Neuroelectrophysiological correlates of extended cessation of consciousness in advanced meditators: A multimodal EEG and MEG study

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Abstract

In some contemplative traditions, "extended cessation" (EC) refers to a state of advanced meditation in which the meditator intentionally suppresses their own consciousness and re-emerges with a profound sense of clarity and equanimity. Here, we present the first electrophysiological study of EC, in which five meditators underwent concurrent electroencephalography (EEG) and magnetoencephalography (MEG) recording. EC significantly reduced alpha power. EC also tended to increase neural complexity, unlike other states in which consciousness is absent (e.g., sleep, anesthesia, disorders of consciousness). Our results indicate that the neural correlates of EC are distinct from other states that induce loss of consciousness and that complexity is not a sufficient condition for consciousness, while also providing new insights into the implications of advanced meditation for human flourishing.

Main Text

Using novel techniques to classify and correlate phenomenology with neural markers, studies in the recent "third wave" of meditation on research have found that advanced meditators can access the upper boundaries of human potential, characterized by profound clarity, peace, and equanimity (*1–6*). Advanced meditation research also seeks to explain the profound shifts in consciousness that can arise from contemplative mastery. One such shift, which we call extended cessation (EC), refers to a rare and temporary suspension of ordinary consciousness (*7*, *8*). That is, after specific and especially deep meditation, all perception and feelings cease entirely for an extended period, which can range from minutes to hours. In Theravada Buddhism, *nirodha samāpatti* is a form of EC that represents a cessation of all mental and sensory activity, and is considered to be among the

highest meditative attainments, or the highest meditative attainment (*9–11*). However, due to ongoing debate regarding the criteria for and implications of nirodha samāpatti, we adopt a tradition-neutral term, extended cessation (EC), to refer to the intentional and sustained non-conscious states reported here (*12*, *13*). EC is phenomenologically distinct from deep sleep, anesthesia, and disorders of consciousness (e.g., coma) for several reasons: EC is intentional; there is no sense of time passing during EC; one cannot be awakened by external stimuli; and meditators typically experience immense clarity and peace after coming out of EC (*11*, *14*). These features suggest that EC constitutes a unique, volitionally induced state that may serve as a novel model system for studying the boundaries and mechanisms of conscious awareness. Preliminary evidence indicates that momentary cessations, which last on the order of seconds, decrease global alpha power and functional connectivity while elevating whole-brain criticality (*7*, *8*, *12*). However, these changes in the brain were observed before and after the cessation, rather than during the cessation itself.

Thus, a central question is whether the neural correlates of EC (volitionally induced loss of consciousness) differ from those of deep sleep, anesthesia, and disorders of consciousness (unintentional loss of consciousness). To address this, we examined four electrophysiological biomarkers of consciousness, both globally and regionally in the brain: spectral power, complexity (Lempel-Ziv complexity [LZc], permutation entropy, and integrated information), global coherence, and functional connectivity as captured by the weighted phase lag index (wPLI).

These markers have well-characterized profiles in unconscious states. For example, loss of consciousness tends to amplify power in lower frequencies (delta, theta bands) while suppressing power in higher frequencies (beta, gamma bands) (*15–18*). Additionally, loss of consciousness reduces the complexity of neural activity, as measured by LZc (*19–22*). Anesthesia decreases global coherence, which measures how much coherence can be explained by the most dominant phase-locked network at that frequency (*23*). Finally, functional connectivity, as indexed by wPLI, varies across unconscious states: deep sleep is characterized by increased delta-band connectivity and decreased alpha-band connectivity, while anesthesia enhances frontal alpha wPLI and patients with disorders of consciousness show elevated theta-band connectivity in frontoparietal networks (*24–30*).

What is the neuroelectrophysiology of EC, and does EC affect the brain differently than deep sleep, anesthesia, and disorders of consciousness? In this first electrophysiological study of EC, conducted in parallel with a functional neuroimaging study (now pre-printed) on the same participants (*31*), we recorded brain activity during EC, as well as two control tasks, in five advanced meditators. We hypothesized that, unlike other states in which consciousness is absent,

EC would increase complexity and global coherence. Based on previous case reports of brief cessations, however, we hypothesized that EC would decrease alpha power and functional connectivity, in line with the other states of loss of consciousness.

Results

Phenomenology of extended cessations

A table reporting the phenomenology of different stages of EC is shown in **Figure S1.** All participants used advanced concentration absorption meditation *jhanas* (ACAM-J) to prepare for EC. ACAM-J is a series of concentration states that includes strong and stable focus, blissful sensations, emotional happiness, and peacefulness, followed by a progressive reduction of the contents of consciousness. With one exception, participants involved elements of advanced investigative insight meditation (AIIM), that is, a close, neutral observation of phenomena, as part of the setup of EC (*32*).

All participants reported that internal verbalization (thinking), body sensations, and feeling ceased during the onset of EC. During EC, conscious experience was completely absent. When exiting EC, all participants reported that autobiographical memory and ego-centered cognitive processing was absent, and there was no awareness of a separation between oneself and the environment. With one exception, all participants reported a strong clarity of mind when exiting EC, the presence of a pristine awareness without an object, and the re-emergence of mind, bodily sensation, and internal verbalization (in that order). After EC, all participants experienced extreme sensory vividness, but also a strong and lasting peace. They all also reported being inclined to solitude. With one exception, an experience of deep joy was also reported.

