the breath hold.

We identified these epochs as we aimed to use the accelerometer data as a proxy for the hypoxic state of an individual (as the headsets lacked pulse oximeter data). The motivation behind the identification of the first breath was based on previous research on intermittent hypoxia-based breathwork practices showing that blood oxygen concentration is lowest at the end of the breath hold sections (Kox et al., 2014). We therefore aimed to investigate whether these sections related to changes in neural complexity at the session-level.

2.6.4 Statistical Analyses

For each specific approach, linear mixed models were computed. In addition to this, generalised linear mixed models were computed for the exploratory data-driven approach, in order to input the neural features into the same model, investigating whether each variable may 'explain away' the effects of LZ complexity. In order to statistically model the experimental design of the study, we included subject, week, and session as nested random effects for each model. Results below are presented on data that has been centred and cleaned of outliers above and below 2.5 standard deviations of the mean LZ complexity. Further, to compare the outputs of the mixed models for the variety of LZ spatial complexity types, each LZ complexity variable was standardised so that the standard deviation was 1. Benjamini-Hochberg multiple comparisons were computed to

adjust the p-values of the models (Benjamini & Hochberg, 1995) using the *mulitcmp* function in MATLAB (Penn, 2023).

2.6.5 Exploratory Analyses

To further investigate associations between psychedelic neural signatures and subjective experience states, we explored the relationship between aperiodic and periodic components of the EEG power spectral density (PSD). We used the fitting oscillations and one-over-f toolbox (fooof; Donoghue et al., 2021), to model periodic and aperiodic components of the power spectra. The fooof toolbox models the offset and exponent of the neural power spectra, and identifies peaks in the signal corresponding to oscillatory power. This therefore distinguishes between oscillatory power and aperiodic components of the EEG PSD.

Peak frequencies were identified and categorised within the canonical frequency bands delta (1-4Hz), theta (4-8Hz), alpha (8-13Hz), and beta (13-30Hz). Gamma oscillations were excluded from this analysis as the data was low-pass filtered at 35HZ, and this frequency band may more likely reflect muscular activity in EEG (Muthukumaraswamy, 2013). Much like the LZ computation above, the relative oscillatory power was subdivided into spatial areas of the EEG device (Frontal with Frontal, Frontal with Occipital, Occipital with Occipital, and Global). The above computation was applied on each four second neural epoch. To bridge the gap between phenomenological data and oscillatory power, the median value of the components taken for

every seven neural epochs (equating to one phenomenological datapoint at 28 seconds) were input for further statistical analyses. If there were multiple oscillatory peaks within the same frequency band in the same neural epoch, the peak power was summed together[2]. While we conducted exploratory analyses for all frequency bands, we present results primarily for alpha power within this paper. This is due to the fact that a reduction in alpha oscillatory power is another robust neural signature of the psychedelic state (Valle et al., 2016; Timmermann et al., 2019; Pallavicini et al., 2019; Mediano et al., 2024).

Additionally, we explored the relationship between the aperiodic exponent and phenomenology. We intended to investigate the aperiodic exponent as psychedelics have a demonstrable impact at the broadband level (Muthukumaraswamy et al., 2013), and measuring the aperiodic exponent may tap in to physiological mechanisms that may be associated with breathwork (such as excitation/inhibition balance; Gao et al., 2017; Fincham et al., 2023a).

3. Results

In total, 301 breathwork sessions were included for phenomenological clustering (Week 1 = 88, Week 2 = 79, Week 3 = 73, Week 4 = 61). The hypothesis-driven statistical analyses were conducted on 146 sessions (Week 1 = 37, Week 2 = 49, Week 3 = 34, Week 4 = 26), data-driven statistical analyses were conducted on 204 sessions (Week 1 = 62, Week 2 = 60, Week 3 = 45,

[2] We acknowledge that separate peaks in the alpha frequency band may represent separate underlying neural mechanisms (Cohen, 2017). However, to simplify the interpretation of the results for the output of this paper, we focus purely on the relative power of the alpha frequency band through the summation of multiple oscillatory peaks if and when they occurred.

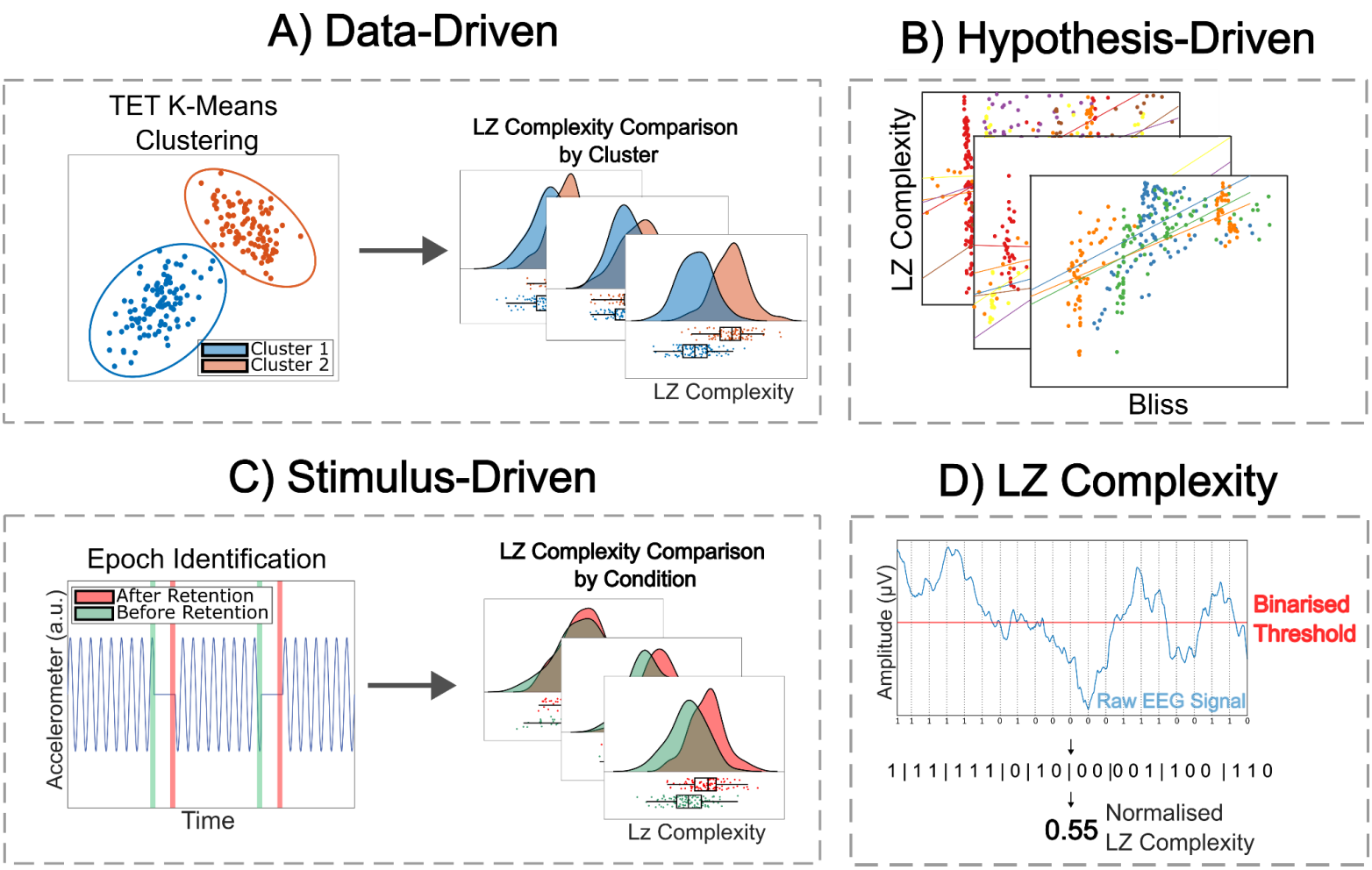


Figure 2: A schematic overview of the three analysis approaches. A) K-means clustering is applied to the TET data from all sessions, and linear mixed models are used to investigate the difference in LZ complexity between clusters, whilst factoring in the random variance of each session. B) Linear mixed models are used to compute the association between LZ complexity and the TET dimension 'bliss'. Each colour within one panel represents the bliss and LZ complexity data for one session within one week for one participant. The linear mixed models are based on evaluating the differing slopes for each individual session, thus factoring in the random variance of each subject, week, and session.. C) Epochs in which the participant took their first breath during the breath hold sections are identified using accelerometer data, and compared to an opposing epoch in a session-wise fashion (again using linear mixed models). D) A schematic illustrating the computation of LZ complexity. For an exemplary epoch of EEG data, the raw signal is converted into a binary score for whether each data point is above or below the binarised threshold. This binarised timeseries is then expressed through the length of a 'dictionary', in which a new dictionary

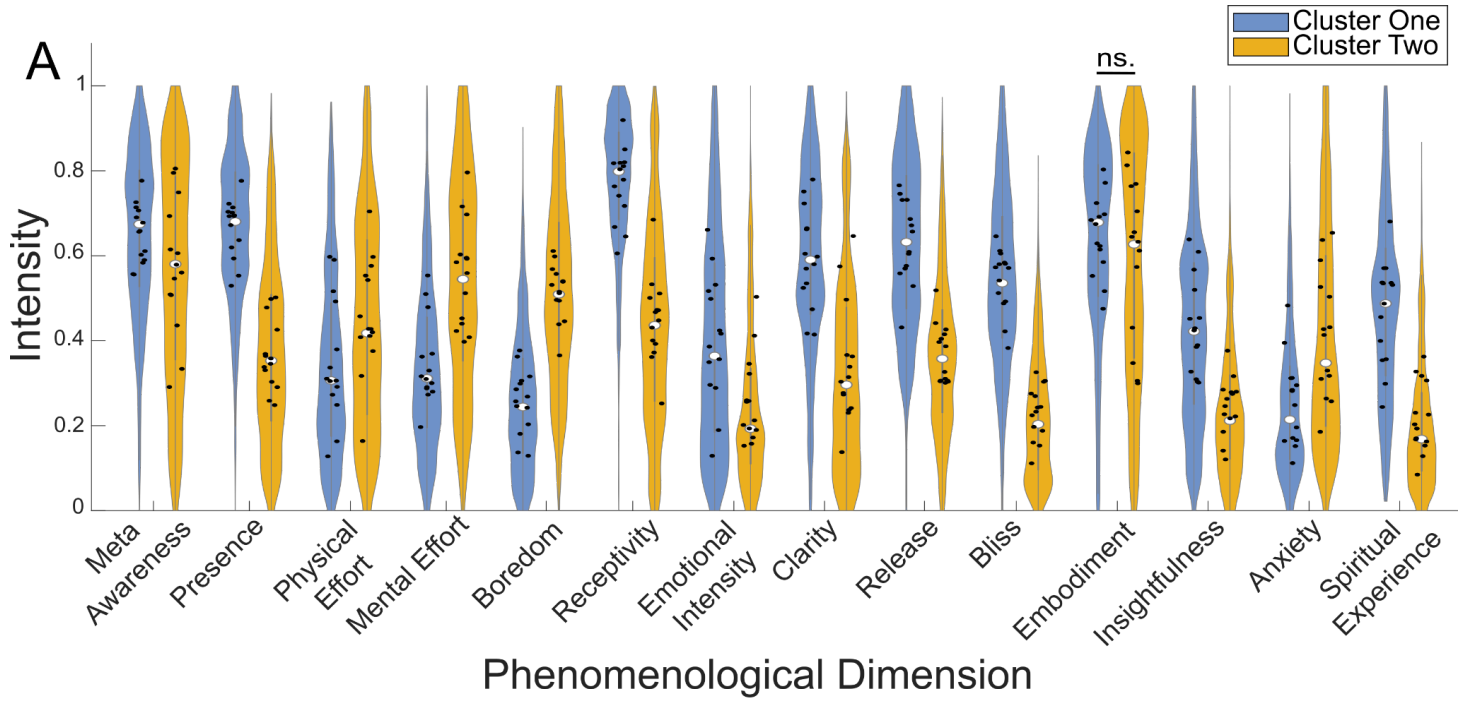
entry refers to a novel sequence within the timeseries. The length of the dictionary is the LZ score - analogous to the compressibility of the signal - which can be normalised by dividing this by the LZ score of the randomly shuffled epoch.

Week 4 = 37), and stimulus-driven statistical analyses were conducted on 201 sessions (Week 1 = 61, Week 2 = 59, Week 3 = 44, Week 4 = 37). For an overview of the number of sessions each subject contributed to the analysis, see Supplementary Figures S2-S5.

3.1 Data-Driven

3.1.1 K-means Extracted Two Phenomenological Clusters: One Loading onto Negative Physical and Mental Dimensions, the Other on 'Psychedelic-Like' Dimensions

K-means clustering was applied to the TET data for all breathwork sessions. The Calinski-Harabasz criterion (Calinski & Harabasz, 1974) found the optimal number of clusters to be two. Clusters were of approximately equal size (12,460 data points in cluster one; 11,660 data points in cluster two). Linear mixed models were computed to assess the difference between clusters on each phenomenological dimension. With the exception of Embodiment, all phenomenological dimensions were significantly different between clusters. Cluster two was significantly lower in the following dimensions (compared to cluster one): Meta-Awareness (-0.06, SE=0.015, $t(24,118)=-4.16$, $p<0.001$), Presence (-0.25, SE=0.011, $t(24,118) = -21.58$, $p<0.001$), Receptivity (-0.2, $t(24,118)=-15.72$, SE=0.012, $p<0.001$) , Emotional Intensity (-0.14, SE=0.012, $t(24,118)=-12.26$, $p<0.001$), Clarity (-0.18, SE=0.012, $t(24,118)=-15.66$, $p<0.001$), Release (-0.21, SE=0.012, $t(24,118)=-18.18$, $p<0.001$), Bliss (-0.24, SE=0.01, $t(24,118)=-23.15$, $p<0.001$), Insightfulness (-0.16, SE=0.01 $t(24,118)=-14.64$, $p<0.001$), and Spiritual Experience (-0.2, SE=0.01, $t(24,118)=-19.6$, $p<0.001$). Cluster two was significantly higher in Physical



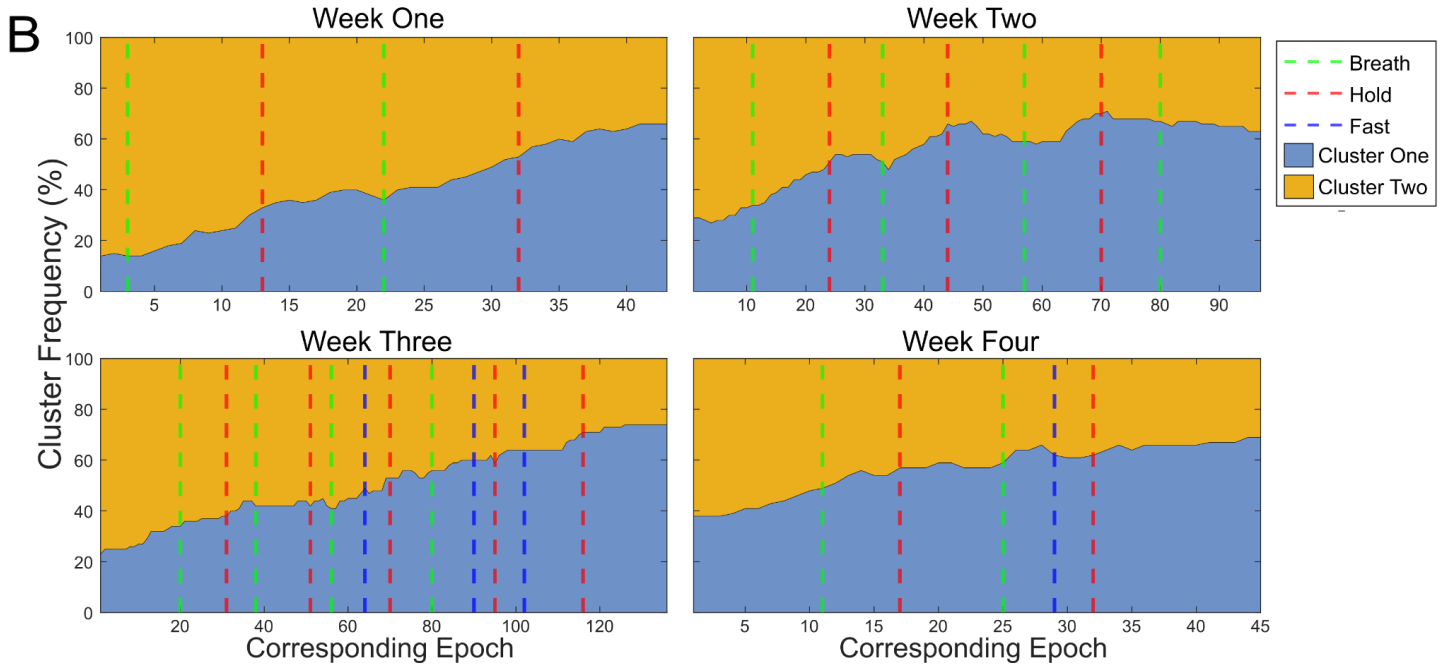


Figure 3: The breathwork session intensity (length) increased the likelihood of the 'psychedelic-like' cluster. A) Violin plots showcasing the data distributions for each phenomenological dimension per cluster. Excluding 'Embodiment', each phenomenological dimension was reliably different between clusters. Black filled circles are the mean intensity for each subject.

B) Sandbox plots representing the proportion of time spent in each phenomenological cluster by week. Participants were ~1.5x more likely to be in cluster one in week three when compared to week one.

Effort (0.07, SE=0.013, t(24,118)=5.28, p<0.001), Mental Effort (0.15, SE=0.012, t(24,118)=11.43, p<0.001), Boredom (0.17, SE=0.013, t(24,118)=13.77, p<0.001), and Anxiety (0.09, SE=0.001, t(24,118)=9.85, p<0.001) (see Supplementary Table S1 for outputs of each mixed model, and Figure 3A for the distributions of each phenomenological dimension by cluster). It is of note that bliss, insightfulness, and spiritual experience are all sub-components of Oceanic Boundlessness, which are strongly associated with the psychedelic experience (Roseman et al., 2018). Comparing these clusters therefore represents a multivariate and theory independent way to examine neural differences between (quantitative) phenomenological dimensions most associated with the psychedelic state.

3.1.2 The Breathwork Session Intensity (Length) Increased the Likelihood of the 'Psychedelic-Like' cluster

Based on the idea that phenomenology would be associated with the intensity of the breathwork session conducted (i.e., contextualised within a dose-response paradigm), we hypothesised that cluster one was more likely to appear in the more intense breathwork sessions (i.e., weeks two and three). When comparing weeks one and four with weeks two and three, the likelihood odds ratio (OR) that cluster one was more likely to occur than cluster two was 1.27 (95% CI [1.20, 1.34]). When comparing week one to week three, the OR that cluster one was more likely to occur than cluster two was 1.54 (95% CI [1.43, 1.67]). This suggests that the phenomenological cluster associated with psychedelic phenomenology is contingent on the intensity of the

breathwork session conducted. The temporal dynamics of each phenomenological cluster is visualised in Figure 3B.

3.1.3 Psychedelic-Like Phenomenological Cluster is Higher in Lempel-Ziv Complexity

To assess the difference in LZ complexity between phenomenological clusters, we computed linear mixed models for each spatial LZ complexity type, with Cluster as the predictor variable. In order to balance parsimony with complexity of the model, we used subject, week, and session as nested random factors, with week and the complexity type as fixed effects. Due to the high degree of correlation between the LZ complexity types (max correlation = 0.89), separate linear mixed models were computed for each spatial complexity type. All spatial complexity types showed that cluster two was significantly lower in complexity compared to cluster one: Frontal - Occipital (F-O) LZSum (-0.2, SE=0.044, $t(13,925)=-4.47$, $p<0.001$), Frontal - Frontal (F-F) LZSum (-0.19, SE=0.046, $t(13,972)=-4.07$, $p<0.001$), Occipital - Occipital (O-O) LZSum (-0.23, SE=0.043, $t(14,117)=-5.39$, $p<0.001$), Global LZSum (-0.25, SE=0.048, $t(13,868)=-5.18$, $p<0.001$), F-O LZc (-0.22, SE=0.046, $t(13,882)=-4.42$, $p<0.001$), F-F LZc (-0.15, SE=0.046, $t(13,975)=-3.3$, $p<0.001$), and Global LZc (-0.16, SE=0.043, $t(13,724)=-3.7$, $p<0.001$). The average session-level difference between clusters by week is visualised in Figure 4B.

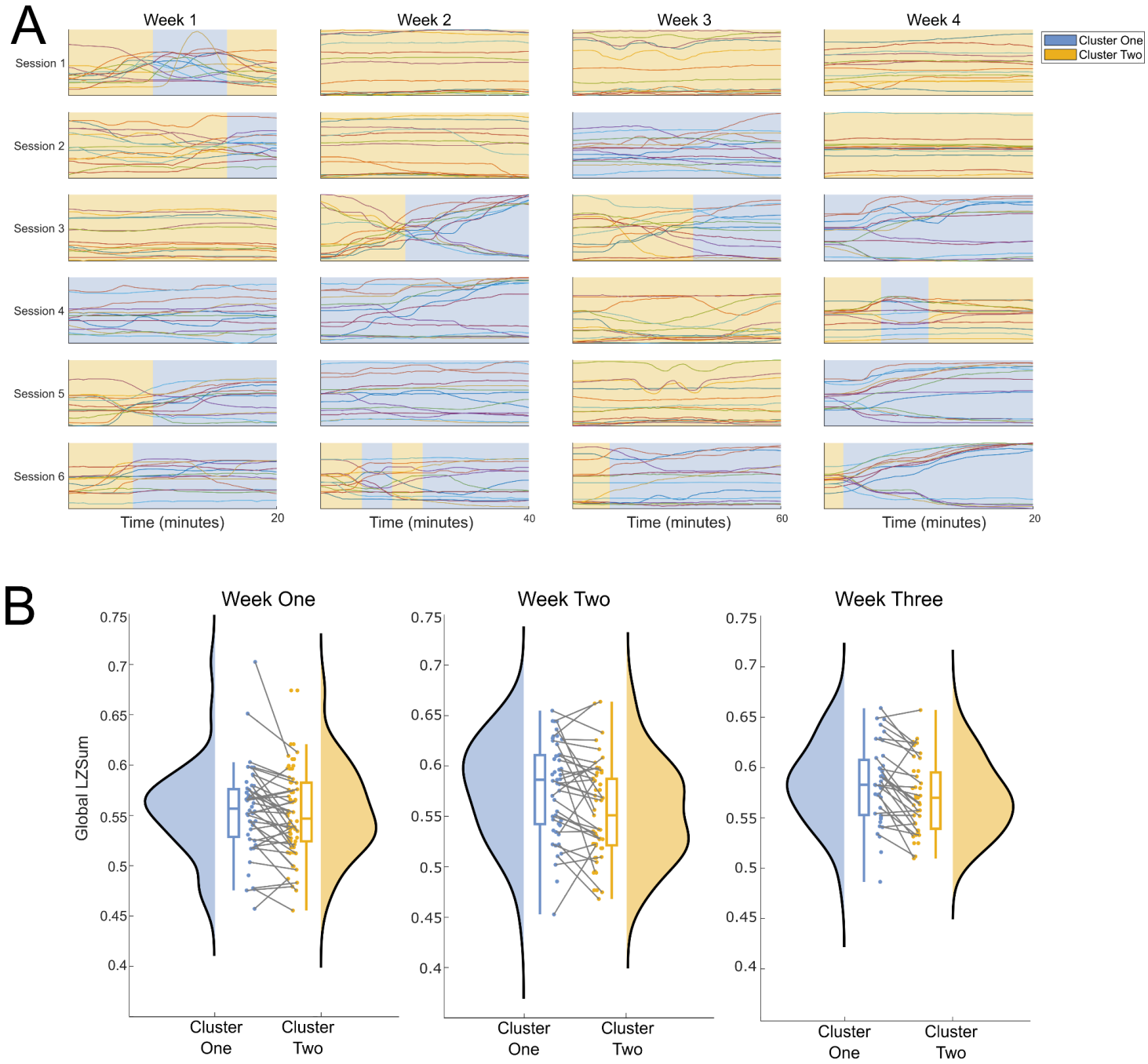


Figure 4: The psychedelic-like phenomenological cluster is reliably higher in LZ complexity across weeks. A) An example of the clustering algorithm as applied to each session for one participant. Each plot contains the TET data for each of the fourteen phenomenological dimensions, with the corresponding cluster identity shaded in blue or yellow for cluster one and cluster two respectively. B) Raincloud plots depicting the average Global LZSum values in a session-wise fashion for each phenomenological cluster show reliably higher complexity for cluster one compared to cluster two in every week. Each data

point is the average complexity value for each cluster within one session, with connecting lines depicting the complexity difference between clusters yet within sessions. For parsimony, only weeks 1-3 are shown here. Week Four can be found in Supplementary Figure S6.