While the core phenomenological features of EC were consistent across individuals, participants noted that the depth or clarity of the experience may have been attenuated during scanning, possibly due to environmental noise or task-related constraints.

EC significantly reduces alpha power

EC significantly reduced power at frequencies in the alpha band in four participants, with respect to both control conditions (**Figure 2**). Only sub003 exhibited increases in alpha power during EC, compared to both control conditions. Participant-specific differences emerged in the precise frequency of the alpha reduction. For example, sub002 showed significant decrease at higher alpha frequencies (12 and 13 Hz), whereas sub004 exhibited lowered alpha power at lower frequencies (8-10 Hz). Delta-theta power significantly increased with respect to both control tasks for sub003

and sub004 and with respect to one control task for sub001 (Counting) and sub005 (Memory). Trends in beta and gamma power were inconsistent.

At the regional level, the most consistent effect was a significant decrease in alpha power in the right occipital pole, which contains the posterior portion of the primary visual cortex (V1) (**Figure S2**). This occurred in sub001, sub004, and sub005 relative to both controls, as well as in sub002 relative to Memory. More broadly, EC reduced alpha power in regions within the visual, somatomotor, and limbic networks in all participants except sub003.

EC significantly increases various measures of complexity in most participants

EC significantly increased LZc in four participants (**Figure 3a**). In particular, sub004 and sub005 exhibited significantly greater LZc during EC compared to both control tasks, whereas sub002 and sub003 had significantly higher LZc during EC compared to one control task (Counting and Memory, respectively). However, in sub003, EC significantly reduced LZc relative to the Memory task.

For sub002, sub003, and sub005, EC significantly altered LZc but not phase-normalized LZc (**Figure 3b**). Since phase normalization preserves the power spectra of the timeseries but not the dynamics, the significant changes in LZc for these participants can be attributed to differences in power spectra rather than dynamics. However, EC significantly raised both LZc and phase-normalized LZc in sub004, suggesting that the actual dynamics of the data gave rise to greater complexity. Of note, for sub001, EC significantly increased LZc but not phase-normalized LZc relative to the Counting task. Phase-normalized LZc, but not LZc, also trended towards significance relative to the Memory task. This indicates that sub001's data on EC is highly complex relative to the power spectrum.

Regionally, EC consistently increased LZc in the right insula and the right precentral gyrus, in nearly all comparisons (**Figure 4**). Significant decreases in LZc tended to occur in more posterior cortical regions, whereas significant increases in LZc tended to occur in more anterior cortical regions.

EC-induced changes in beta-band PE, another measure of neural complexity, were similar to changes in LZc; every participant except sub003 exhibited a significant increase in beta-band PE with respect to at least one control task (**Figure 3c**). In other frequency bands, changes in PE varied by individual, but the overall trend remained consistent: EC tends to increase PE, regardless of the frequency band (**Figure S3**).

EC also significantly elevated empirical Φ, a measure of neural complexity that specifically captures the amount of integrated information in brain activity, with respect to both control

conditions in sub002 and sub005 (**Figure S4**). Increases in empirical Φ relative to the Memory task trended towards significance for sub004. The only participant who experienced a reduction in empirical Φ was sub003, relative to the Counting task.

EC has inconsistent effects on global coherence

EC did not significantly alter global coherence at any frequencies in sub002 and sub005 (**Figure S5**). Both sub003 and sub004 exhibited significant decreases in global coherence in the high beta and gamma bands during EC, whereas sub001 showed significant increases in global coherence in the gamma band. EC significantly raised global coherence in the alpha range in sub003, yet decreased it in sub004. EC also inconsistently affected regional contributions to the globally coherent network at 11 Hz, which we focused on due to prior literature (*23*). The most common effect was an increase in the contribution of left V1, which occurred in sub001, sub003, and sub004 with respect to both control tasks (**Figure S6**).

Changes in functional connectivity on EC vary across participants

EC did not significantly alter functional connectivity, as measured by the weighted phase lag index, between any pairs of networks in two out of five participants, specifically for sub002 and sub005 (**Figures S7-S12**). For sub003, EC significantly increased between-network functional connectivity predominantly in the theta band; there was a single connection (dorsal attention network to default mode network) that was stronger for sub003 in the alpha band during EC. Compared to the other participants, sub001 exhibited the most dramatic and widespread increases in functional connectivity in all bands except alpha. Perhaps for this reason, sub001 was the only participant that showed significant differences under EC in multiple topological properties of the functional connectivity network, such as global efficiency, mean local efficiency, and modularity (**Figure S13**). Sub004 also displayed strong changes in functional connectivity, but they were less consistent across bands compared to those of sub001. In particular, the effects of EC on beta-band functional connectivity in sub004 were weaker than on other bands.

Discussion

Here, we report the first evidence of neuroelectrophysiological correlates of extended cessations of consciousness in advanced meditators. Notably, we found that EC exhibits distinct neural signatures compared to loss of consciousness via deep sleep, anesthesia, or disorders of consciousness. While EC did suppress alpha power in most participants, it did not have a consistent effect on power in other frequency bands. In contrast to other states of

unconsciousness, EC elevated LZc, phase-normalized LZc, permutation entropy, and/or integrated information in most participants. Finally, EC did not affect global coherence or functional connectivity uniformly across participants.