3.2 Hypothesis-Driven

We assessed the association between the retrospectively rated intensity of bliss (as a proxy psychedelic-like phenomenological dimension) and neural complexity. As above, we statistically analysed this through the use of linear mixed models.

3.2.1 Bliss is Associated with Neural Complexity but not Modulated by the Intensity of the Breathwork Session

We first hypothesised that there would be an association between bliss and neural complexity, due to the fact that the phenomenological dimension of bliss is reliably increased as a function of psychedelic use (Hirschfield & Schmidt, 2021; Roseman et al. 2018). In order to assess this potential relationship, we used linear mixed models, with week and complexity type as fixed effects, and subject, week, and session as nested random effects. All complexity types were significantly associated with the phenomenological dimension of bliss, where an increase in bliss was associated with an increase in complexity at the population level: F-O LZSum (0.04, SE=0.006, $t(11,298)=6.24$, $p<0.001$), F-F LZSum (0.03, SE=0.008, $t(11,350)=4.06$, $p<0.001$), O-O LZSum (0.06, SE=0.007, $t(11,489)=8.61$, $p<0.001$), Global LZSum (0.04, SE=0.007, $t(11,248)=5.76$, $p<0.001$), F-O LZc (0.04, SE=0.005, $t(11,324)=7.02$, $p<0.001$), F-F LZc (0.03, SE=0.008, $t(11,349)=4.26$, $p<0.001$), and Global LZc (0.05, SE=0.007, $t(11,124)=6.81$, $p<0.001$).

In addition to this, we hypothesised that the type of breathwork session conducted, in terms of intensity, would modulate this relationship. That is, we hypothesised that the magnitude of association would increase as a function of the length of the breathwork session conducted. We tested this hypothesis through the inclusion of week as an interaction term. For these models, all main effects were significant, where an increase in bliss was associated with an increase in complexity at the population level: F-O LZSum (0.04, SE=0.013, $t(11,295)=3.24$, $p=0.004$), F-F LZSum (0.04, SE=0.016, $t(11,347)=2.62$, $p=0.02$), O-O LZSum (0.06, SE=0.014, $t(11,486)=4.22$, $p<0.001$), Global LZSum (0.04, SE=0.014, $t(11,245)=2.45$, $p=0.035$), F-O LZc (0.05, SE=0.01, $t(11,321)=4.84$, $p<0.001$), F-F LZc (0.04, SE=0.016, $t(11,346)=2.68$, $p=0.02$), and Global LZc (0.05, SE=0.02, $t(11,121)=3.81$, $p<0.001$). However, none of the interactions with week and spatial complexity types were significant, when comparing the magnitude of association to the first week (Supplementary Figure S7). This suggests that the phenomenological dimension of bliss has a consistent relationship with neural complexity across weeks of the breathwork course (Figure 5).

3.3 Stimulus-Driven

As a method to induce an ASC, the phenomenological and neural consequences of breathwork may be contingent on the physiological changes that underpin the practice. Previous research has found that blood oxygen saturation decreases as a function of breath retentions, with the lowest blood oxygen saturation at the point in which the participants take their first breath (Kox et al., 2014). While the EEG devices were not fitted with a pulse oximeter, accelerometer data was accessible. Therefore, we used data from the z-axis of the accelerometer to identify timepoints in

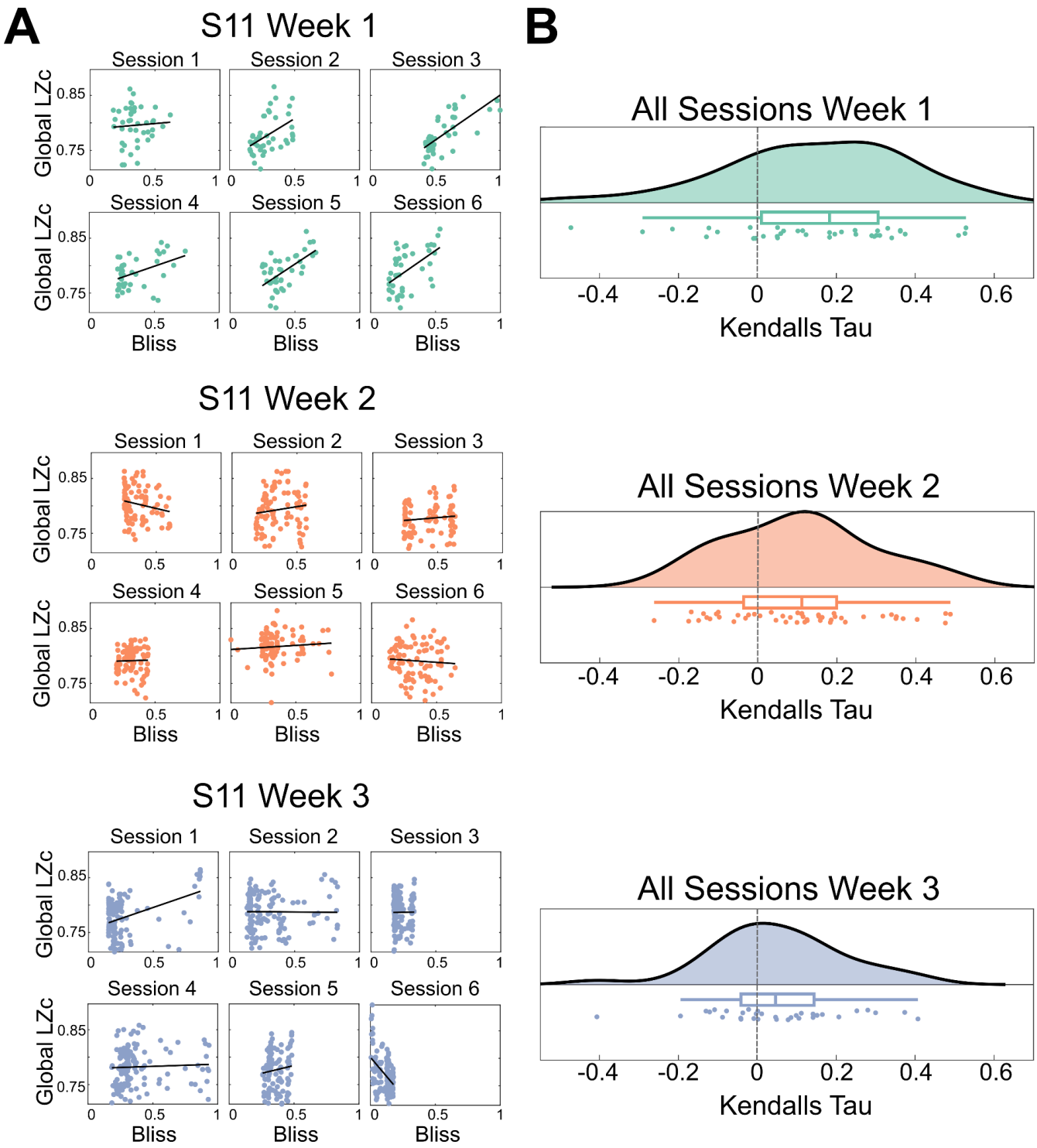


Figure 5: There is a consistent and positive relationship between bliss and LZ complexity for all weeks. A) Scatterplots of bliss and Global LZc for the first six sessions of eeeks 1-3 for subject 11. Lines of best fit were plotted with *lsline* in MATLAB. Plotting the individual sessions highlights the variability between sessions within participants, but exemplifies the enduring positive association between bliss and LZ complexity. B) Raincloud plots highlighting the distribution of every session separated

by week. Each data point is the strength of association (Kendall's tau) between bliss and Global LZc. While there is no systematic difference between association strength across weeks, the plots highlight that there is a general trend towards positive bliss and Global LZc correlations. For the sake of parsimony, only weeks 1-3 are shown.

which the participant took their first inhalation after engaging with the breath hold conditions during the breathwork sessions (explained in Methods).

3.3.1 Breath Retentions are Associated with a Small Increase in Lempel-Ziv Complexity

Linear mixed models were used to assess the difference in LZ complexity before and after breath retention. LZ complexity was higher following the breath hold in comparison to the epoch prior to the breath hold commencing in O-O LZ (0.18, SE=0.034, $t(1,037)=5.27$, $p<0.001$), F-O LZc (0.16, SE=0.039, $t(1,018)=4.06$, $p=0.002$), and Global LZc (0.11, SE=0.034, $t(1,011)=3.08$, $p = 0.037$). This tentatively suggests that the breath retentions during the sessions are associated with an increase in neural complexity.

Based on the idea that blood oxygen saturation may be associated with neural complexity changes, we hypothesised that neural data associated with the period in which the participant took their first breath after a breath retention would be significantly different in LZ complexity compared to neural data associated with the period before the start of the breath hold. Further to this, we hypothesised that the strength of the difference would increase as a function of the intensity of the breathwork session conducted (i.e., peaking at week 3). However, when running linear mixed models with week as an interaction term, none of the main effects for any spatial complexity type were significant. Further to this, no interaction terms were significant after FDR

correction. This suggests that the complexity differences may be explained away by week as a moderator of the effect.

3.3.3 Lempel-Ziv Complexity is Modulated by the Amount of Breath Holds

Kox et al. (2014) found that blood oxygen saturation reduces as a function of the amount of breath holds completed within one session. Based on this, we included the breath hold number as an interaction term within linear mixed models for each spatial complexity type. None of the main effects for any spatial complexity type were significant. However, F-O LZc was significant for the interaction terms for the third breath hold (0.32, SE=0.11, $t(1,007) = 2.88$, $p = 0.047$) and the fifth breath hold (0.64, SE=0.168, $t(1,007) = 3.83$, $p = 0.003$), while the interaction term for the fifth breath hold was significant for O-O LZ (0.42, SE=0.156, $t(1,026) = 2.96$, $p = 0.04$). These findings further tentatively suggest that LZ complexity may be associated with the hypoxic conditions associated with breathwork. However, further analyses may be required to more clearly elucidate this relationship. The session-level differences for O-O LZ complexity are visualised in Figure 6.