EC-induced decreases in alpha power may play a role in suppressing consciousness

Loss of consciousness is typically associated with increases in slow-wave activity (*16–18*). Sleep and disorders of consciousness also diminish alpha power; in particular, diminished absolute alpha power is one of the most reliable biomarkers for distinguishing a more severe unresponsive wakefulness syndrome from less severe minimally conscious state (*33–38*). General anesthesia tends to "anteriorize" alpha power, that is, suppressing alpha power in occipital regions of the brain while elevating alpha power in frontal regions (*39–41*). A similar topography is seen in N2 sleep spindles (one stage above deep sleep), which are predominantly localized to frontal midline regions (*42*).

EC, compared to both control conditions, significantly decreased power in at least some alpha frequencies in all participants except sub003. Loss of alpha power is therefore common to EC, sleep, and disorders of consciousness. Our findings align with a prior case report in which brief, momentary cessations of consciousness were also associated with reductions in alpha power (*7*). While our findings are consistent, it is important to note that momentary cessations in this case report tended to last less than 10 seconds at an instance, whereas extended cessations in this study were usually at least several minutes.

Importantly, while sleep and disorders of consciousness are known to "anteriorize" alpha power, EC did not follow this trend. Instead, EC was just associated with decreased alpha power in the occipital cortex, especially right posterior V1, without an increase in frontal alpha. The previous case report also showed that momentary cessations reduce alpha power specifically in the occipital cortex before the onset of cessation, albeit dropping globally during the cessation event (*7*). Although two participants exhibited modest frontal alpha increases, these were not consistent across the sample. In sub003, alpha power increased more in posterior than in anterior cortex.

Alpha oscillations are generated by thalamic activity, and increases in alpha power in frontal cortex tend to indicate that thalamic communication, including signal diversity, with frontal brain regions is restricted to the alpha band (*40*, *41*). The absence of anteriorization in EC suggests that broader-band connectivity between thalamus and frontal cortex may be preserved. Such preservation could allow the thalamus to continue modulating top-down attentional control signals from the frontal cortex (*43*, *44*). This mechanism may be particularly relevant for EC, where volitional control is believed to suppress the neural substrates of perception, language, and self-

reflection. If the thalamus remains capable of transmitting frontal signals with a broader bandwidth, it may facilitate the intentional silencing of these processes, enabling a state of unconscious stillness. In contrast, anesthesia may impair this regulatory function by constraining the signal to thalamocortical alpha bandwidth.

Further support for this hypothesis comes from the absence of consistent increases in delta and theta power during EC. Under anesthesia, increased slow-wave activity becomes desynchronized across the cortex, leading to "functional segregation" and therefore an inhibition of intra-cortical communication (*41*, *45*). In EC, the preservation of low-frequency power may reflect sustained intra-cortical communication. This would enable the frontal cortex to continue to downregulate activity in the other cortical regions, strengthening the top-down attentional mechanisms for suppressing consciousness.

Increases in complexity during EC challenge prevailing theories about consciousness

According to the Entropic Brain Hypothesis, the richness of conscious content is encoded in the entropy, that is, the amount of variability or complexity, of brain activity (*46*). Psychedelics, which enhance the richness of conscious experience, are known to increase the entropy of brain activity, though there have been difficulties replicating some of these findings in independent datasets (*47–51*). Depressed conscious states such as deep sleep, anesthesia, and disorders of consciousness, typically diminish LZc, PE, integrated information, and other indices of neural complexity, though there have been reports of increases in LZc after propofol-induced anesthesia (*19–22*, *52–54*).

One would therefore expect EC, which leads to an absence of consciousness, to decrease neural complexity. Surprisingly, our results showed the opposite pattern in most participants. Four out of five meditators exhibited increased or unchanged LZc, PE, and integrated information, while one participant (sub003) displayed a reduction in these metrics. This finding is consistent with a previous case report that observed during brief cessations an increase in "criticality," a physical quantity that is related to complexity (*8*); however, the relationship between criticality and complexity is far from straightforward (*55*).

One possible explanation is that the observed increases in complexity may reflect the intensely concentrated state that is required to enter EC. While unconsciousness induced by sleep or anesthesia arises passively or exogenously, EC is voluntarily cultivated and typically preceded by advanced meditation training. In this study, all participants engaged in ACAM-J prior to entering EC, and most also incorporated elements of AIIM. These preparatory practices involve not only sustained attentional control, but also refined phenomenological insight into the mind. In general, focused attention meditation is an activity that requires meditators to consistently deviate from

resting-state activity, since the mind wanders during the resting state and the meditation leads participants to return their concentration to the breath whenever they become distracted. Thus, focused attention meditation increases LZc relative to resting-state, especially for more advanced meditators, whereas mind-wandering during meditation, which leads to a decline in concentration, decreases LZc (*56–58*). Moreover, previous work from our group has shown that ACAM-J elevates LZc (*59*). It is possible that, even though there is reportedly no consciousness during EC, the concentrated state in ACAM-J persists into EC; indeed, advanced meditators may be so well-trained in focused attention that it can arise without their conscious awareness.