3.4 Exploratory Analysis: Periodic and Aperiodic Neural Signal Components.

As we found positive results highlighting neurophenomenological associations with psychedelic-like subjective experience states and LZ complexity, we aimed to explore further neurophenomenological associations that may be more closely associated with psychedelic neural signatures. Based on the above results demonstrating that there is an increase in LZ complexity in association with bliss and multi-dimensional phenomenological clusters high in subjective experiences closely linked with the psychedelic state, we explored how

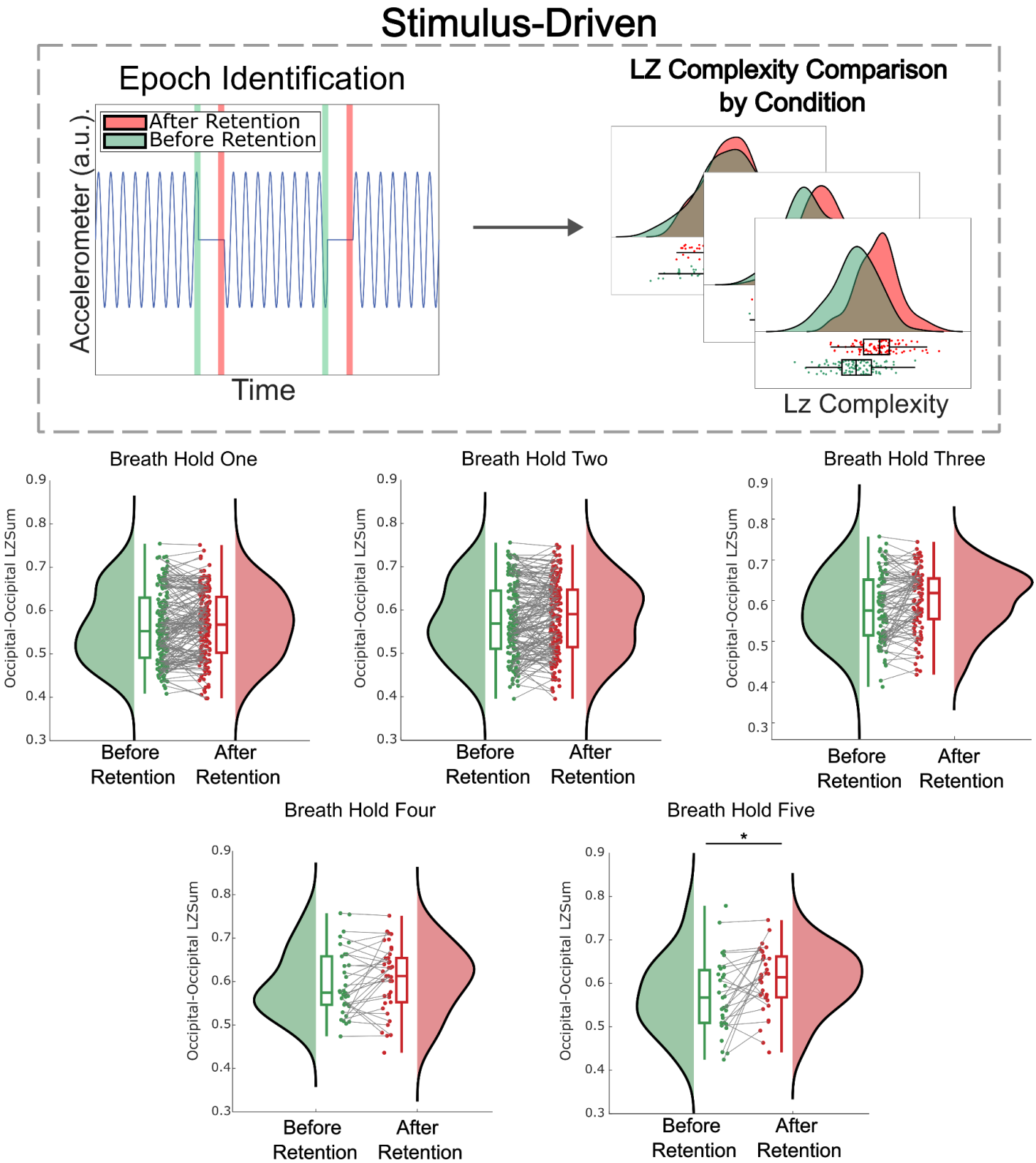

Stimulus-Driven
Epoch Identification
After Retention
Before Retention
Accelerometer (a.u.)
Time
LZ Complexity Comparison by Condition
Lz Complexity
Breath Hold One
Breath Hold Two
Breath Hold Three
Breath Hold Four
Breath Hold Five
Occipital-Occipital LZSum
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Before Retention
After Retention
*

Figure 6: Differences in LZ complexity are heightened due to the amount of breath holds a participant completes during the session. The below raincloud plots are session-level comparisons of occipital-occipital neural complexity both before retention and after retention for each breath hold. As participants increase the number of breath holds, there is a larger difference in neural complexity, with a significant interaction effect for breath hold number five. *$p<0.05$ FDR corrected.

phenomenology and LZ complexity may relate to aperiodic and periodic components of the EEG PSD.

Based on previous research demonstrating that serotonergic psychedelic administration is associated with a reduction in alpha power (Ville et al., 2016; Pallavicini et al., 2019; Timmermann et al., 2019), we hypothesised that alpha power is negatively associated with the psychedelic-like phenomenological cluster, and the phenomenological dimension of bliss. In addition to this, based on previous research highlighting that LZ complexity outperformed alpha power when correlated with the subjective effects of psilocybin (Mediano et al., 2024), we also hypothesised that the neurophenomenological associations between bliss and LZ complexity will not be explained away by alpha power.

3.4.1 Alpha Power is Not Robustly Associated with Phenomenological Cluster or Bliss

As above, we computed a variety of linear mixed models, increasing in model complexity (Supplementary Table S2), to explore the potential differences between phenomenological clusters in alpha oscillatory power. Most models did not reach (uncorrected) levels of significance at the alpha criterion of 0.05, suggesting that the phenomenological clusters are not robustly associated with alpha power. Further to this, when using the hypothesis-driven approach, most linear mixed models did not find any significant associations between alpha

oscillatory power and the phenomenological dimension of bliss (Supplementary Table S3). These results together suggest that there are no robust neurophenomenological associations between alpha oscillatory power and psychedelic-like phenomenology.

3.4.2 Reduction in Alpha Power and Increase in Global Complexity for Most Breathwork Conditions Compared to Baseline

Due to the lack of robust associations between phenomenology and alpha power, we also explored how alpha power changed as a function of the condition the participant was in. We found that, when compared to the introduction of the session, alpha power was significantly lower in the Breath (-0.106, SE=0.044, $t(13,322) = -2.39$, $p=0.024$) , Rest (-0.216, SE=0.054, $t(13,322) = -3.99$, $p <0.001$), and End (-0.273, SE=0.061, $t(13,322) = -4.43$, $p<0.001$), portions of the breathwork sessions. Similarly, when compared to the introduction of the session, Global LZc increased for the Breath (0.15, SE=0.039 $t(13,723) = 3.83$, $p <0.001$), Hold (0.228, SE=0.041, $t(13,723) = 5.57$, $p<0.001$), Rest (0.286, SE=0.041, $t(13,723) = 6.87$, $p<0.001$), and End (0.36, SE=0.048, $t(13,723) = 7.41$, $p<0.001$) conditions, and Global LZSum increased for all conditions: Breath (0.32, SE=0.039 $t(13,867) = 8.22$, $p <0.001$), Hold (0.434, SE=0.039, $t(13,867) = 11.25$, $p<0.001$), Rest (0.39, SE=0.043, $t(13,867) = 9.03$, $p<0.001$), Fast (0.335, SE=0.058, $t(13,867) = 5.8$, $p<0.001$) and End (0.505, SE=0.049, $t(13,867) = 10.41$, $p<0.001$). The data distributions of these are visualised in Supplementary Figure S8. These results concord with similar lines of research demonstrating that alpha power reduces, and LZ complexity increases, as a function of psychedelic administration (Mediano et al., 2024; Schartner et al., 2017; Timmermann et al., 2019; Pallavicini et al., 2019).

3.4.3 Exponent, but Not Alpha, is Associated with Phenomenological Cluster and Bliss

Contextualising these results within a neurophenomenological approach, we explored the potential relationships between (i) Global LZ complexity, (ii) alpha oscillatory power, and (iii) exponent of the PSD as predictor variables, and phenomenological cluster and bliss as response variables. We computed these models to explore whether the exponent of the PSD may also be predictive of both uni-dimensional and multi-dimensional phenomenology. Both Global LZc (0.015, SE=0.006, $t(10,298) = 2.70$, $p = 0.011$) and Global LZSum (0.019, SE=0.007, $t(10,448) = 2.7$, $p = 0.009$) were significantly associated with bliss. However, only Global LZsum was significantly predictive of the phenomenological cluster (-0.313, SE=0.146, $t(12,766) = -2.15$, $p = 0.045$). The aperiodic exponent was significantly associated with bliss (-0.04, SE=0.005, $t(10,298) = -7.43$, $p< 0.001$), and phenomenological cluster (0.72, SE=0.116, $t(12,607) = 6.25$, $p<0.001$). Alpha power was not significantly associated with phenomenological cluster or bliss. Figure 7 displays the average difference in exponent at the session level, when parsing the data by week.

3.4.4 No Change in Exponent for Breath Holds

Finally, to explore whether the exponent could successfully distinguish between hypoxic states and non-hypoxic states (as induced by breath holds), we computed linear mixed models in line with the stimulus-driven approach as above, but using the aperiodic exponent as response variables instead of LZc. However, the analysis did not outperform the complexity analyses (as computed above).

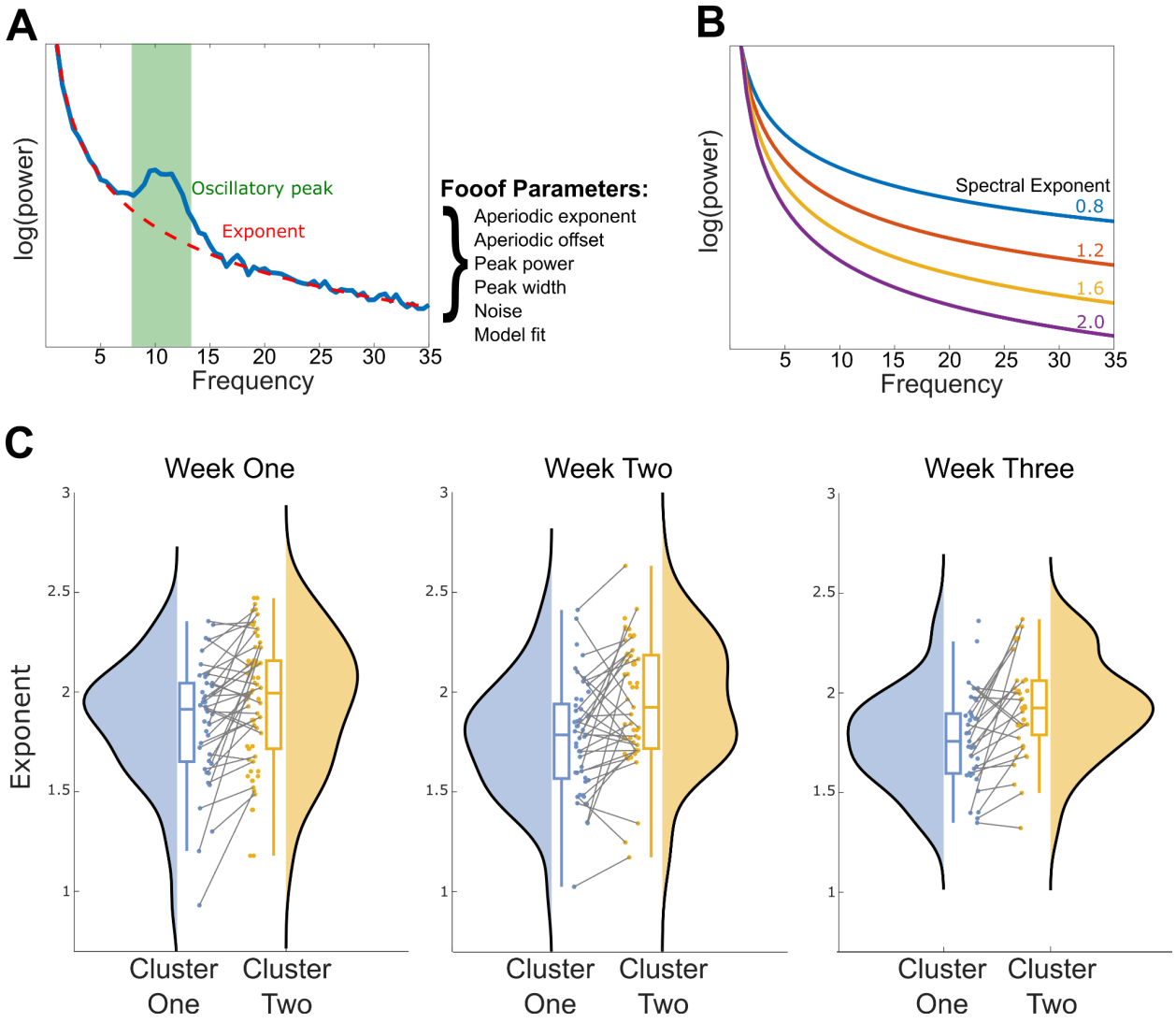


Figure 7: The aperiodic exponent of the PSD shows similar differences between clusters as LZ complexity, where the psychedelic-like cluster (cluster one) is consistently lower in the aperiodic exponent. A) A schematic illustration of the fitting oscillations and one over f (fooof) toolbox. An exemplary neural power spectral density is modelled through the parameterisation of various phenomena, including the aperiodic exponent and the oscillatory peak power. Within this study, we identified neural oscillations as well as parameterised the aperiodic exponent of each neural epoch. B) A schematic example of four separate aperiodic exponent parameters. A higher aperiodic exponent entails a PSD that decays quicker at higher frequencies. C) Session level differences between the average aperiodic exponent for cluster one and cluster two. Cluster one consistently displays a lower aperiodic exponent in comparison to cluster two, even when averaging the data at the session-level.

4. Discussion

In a large-scale neurophenomenological analysis of breathwork as a non-pharmacological ASC, we present several overarching findings; First, we show that phenomenological intensity can be quantitatively captured over time within predetermined dimensions of experience using Temporal Experience Tracing (TET). Second, that these breathwork-induced experiences separate into two distinct clusters, a positive 'psychedelic-like' cluster, and a negative phenomenological cluster loading onto boredom and physical/mental effort. Third, these distinct phenomenological clusters were also separable at the neural level, with the positive psychedelic-like cluster higher in LZ complexity. Finally, while the relationship between LZ complexity and proxy hypoxic state was less robust, we found positive associations between neural complexity and the phenomenological dimension of bliss. When conducting exploratory analyses, we found that alpha power did not yield any robust neurophenomenological correlates using our previous approaches, contrary to previous research with psychedelics (Timmermann et al., 2019; Mediano et al., 2024). However, the aperiodic exponent of the PSD followed similar neurophenomenological associations as LZ complexity, and was higher within the psychedelic-like subjective experience cluster.

4.1 The Cognitive Neuroscience of Breathwork

Despite its rich history within Eastern spirituality, the investigation of high-ventilation breathwork practices, where an individual increases their respiratory rate, is in its infancy within contemporary science (Fincham et al., 2023a), with very few studies exploring the neural underpinnings of the practice. Moreover, much like meditation as a broad taxonomic term (Tang et al., 2015; Lutz et al., 2008), breathwork constitutes a plethora of practices, each with their own distinct phenomenological and physiological profiles and goals (see Fincham et al., 2023a for a

review). SOMA breathwork, used within this study, is similar to the Wim Hof method (Kox et al., 2012; 2014), in that it utilises a continuous and standardised breathing pattern in combination with breath retentions to induce a hypoxic state. Both practices have roots in g-tummo meditation (Benson et al., 1982; Benson et al., 1990), a practice from Vajrayana Buddhism combining breathwork and meditation which can induce large core body temperature increases (Benson et al., 1982). Kozhevnikov et al. (2013) tested the neural and physiological effects of g-tummo meditation in expert practitioners in Tibet, and showed that core body temperature increases were strongly associated ($r = 0.82$) with increases in alpha power. Within our study, we did not find similar increases in alpha power as a consequence of the practice. Contrarily, alpha power decreased in the Breath, Rest, and End conditions, when compared to the introduction of the session as a resting-state baseline (with no breathwork-based instructions; Supplementary Figure S8). These discrepant results may be due to (i) the potential differences in phenomenological and physiological goals of each practice, and (ii) the expert nature of the participants within Kozhevnikov et al. (2013).

In addition to the above, a recent study investigated the phenomenological and neural effects of conscious connected breathing (Bahi et al., 2023). Unlike the modality practised within this study, conscious connected breathing comprises an unbroken series of inhalations and exhalations, with its rhythm guided by the practitioner. The researchers examined power in the canonical frequency bands, finding decreases in delta, theta, beta 1 (12-15Hz) and beta 2 (15-20Hz) when comparing pre- and post-breathwork resting state data. While the researchers did not investigate neural signal diversity or aperiodic components of the PSD, comparing the neural findings to the current study we only found a decrease in alpha power when comparing

the end of the breathwork session to the uninstructed introduction portion (Supplementary Figures S8 and S9). However, it must be noted again that these are two distinct practices, which may yield separate neurophysiological and phenomenological profiles. These potentially discrepant findings reinforce the necessity to continue investigating the potential neural and phenomenological differences between breathwork modalities.

4.2 Nonlinear Neural Metrics Supersede Oscillatory Alpha Power Regarding Neurophenomenological Associations

There is an increasing body of research showing that signal diversity is a robust neural marker that can distinguish between conscious states, such as sleep (Schartner et al., 2017; Aamodt et al., 2021; 2023; Pascovich et al., 2022), anaesthesia (Schartner et al., 2015; Varley et al., 2020b; Pal et al., 2020), and psychedelic administration (Schartner et al., 2017; Timmermann et al., 2019; Mediano et al., 2020; Timmermann et al., 2023b; Pascovich et al., 2022). Additionally, LZ complexity maps on to differences in the perceptual contents of consciousness in bistable paradigms (Canales-Johnson et al., 2020; 2023). However, it remains difficult to disentangle the relationship between the *contents* of consciousness and neural signatures outside of strict task-based paradigms (e.g. Aamodt et al., 2021; 2023). Within the present study, we were able to reveal associations between nonlinear neural markers and subjective experience states during breathwork sessions. This may be due to the comparatively large amount of data collected per participant, both in terms of the number of sessions collected and the temporal granularity of TET compared to likert scales. Interestingly, both LZ complexity and the exponent of the PSD were associated with the contents of consciousness within breathwork, where previous research

was focused primarily on the subjective intensity of a psychedelic experience (Schartner et al., 2017; Timmermann et al., 2019).

Unlike the parameterization of oscillatory activity, both LZ complexity and the aperiodic exponent are nonlinear -more encompassing- measures of EEG signals, they may be tapping into the same underlying neurophysiological mechanism; LZ complexity is a quantification of the number of novel patterns within a timeseries, decreasing when the EEG signal is more predictable. LZ complexity changes within ASCs may be related to a change in the aperiodic exponent of the PSD, demonstrated by Colombo et al. (2018), as many of these reduced conscious states are characterised by a dominance of periodic low frequency activity, thus contributing to a more predictable neural signal (lower in LZ complexity) (however see Frohlich et al., 2023 for a discrepant result). Conversely, it has been found that changes in LZ complexity within the psychedelic state have been ascribed to increases in high-frequency (>25Hz) activity (Mediano et al., 2023), with broadband spectral changes across a variety of psychedelic substances (Muthukumaraswamy et al., 2013; Carhart-Harris et al., 2016; Pallavicini et al., 2019), thus implicating a change in aperiodic activity. Muthukumaraswamy & Liley (2018) supported this notion in a pharmaco-MEG study, finding that low frequency (0.1-2.5Hz) activity decayed quicker, and high frequency activity (5-100Hz) decayed slower under the influence of both the serotonergic agonist psychedelic LSD and the NMDA receptor antagonist ketamine compared to placebo. Our results concord with this line of research, as we found that LZ complexity and the aperiodic exponent were inversely related, with both yielding robust neurophenomenological associations with the psychedelic-like phenomenology of breathwork.

Relating these findings to the physiology of breathwork, some researchers have theorised that hypoxia and alkalosis induced through 'high-ventilation' breathwork practices may cause a shift towards excitability in the excitation/inhibition (E/I) balance (Fincham et al., 2023a), due to the disinhibition of GABAergic inhibitory cortical circuits (Sun et al., 2012; Li et al., 2012). A flattening of the PSD has been ascribed as a marker of a neurophysiological shift towards excitability (Donoghue et al., 2021; Gao et al., 2017), demonstrating that the results in the present study support the aforementioned hypothesis with regards to E/I balance. However, other neuroimaging modalities at finer spatial scales (such as ECoG/LFP) are required in order to more fully understand how E/I balance at multiple scales relate to the aperiodic exponent (Ahmad et al., 2022), with some researchers unconvinced by this relationship (Muthukumaraswamy & Liley, 2018).

4.3 Proxy Hypoxic State Not Robustly Associated with LZ Complexity

Experimental evidence has previously demonstrated how respiration is dynamically coupled with perception, action, and the brain; respiration is tied to reaction times in sensory-cognitive paradigms (Johannknecht & Kayser, 2022; Nakamura et al., 2018), and modulates neural oscillatory activity in animal models (Zelano et al., 2016; Ito et al., 2014; Karalis & Sirota, 2022). Further to this, physiological states and interoception are becoming increasingly integrated with theories of emotion, cognition, and conscious experience (Seth, 2013; Seth et al., 2012; Tsakiris & Critchley, 2016). Based on these strong interplays between respiration, cognition, and neural dynamics, we hypothesised that neural complexity would be influenced by the (proxy) hypoxic state. However, using the analysis approach above, we only found significant differences in occipital-occipital LZ complexity, frontal-occipital LZc, and global

LZc between breath holds, where there was a small increase in complexity after breath retention as compared to before. Further to this, when assessing the differences in breath holds as a function of how many breath holds were conducted that session, F-O LZc yielded strong and significant differences in breath holds three and five, while O-O LZ complexity yielded significant differences in breath hold five. These results suggest a relationship between the physiological state of the participant and neural complexity, However, the results of this approach were not as robust as the neurophenomenological associations.

We may therefore speculate that the lack of robust associations could be related to the relatively 'discrete' analysis approach; within our analysis we identified relative hypoxic epochs through accelerometer data during the breath hold conditions, comparing these to EEG epochs immediately prior to the beginning of that specific breath hold phase, on a session-by-session basis. However, there may be more pronounced effects of hypoxic breath holds over longer temporal scales, or they may more likely influence other neural markers, such as whole-brain connectivity (Annen et al., 2021), more robustly. Further analysis on this dataset may therefore reveal more complex nonlinear relationships between physiological state, neural signatures and phenomenology.

4.4 Moving Forward in Neurophenomenological Research

Much of the previous research evaluating relationships between subjective experience in ASCs and neural signatures has adopted a uni-dimensional phenomenological approach, in that associative metrics are applied between a single phenomenological dimension and a neural feature of interest (e.g., Bahi et al., 2023; Timmermann et al., 2019; Schartner et al., 2017).

However, theoretical work emphasises that ASCs such as psychedelics are phenomenologically multi-dimensional (Bayne and Carter, 2018; Fortier-Davy & Milliere, 2020). Applying k-means clustering to the TET data permitted the extraction of such multi-dimensional phenomenological substates, allowing us to distinguish how the contents of consciousness relates to neural dynamics. What is noteworthy is that, despite the relatively simplistic and 'coarse' analysis approach in the clustering of phenomenology within this study (k-means clustering is a straight-forward technique, finding roughly equal cluster sizes), we found robust neurophenomenological correlates. It should be emphasised that more sophisticated techniques may be used to cluster phenomenological data into, for example, uneven sizes (Bezdek et al., 1984), or into path trajectories (Bengochea et al., 2023; Malkinson et al., 2021). While we plan to implement more complex clustering approaches in future analyses of this dataset, a simple preliminary approach was necessary to form a more fundamental understanding of this breathwork modality as a novel and understudied ASC.

It is also interesting to speculate how TET may be applicable in the neuroscience of psychedelics and other ASCs, to further distinguish between the contents of consciousness elicited by these manipulations. The phenomenological (and neurophysiological; Mediano et al., 2024) consequences of psychedelics are not only determined by their pharmacology, but also by 'external' factors such as emotional state and environmental setting (Hartogsohn, 2017; Carhart-Harris et al., 2018). The application of TET combined with the modulation of these external factors may allow researchers to disentangle how the phenomenological dynamics change under specific factors, contributing to a more nuanced understanding of psychedelics. Further, when embedded within a psychedelic-assisted psychotherapy (PAP) paradigm, TET may

track long-term symptom dynamics (Niedernhuber et al., 2023), moving away from discrete sampling and towards a more comprehensive approach to the study of mental health disorders (Lewis-Healey et al., 2022). Additionally, within our study, one cluster was phenomenologically similar to an extracted cluster in a previous study on meditation using TET (Jachs et al., 2022), high in the intensity of boredom and effort. Applying TET in future studies may also allow researchers to compare and contrast similar multidimensional phenomenological substates across ASCs, thus identifying converging neural markers and contributing to a more refined taxonomy of altered states.