Another possibility is that elevated LZc is associated with the latent reorganization of neural dynamics that shapes the qualities of experience upon re-emergence from EC. Post-cessation states are often described as clear, equanimous, and "luminous". Luminosity is described as the innate ability of the mind to reveal experience with total clarity, unimpeded by the beliefs, judgments, and fears that typically distort perception (*60*). We do not attribute elevated LZc to increased luminosity directly. Rather, our results raise the possibility that higher LZc reflects a brain state characterized by neural reorganization that makes the mind less susceptible to repetitive loops of perception, thought, or self-narration, and instead supports a condition of openness in which new experiential "frames" can continually arise. LZc quantifies the diversity and unpredictability of neural time series, reflecting the degree to which brain activity resists compression into repetitive patterns. Higher LZc indicates that the system is generating a rich, high-dimensional repertoire of microstates, each distinguishable from the last. In this sense, LZc could serve as a neural correlate of brain reorganization that facilitates the mind's "reset" when consciousness resumes.

Furthermore, LZc may be less an index of the richness of experience and more a reflection of deviations from resting-state activity. For instance, broadband LZc increases when participants are engaged in tasks and even when participants ingest caffeine, even though consciousness is not necessarily becoming "richer" in either case (*61*, *62*). Because EC is not a conventional resting state and its preparation instead demands a high degree of concentration, LZc could plausibly increase even though the richness of conscious experience is decreased.

Thus, EC presents a unique scenario in which consciousness is absent in spite of greater neural complexity. This challenges the Entropic Brain Hypothesis and other theories that claim that complexity is a sufficient condition for consciousness. In other words, consciousness may require not just complexity per se, but specific network configurations of complex activity that were intentionally disrupted during EC. EC elevates complex activity in *local* brain networks, but these activities never coalesce into the unified, metastable patterns associated with conscious perception

and cognition. For instance, EC increases LZc in specific regions of the brain, such as the right insula, but decreases it in other areas, such as occipital cortex. On the other hand, deep sleep, anesthesia, and disorders of consciousness tend to homogeneously decrease complexity across the whole brain (*21*, *63*, *64*).

We speculate that these "pockets" of elevated LZc in the brain reflect subconscious neural processing that prepares the meditators for the insights and profound feelings of equanimity that they experience after EC. In other words, while the mind is offline, latent neural activity may prime the brain for an extraordinary afterglow. All meditators in this study reported sensory vividness and strong sensations of peace during the afterglow, and all but one described feelings of deep joy. Under psychedelics, increases in complexity or entropy correlate with subsequent improvements in trait openness, as well as positive mood, ego dissolution, and vivid imagery during the experience (*48*, *65*, *66*). Although there is no evidence causally linking complexity to the subjectively experienced benefits of psychedelics, we speculate that the "reservoirs" of neural complexity in EC may facilitate the rapid re-binding of neural assemblies, leading to an affective reset once meditators return to consciousness (*67*). This phenomenon further distinguishes EC from deep sleep, anesthesia, and disorders of consciousness, in which participants, upon returning to consciousness, do not typically feel the sublime emotions that characterize the EC afterglow.

Increased LZc in the right insula during EC may reflect more than changes in bodily awareness; it may index the persistence of integrative hubs that are essential for conscious access, even when sensory content is absent. The right anterior insula is a key node of the salience network, coordinating dynamic switching between internally- and externally-focused modes of processing (*68*) and integrating interoceptive, emotional, and cognitive information into a unified subjective state (*69*). In typical conscious experience, the insula binds bodily signals to higher-order representations, but during EC, bodily sensations are absent, according to the phenomenological reports of all five participants. We speculate that elevated LZc in this context could signify that the insula is maintaining a high-dimensional, flexible representational space without populating it with specific sensory content, a kind of silent readiness that preserves the architecture for consciousness without instantiating experience. This interpretation aligns with recent work on advanced meditation stages showing that equanimity and cessation states preserve or even enhance neural differentiation in salience and interoceptive hubs while globally reducing sensory and self-referential activity (*32*, *59*). In this view, the insula's elevated complexity may not represent perception per se, but rather the capacity for conscious integration that enables the rapid reconstitution of rich, coherent experience, as well as the profound clarity and equanimity, reported in the afterglow of EC.

It is worth noting that changes in power apparently drove the increases in LZc during EC, since there were no significant differences in LZc in some participants after their timeseries were phase-normalized. In other words, EC may amplify the spectral diversity of the brain, perhaps by reducing the dominance of alpha rhythms, without altering the temporal dynamics. This is consistent with the lack of changes in functional connectivity during EC, as explained below.

The increase in empirical Φ on EC in some of the participants also suggests that integrated information may not be a sufficient condition for consciousness. Integrated information theory claims that consciousness can be measured as Φ, though there are several different methods for calculating Φ. Previous studies have also shown that loss of consciousness is not always associated with decreases in Φ and can depend on certain parameters of the data, such as sampling rate (*54*, *70*). One possibility is that Φ in EC reflects a latent capacity for consciousness, not the actual presence of conscious experience. That is, as stated above, the brain is temporarily offline, but its intrinsic architecture remains highly organized and integrated, like a primed but idle system.

Inconsistent changes in coherence and functional connectivity may reflect idiosyncrasies in EC

Global coherence, defined as the proportion of total spectral power explained by the most coherent component across brain regions, did not exhibit consistent increases or decreases across participants during EC. This contrasts with prior work showing that unconscious states like anesthesia are marked by decreases in global coherence at most frequencies, sometimes with a paradoxical increase in narrow-band frontal alpha coherence (*23*). In EC, some participants showed increases in coherence in high-frequency bands, while others showed reductions, particularly in beta and gamma bands. These inconsistent and individualized patterns suggest that EC does not uniformly synchronize brain networks, but rather alters the coherence landscape in a more participant-specific way.