We therefore hope that the application of TET may successfully push forward the field of neurophenomenology. Data-driven approaches with TET may provide the 'reciprocal constraints' between first-person experiential and third-person physiological measures, whilst the ability to have both phenomenological and neural data in the same analytical quantitative space can "narrow the epistemological and methodological distance in cognitive neuroscience between subjective experience and brain processes" (Lutz & Thompson, 2003, p.49).

4.5 How Phenomenologically Similar is Breathwork to 'Psychedelic States'?

With the ostensible neurophenomenological similarities between psychedelics and breathwork, one overarching question arises from this study: how similar *are* these states at the phenomenological level? Although arguably much more informative than likert scale questionnaires, TET remains a reductionist approach to the study of subjective experience. While one phenomenological cluster yielded similarities to positive psychedelic phenomenology (Hirschfield & Schmidt, 2021) and neural markers of psychedelics (Schartner et al., 2017;

Timmermann et al., 2019), there are most likely a variety of phenomenological distinctions between the two states, much like the phenomenological nuances between different psychedelics (Shinozuka et al., 2023). It may thus be more useful to characterise this breathwork modality, along with psychedelics, as a 'high-arousal' ASC, rather than 'high-relaxation', as has been previously suggested as a useful taxonomic category for Eastern spiritual practices (Amihai & Kozhenivkov, 2014; 2015). We therefore emphasise the necessity of analysing and integrating qualitative phenomenological data into future studies of ASCs, as this has previously been successful in highlighting similarities between, for example, psychedelic and near-death experiences (Martial et al., 2019; Timmermann et al., 2018), and may serve as a useful foundation for phenomenological understanding (Lawrence et al., 2022).

4.6 Clinical Future Directions

While our study is primarily a neurophenomenological investigation, future researchers may wish to investigate the effects of breathwork as a potential clinical intervention. While we remain in relatively seminal research stages, evidence is increasingly highlighting the transdiagnostic clinical efficacy of PAP (Goodwin et al., 2022; Carhart-Harris et al., 2021; Bogenschutz et al., 2022; Gukasyan et al., 2022). Previous research has also pointed towards the importance of the phenomenology of the psychedelic experience within a PAP framework (Yaden & Griffiths, 2020), showing that it may be predictive of clinical outcomes (Garcia-Romeu et al., 2015; Roseman et al., 2018; Ko et al., 2022; however, see Olson, 2020). Further to this, in a recent meta-analysis, Fincham et al. (2023b) found that breathwork interventions may be associated with moderate-to-small differences in stress, depression, and anxiety when compared to controls (in non-clinical populations). Due to the potential neural and phenomenological similarities

between breathwork and the psychedelic experience highlighted within the current study, we advise researchers to investigate breathwork as a potential non-pharmacological clinical intervention that may be utilised similarly to PAP, with care and investigative attention given towards phenomenology, set and setting (Hartogsohn, 2017; Carhart-Harris et al., 2018), and embedding the experience(s) within a psychotherapeutic paradigm (Gründer et al., 2023).

4.7 Limitations

While this study leverages a powerful within-participant design, as well as temporal phenomenological dynamics in a neurophenomenological paradigm, a number of limitations should be mentioned. First, we may not be sure to what degree the phenomenology elicited here is due to the elements of respiratory modulation within breathwork as a practice; we do not, for example, have a control group (Szigeti et al., 2021). While we did not deem it necessary to do so within this neurophenomenological study, it may be necessary for future clinical trials investigating breathwork. Much like clinical psychedelic and meditation research (Nayak et al., 2023; Muthukumaraswamy et al., 2021; Van Dam et al., 2018), ample thought is required regarding what sufficient controls and blinding would look like within trials investigating the clinical efficacy of breathwork.

Second, at the inception of this study, there was very little phenomenological research investigating breathwork as an ASC. Due to this, the phenomenological dimensions used for the TET data were decided upon based on (i) previous research with ASCs (Studerus et al., 2010), (ii) the primary author's completion of the breathwork in an ethnographic and phenomenological research style, and (iii) conversations with experienced breathwork practitioners regarding

phenomenology. However, there may be phenomenological elements central to the practice that may have been missed, such as the intensity of felt bodily sensations due to the somatic nature of the practice. We therefore present the phenomenological dimensions here as an overarching yet incomplete overview of this breathwork modality, and reiterate the necessity of the collection of qualitative data.

One final limitation of the present study is the low-density nature of the EEG headsets used. A lack of spatial information with regards to neural markers here prevents us from drawing further similarities between breathwork and psychedelics at the neural level. For example, functional connectivity measures have been extensively investigated in the literature on psychedelics (Barnett et al., 2020; Tagliazucchi et al., 2016; Carhart-Harris et al., 2017). With a limited number of channels in the EEG headset, more comprehensive functional connectivity analyses would not be applicable to this dataset. However, the application of these portable EEG headsets facilitated the large-scale data collection within this study, leading to robust neurophenomenological associations.

5. Conclusion

In summary, our study demonstrates how breathwork may yield neural and phenomenological consequences similar to serotonergic psychedelics. An increase in LZ complexity was associated with psychedelic-like subjective experience states, when investigated in a phenomenologically unidimensional and multidimensional manner. In exploratory analyses, we found that the exponent of the neural PSD was also strongly associated with psychedelic-like phenomenology, whereas alpha oscillatory power did not demonstrate robust neurophenomenological

associations. While further research is required to gain a more comprehensive mechanistic understanding of breathwork as an ASC, our findings and experimental framework set a path to simultaneously evaluate neural and phenomenological dynamics. We therefore encourage researchers to further explore the effects of breathwork at the subjective and neural level, and how it may be implemented as a non-pharmacological ASC within clinical paradigms.

Acknowledgements

We wish to thank Vanessa Potter for help in shaping the experiential dimensions of this project. We also wish to thank Niraj Naik for creating the breathwork course used within this study, and for providing online instruction and guidance for participants' throughout the study. This work was supported by PJJR.GAAA to Tristan Bekinschtein and an ESRC DTP fellowship to Evan Lewis-Healey.

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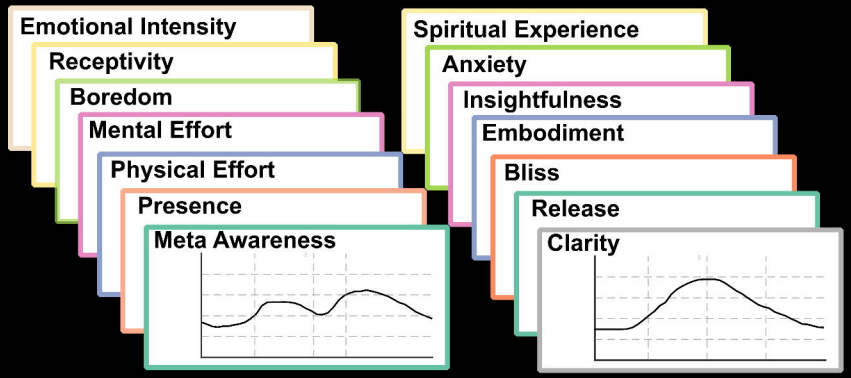
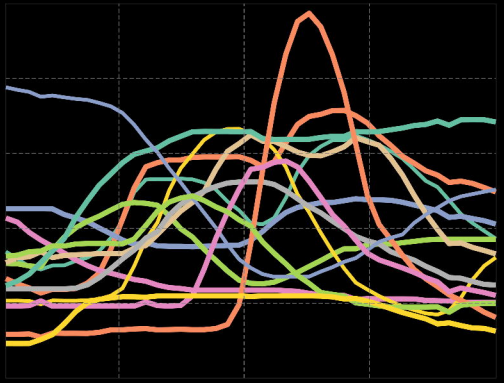
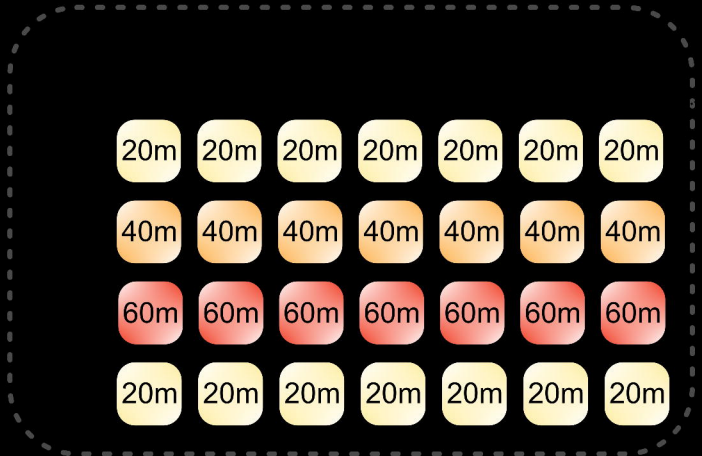
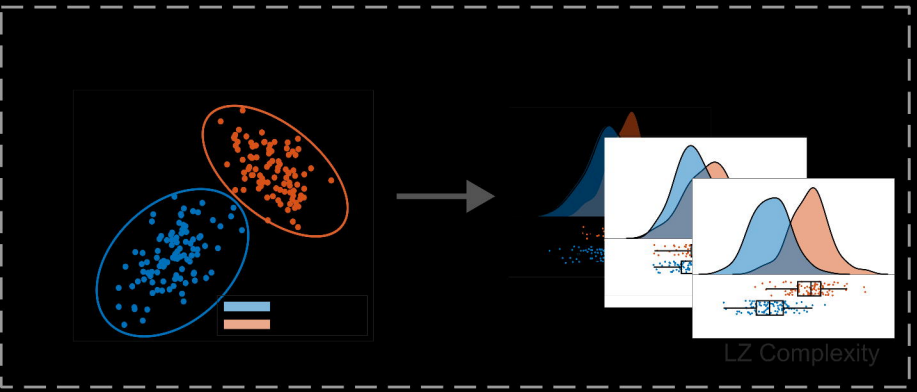






TET Traces
Portable EEG Data
Accelerometer Data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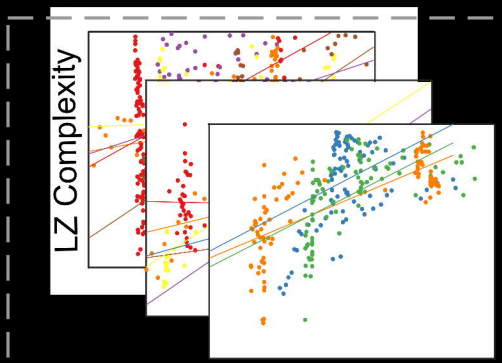
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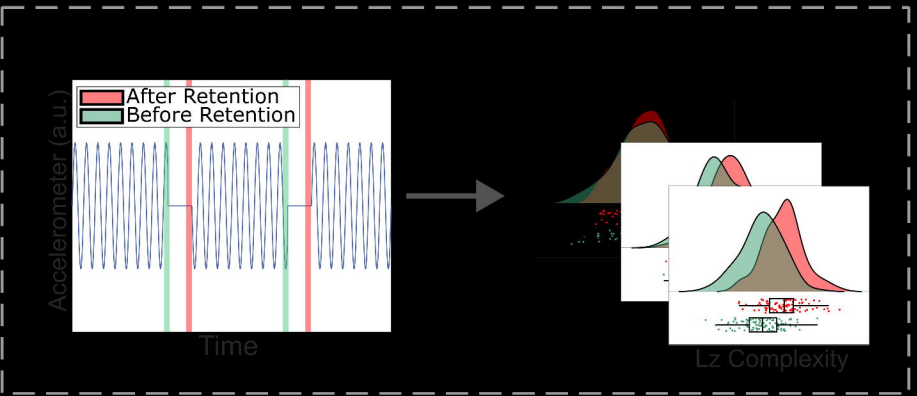
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Accelerometer (a.u.)
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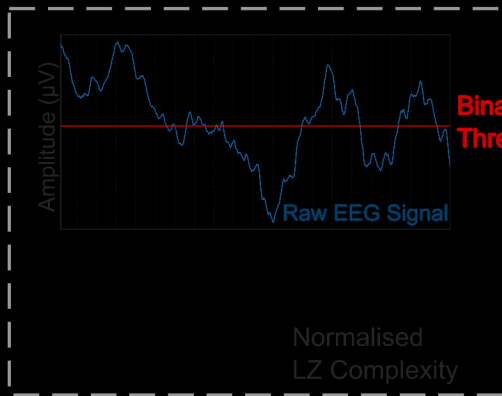
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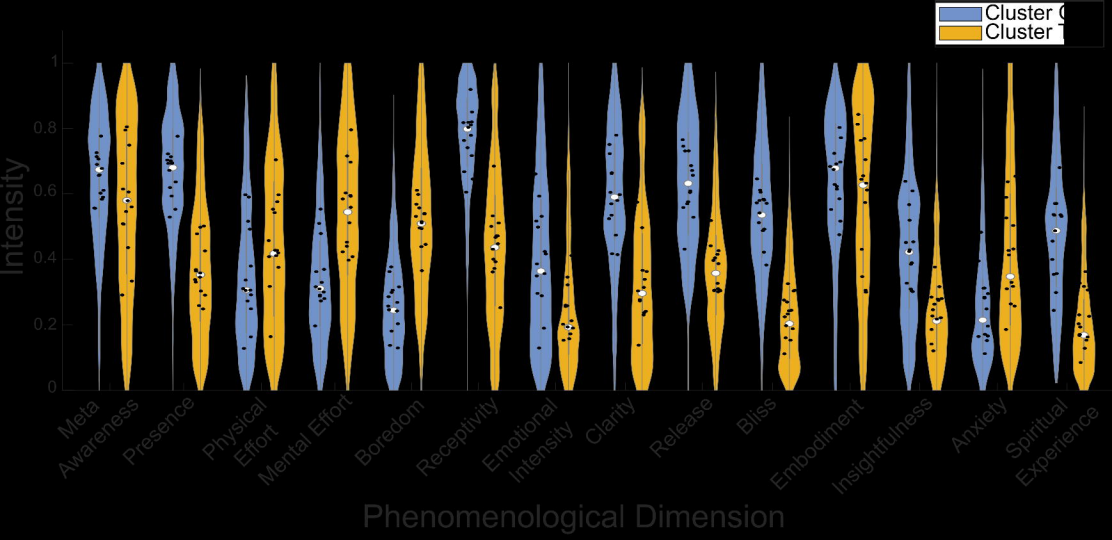
Threshold
Raw EEG Signal
Normalised
LZ Complexity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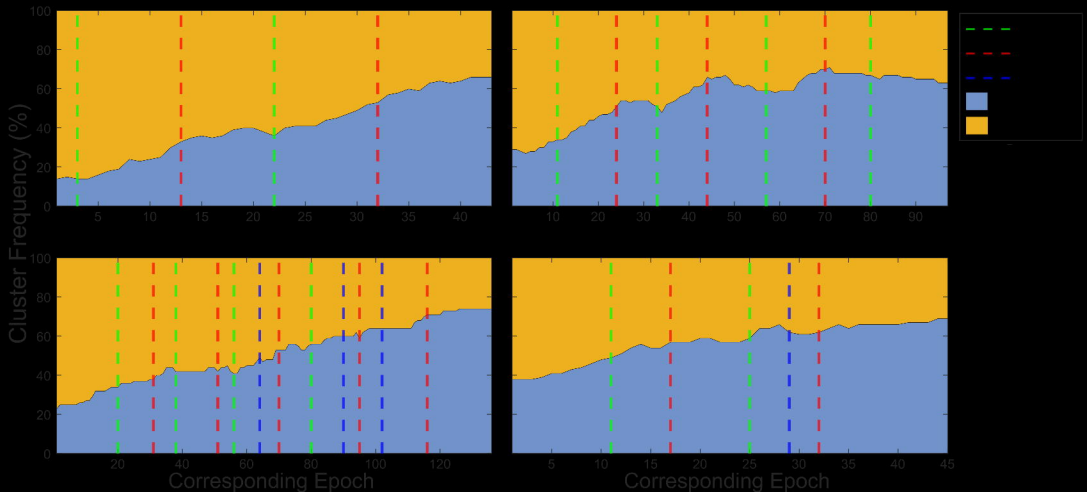
Meta Awareness
Presence
Physical Effort
Mental Effort
Boredom
Receptivity
Emotional Intensity
Clarity
Release
Bliss
Embodiment
Insightfulness
Anxiety
Spiritual Experience
Phenomenological Dimension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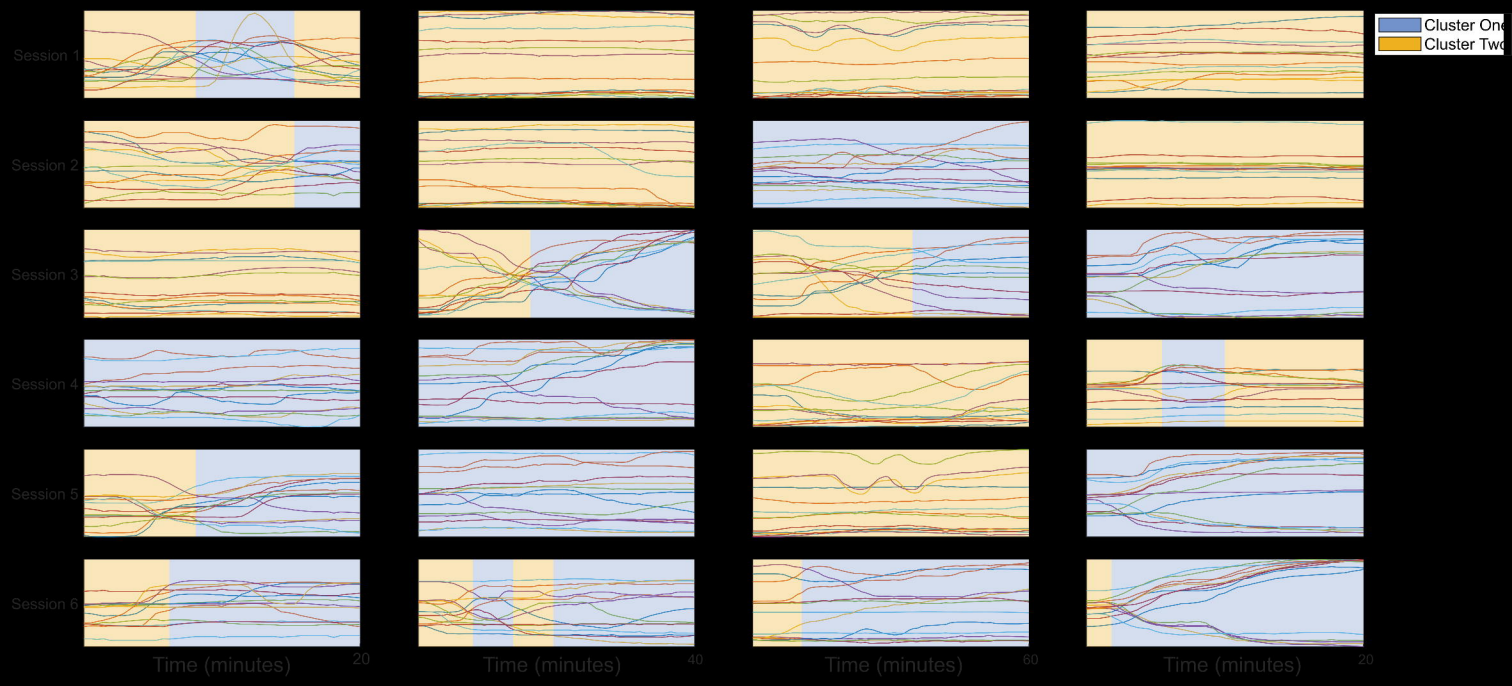
Cluster One
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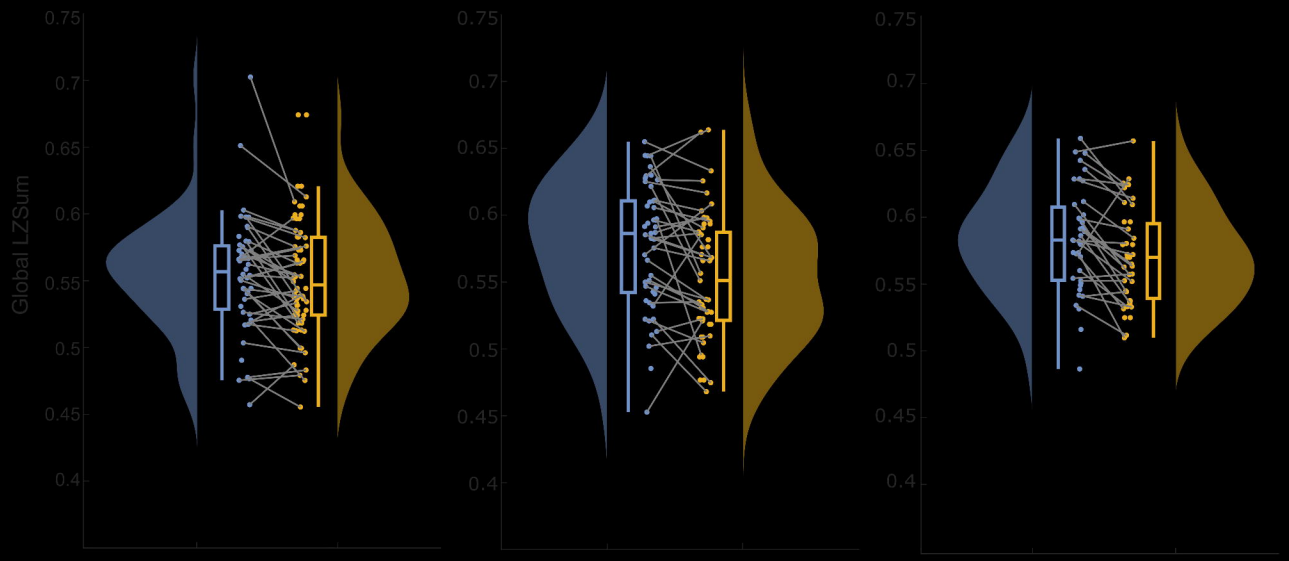
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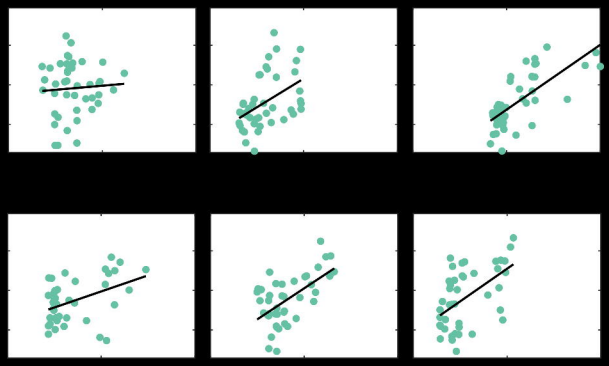