At the regional level, we observed increases in narrow-band *occipital* alpha coherence; in particular, EC elevated the contribution of left V1 to the dominant 11 Hz coherent network in several participants. This is yet another indication that EC does not anteriorize alpha oscillations; EC, unlike anesthesia, does not significantly increase frontal alpha power or frontal contributions to global coherence. EC is unique among states of unconsciousness.

No consistent pattern of increased or decreased inter-network coupling emerged across participants or frequencies. Sub001 and sub004 exhibited decreases in functional connectivity in the alpha band and increases in most other bands, yet changes in functional connectivity in the other participants did not meet the threshold for statistical significance. (However, the findings in sub001 and sub004 are aligned with a previous case report, in which average alpha PLI decreased

prior to cessation (*12*).) Graph-theoretic analyses of the functional connectivity matrices further reinforce the lack of consistency between participants in this study. Only one participant (sub001) showed changes in global network properties (e.g., efficiency, modularity), and these effects were not replicated in others. Meanwhile, anesthesia consistently increases alpha-band modularity while diminishing alpha-band global efficiency, while also elevating other measures such as the diameter and eccentricity of the minimum spanning tree of the whole-brain functional network (*25*, *70–73*). Similar effects on modularity and global efficiency are observed in deep sleep and disorders of consciousness (*74–76*). In those states, uniform network reconfiguration reflects functional disintegration. By contrast, EC preserves the scaffolding for integration, with connections idled rather than dismantled. In other words, consciousness may not be shut down but rather "dormant," which may facilitate the very peaceful, clear state that occurs during the afterglow.

Pure consciousness and minimal phenomenal experiences

Although it is reported as a lack of consciousness, EC parallels descriptions of "pure consciousness" in both contemplative traditions and empirical research: a mode of experience devoid of sensory, cognitive, and affective content, yet not characterized by confusion, disorientation, or loss of lucidity. Scholars such as Forman and Josipovic have argued that pure consciousness represents a content-free awareness, irreducible to either perception or thought, and often reported during advanced meditation (*77*, *78*). Metzinger has recently introduced the concept of minimal phenomenal experience (MPE) to capture such content-free states, characterizing them as episodes with extremely low informational content, minimal phenomenal selfhood, and a high degree of experiential unification (*79*). MPEs, in Metzinger's account, may occur naturally (e.g., in dreamless sleep) or be cultivated through meditative practice, and they hold potential value for clarifying the necessary neural and representational conditions for consciousness.

Our neural findings on EC both converge with and challenge aspects of the MPE framework. On one hand, the global reductions in alpha power, absence of widespread functional connectivity reconfiguration, and preservation of local complexity in regions such as the right insula are consistent with a highly unified but low-content state. On the other hand, increased empirical Φ and localized LZc elevations in some participants suggest that EC may preserve, and in some cases enhance, the brain's capacity for rich integration, even in the absence of phenomenally accessible content. This pattern may indicate that EC, unlike spontaneous MPEs such as dreamless sleep, represents an intact but voluntarily silenced workspace for consciousness, which is rapidly

reactivated upon re-entry, possibly contributing to the distinctive afterglow effects reported by practitioners.

In this light, EC, in spite of being described as a state without any consciousness, may provide a uniquely tractable experimental model for studying pure consciousness and MPEs under controlled, repeatable conditions, allowing researchers to disentangle the neural markers of conscious *capacity* from those of conscious *content*. This distinction, which Metzinger and others have highlighted as critical for a mature science of consciousness, is rarely accessible in naturally occurring states but is made possible here by the extraordinary volitional control of advanced meditation practitioners (*79*).

Relation to recent findings on advanced meditation

In recent years, the "third wave" of meditation research has investigated the flourishing of human potential that can lead to and result from advanced meditation (*6*). Profound changes in consciousness arising from advanced meditation, referred to in the scientific literature as meditative endpoints, are described across contemplative traditions with terms such as "awakening," "enlightenment," or "salvation" (*80–83*). Practitioners reporting these endpoints describe lasting transformations in awareness and self-related processing. These investigations contribute to a broader scientific effort to understand emergent and altered states of consciousness, which are increasingly recognized as widespread tools for improving mental health (*84*, *85*).

Prior advanced meditation research has focused on ACAM-J, and to a lesser extent, AIIM, both of which served as preparatory practices for EC. Across a series of intensive case studies, ACAM-J has been associated with reduced broadband EEG power; increased EEG LZc; decreased fMRI within-network connectivity; and increased fMRI between-network connectivity; reduced alpha-band wPLI and weighted symbolic mutual information; and enhanced fMRI activity in the visual cortex and many other cortical and subcortical regions (*59*, *86–88*). Additionally, ACAM-J increased global integration or connectivity, though one analysis found that this became less prominent in the later ACAM-J (*59*, *89*, *90*).