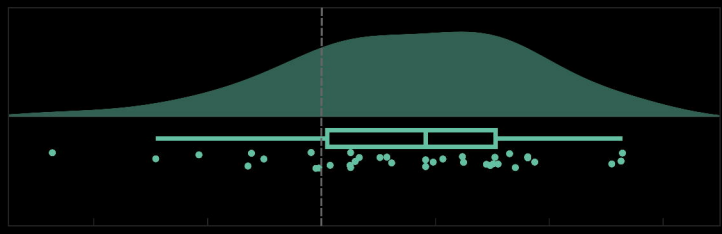

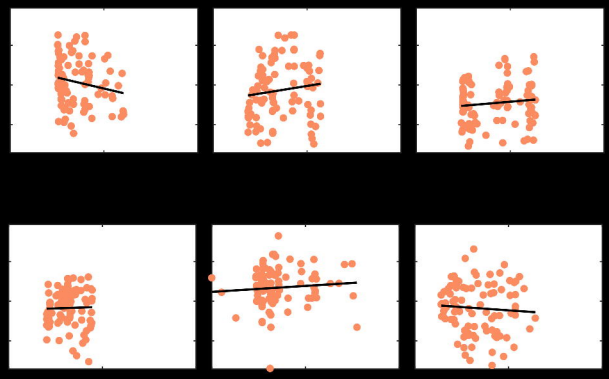

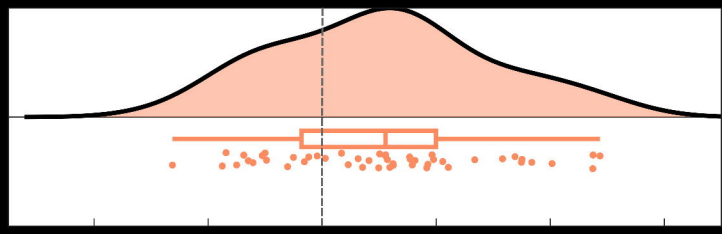

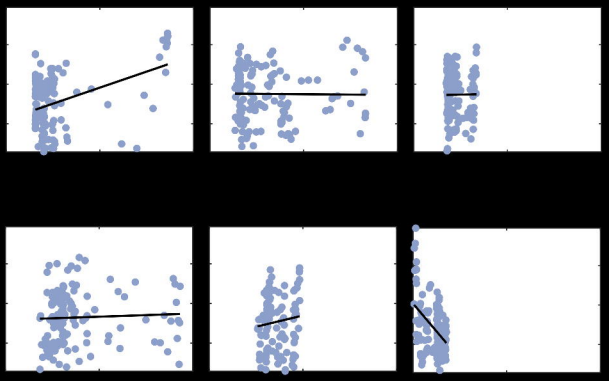

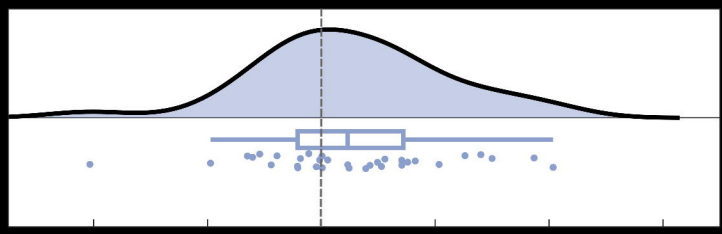

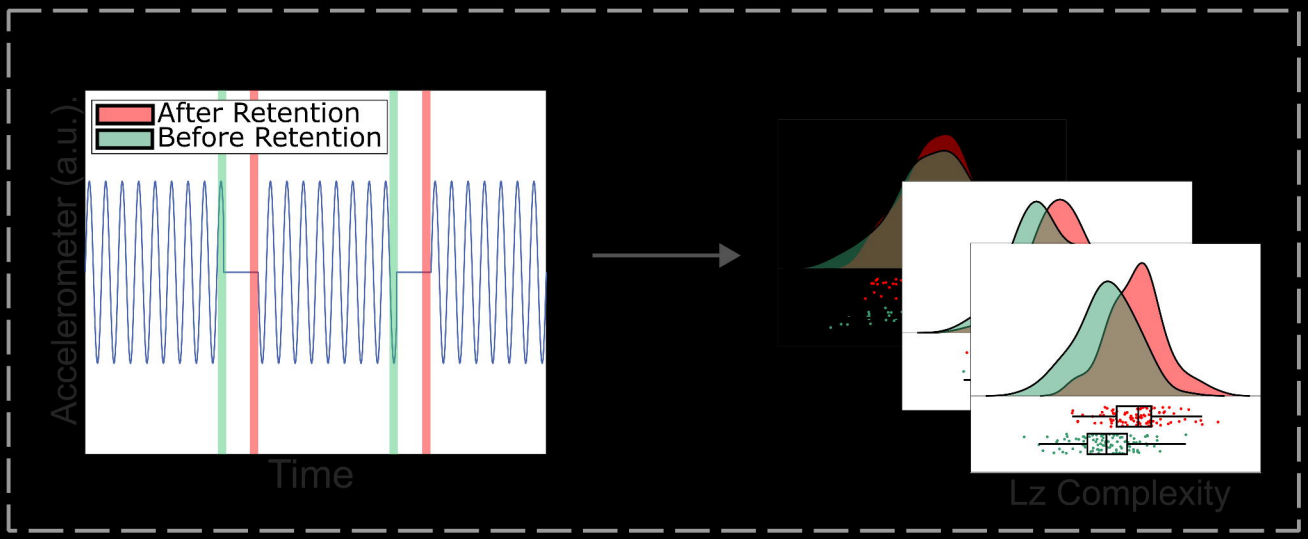
After Retention
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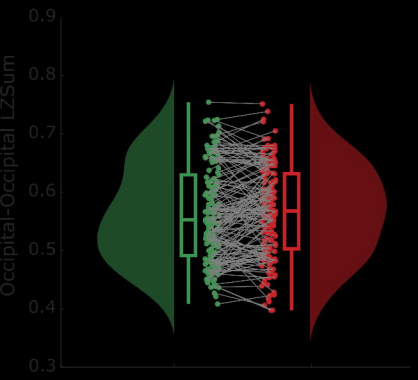
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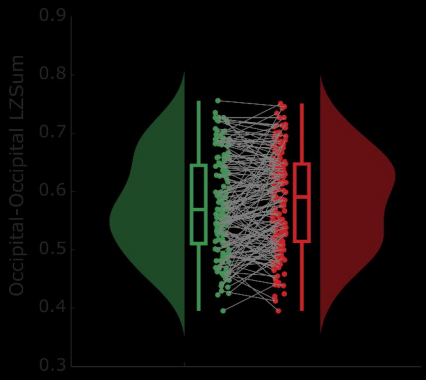
Occipital-Occipital LZSum
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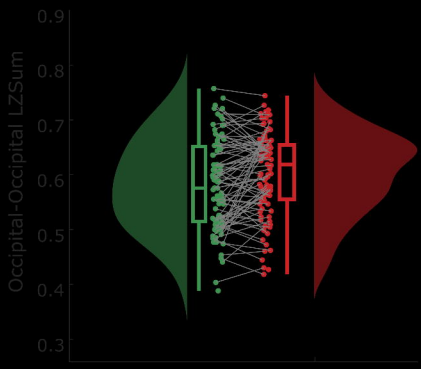
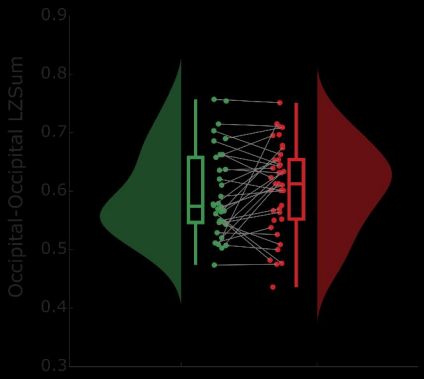
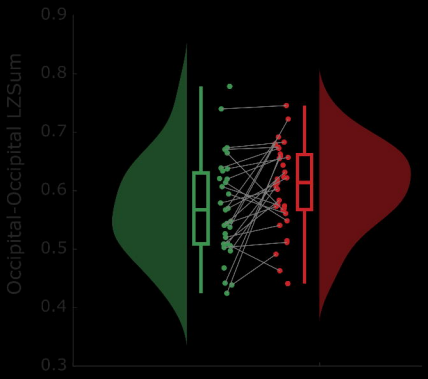
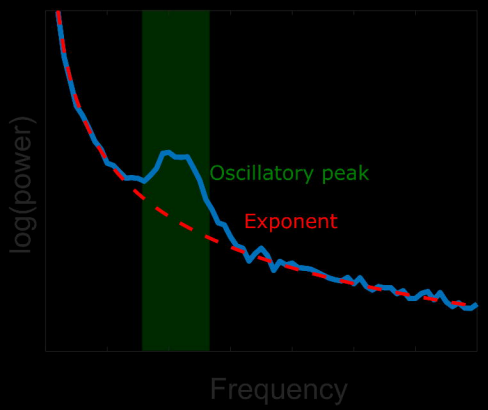
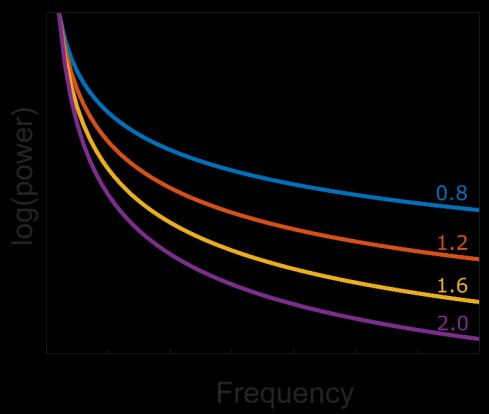
0.4
0.3

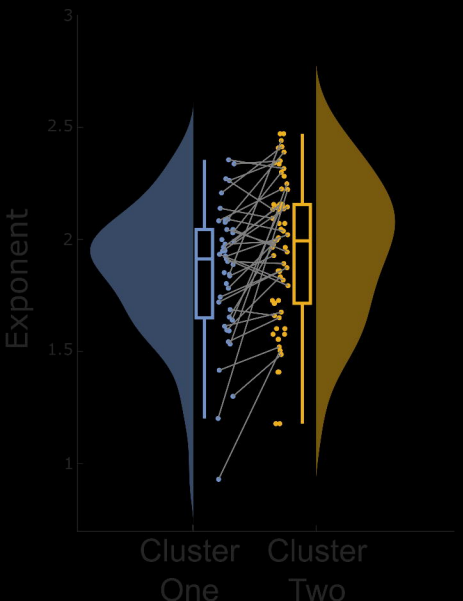

Occipital-Occipital LZSum
0.9
0.8
0.7
0.6
0.5
0.4
0.3

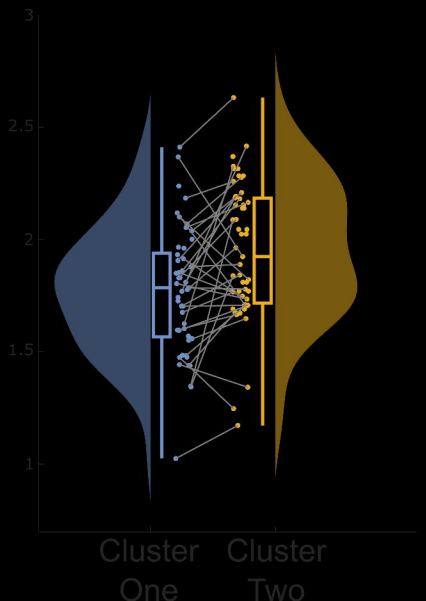

Occipital-Occipital LZSum
0.9
0.8
0.7
0.6
0.5
0.4
0.3

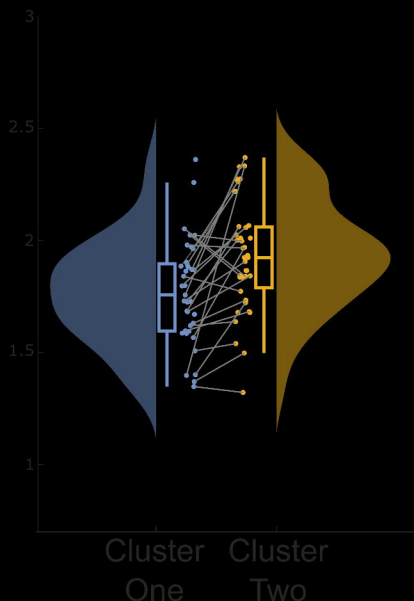

Occipital-Occipital LZSum
0.9
0.8
0.7
0.6
0.5
0.4
0.3


log(power)
Oscillatory peak
Exponent
Frequency


log(power)
0.8
1.2
1.6
2.0
Frequency


Exponent
3
2.5
2
1.5
1
Cluster One
Cluster Two


3
2.5
2
1.5
1
Cluster One
Cluster Two


3
2.5
2
1.5
1
Cluster One
Cluster Two