In our data, EC converges with ACAM-J and AIIM on two local markers: reduced alpha power, especially in the visual cortex, and elevated LZc. Decreases in EEG/MEG alpha power in the primary visual cortex are consistent with an increase in fMRI activity in this area. This reduction in V1 alpha power aligns with the case-study fMRI reports of increased visual cortex activity during the stages of insight during AIIM (*32*). This mirrors our observation in EC that sensory-related regions may remain neurally differentiated even in the absence of phenomenally accessible

perception, suggesting that the visual cortex and possibly other modality-specific cortices may enter EC in a state of heightened readiness rather than complete shutdown.

In contrast, EC diverges from ACAM-J and AIIM in its effects on global coherence and connectivity. While ACAM-J and AIIM both show evidence for transient increases in large-scale integration and inter-network communication, EC did not display a consistent pattern of change in global coherence or wPLI across participants. This dissociation suggests that some neural signatures from the preparatory states (e.g., suppressed occipital alpha, elevated LZc) carry forward into EC, while the more global markers of network reorganization do not. One interpretation is that ACAM-J and AIIM progressively alters sensory awareness, which may facilitate the transition into EC, but that the global integration characteristic of these preparatory states is deliberately suspended during EC, consistent with a volitional disengagement of integrative network dynamics. Hence, although ACAM-J and AIIM were both used to prepare for EC in this study, consciousness is still present during ACAM-J and AIIM but absent during EC.

Given that published studies on ACAM-J and AIIM to date have mostly been case reports, larger samples are needed to test if the preparatory markers of EC function as reliable biomarkers for entry into EC rather than explicit markers of EC. We therefore understand EC as a distinct, non-conscious state marked by local dynamical changes with relative large-scale decoupling.

Limitations

This study is the first of its kind and, as such, comes with important limitations. The sample size was small (n = 5) since there are very few meditators that are capable of achieving EC; thus, these results should be considered preliminary and not necessarily generalizable to broader populations. That being said, our subject-level statistical approach, which is found in studies with small samples both in primates and humans, ensured that we did not make invalid group-level inferences (*23*, *91–94*). There was also inherent uncertainty in determining the precise onset and offset of EC, since the timing of consciousness cessation was based on participants' subjective reports and behavioral cues. Small timing offsets could dilute or obscure transient neural changes around the state transition. Additionally, we observed notable inter-participant variability in some measures. For example, one meditator showed increased occipital alpha power rather than the decreases seen in others, and not all participants showed complexity increases once spectral factors were accounted for. Such variability could stem from differences in individual technique, depth of EC, or physiological factors. Moreover, our analyses focused on EEG/MEG measures in the cortex; subcortical activity (e.g. in the thalamus or brainstem) was not directly observed, and this could

play a pivotal role in orchestrating EC. Spatial resolution was limited by the source reconstruction approach, and subtle regional effects (especially in deep structures) might have gone undetected.

In summary, this is the first neuroelectrophysiological study of EC, revealing EC as a state that challenges our assumptions about the neural mechanisms of unconsciousness. Rather than simply diminishing brain activity, EC shuts down consciousness while the brain remains complex, dynamic, and organized even without reportable experience. Our research has shown that decreases in complexity are not a sufficient condition for loss of consciousness; in fact, complexity increased in most cases during EC. The inconsistent effects of EC on global coherence and functional connectivity warrant future research on the idiosyncratic neural mechanisms that subserve different subjective experiences of the preparation for and afterglow of EC. Continued research into EC and advanced meditation more generally promises to yield further theoretical insights into consciousness and to inform our understanding of wellbeing and flourishing.

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Author contributions

M.D.S. conceptualized and supervised the study, edited the manuscript, and acquired funding. K.S. preprocessed and source-reconstructed the data, conducted analyses, and wrote the first draft of the manuscript. R.M.P. W.F.Z.Y., and T.S. acquired the data and edited the manuscript. R.M.P. also assisted with data preprocessing.

Competing interests

The authors declare that they have no competing interests.

Data and materials availability

Code for the preprocessing, source reconstruction, and analyses are available upon request by contacting the corresponding author.

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Figures

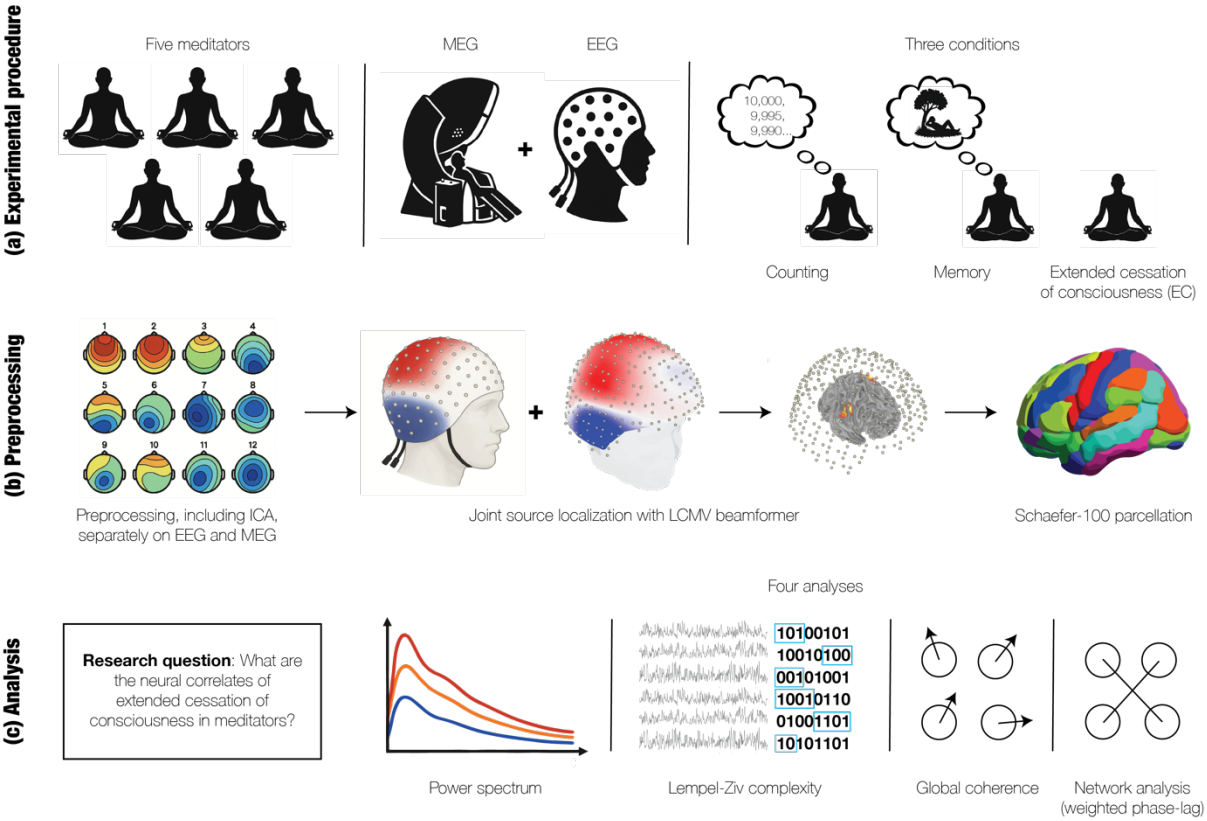

Figure 1. Study Design Overview. *(a) Five advanced meditators were examined in three different conditions: extended cessation of consciousness (EC), a control Memory task in which participants reminisced on recent events, and a control Counting task in which participants counted down from 10,000. One participant was scanned with just EEG; for another participant, only MEG data was analyzed; and for the remaining three participants, simultaneous EEG and MEG data were acquired and analyzed. (b) EEG and MEG data were preprocessed separately, and then joint source reconstruction was performed by concatenating the respective leadfields. The sources were the centroids of the regions in the Schaefer-100 parcellation. (c) All analyses were conducted in source-space. Power spectra, Lempel-Ziv complexity, global coherence, and network functional connectivity were measured. These measures were chosen because they have been previously analyzed in research on loss of consciousness.*

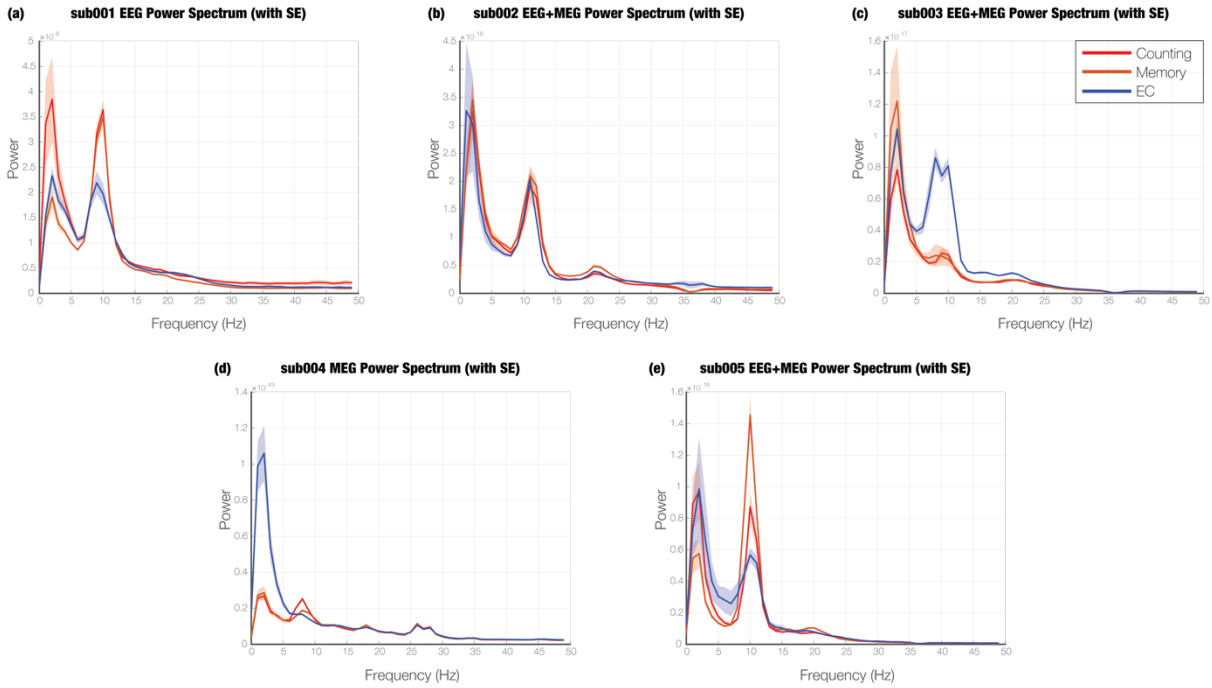

Figure 2. EC significantly reduces alpha power. *EC significantly decreased power at frequencies in the alpha range in four participants, with respect to both control tasks. Only one participant, sub003, exhibited increased power across the whole alpha band during EC. EC significantly lowered alpha power at higher frequencies (12-13 Hz) in sub002 and lower frequencies (8-10 Hz) in sub004. EC significantly increased delta-theta power in sub003, sub004, and sub005. The effect of EC on beta power was mixed; for sub002 and sub004, EC significantly increased beta power at some frequencies but not others. EC significantly amplified gamma power in sub002, sub003, and sub004.*

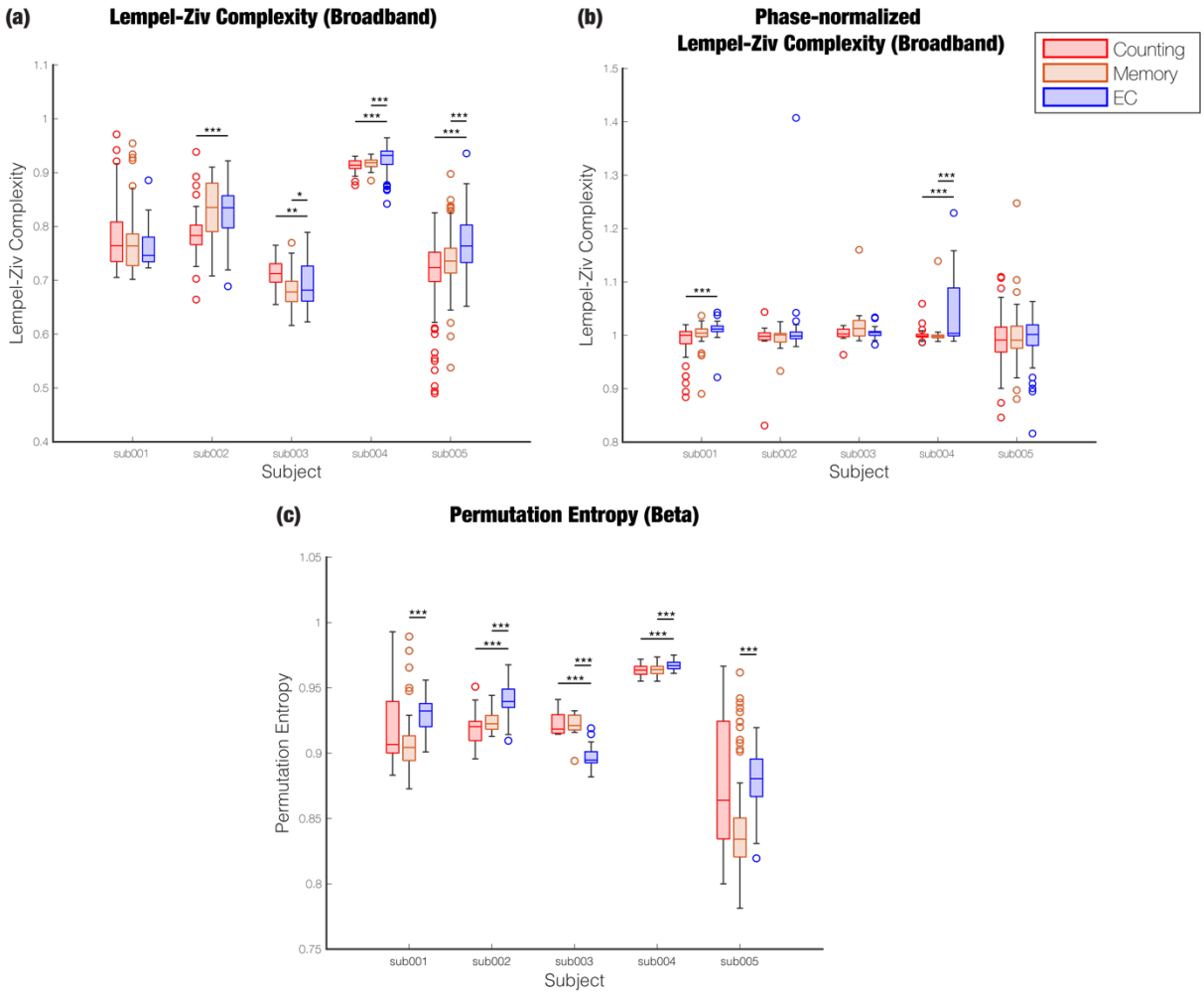

Figure 3. EC significantly increases Lempel-Ziv complexity (LZc) and permutation enttropy, but not phase-normalized LZc, in most participants. *(a) Sub004 and sub005 exhibited significantly higher LZc in EC compared to both control tasks, whereas EC significantly increased LZc relative to one control task in both sub002 and sub003. However, EC significantly decreased LZc relative to the Memory task in sub003. (b) EC did not have a significant effect on phase-normalized LZc in sub002, sub003, and sub005, indicating that EC alters LZc in these participants by changing the power spectrum rather than the dynamics of the timeseries. Meanwhile, sub004's increases in both LZc and phase-normalized LZc suggest that EC elevates complexity in the brain by actually disrupting the dynamics of the timeseries. (c) Changes in beta-band permutation entropy, another measure of complexity, are similar to changes in LZc.*

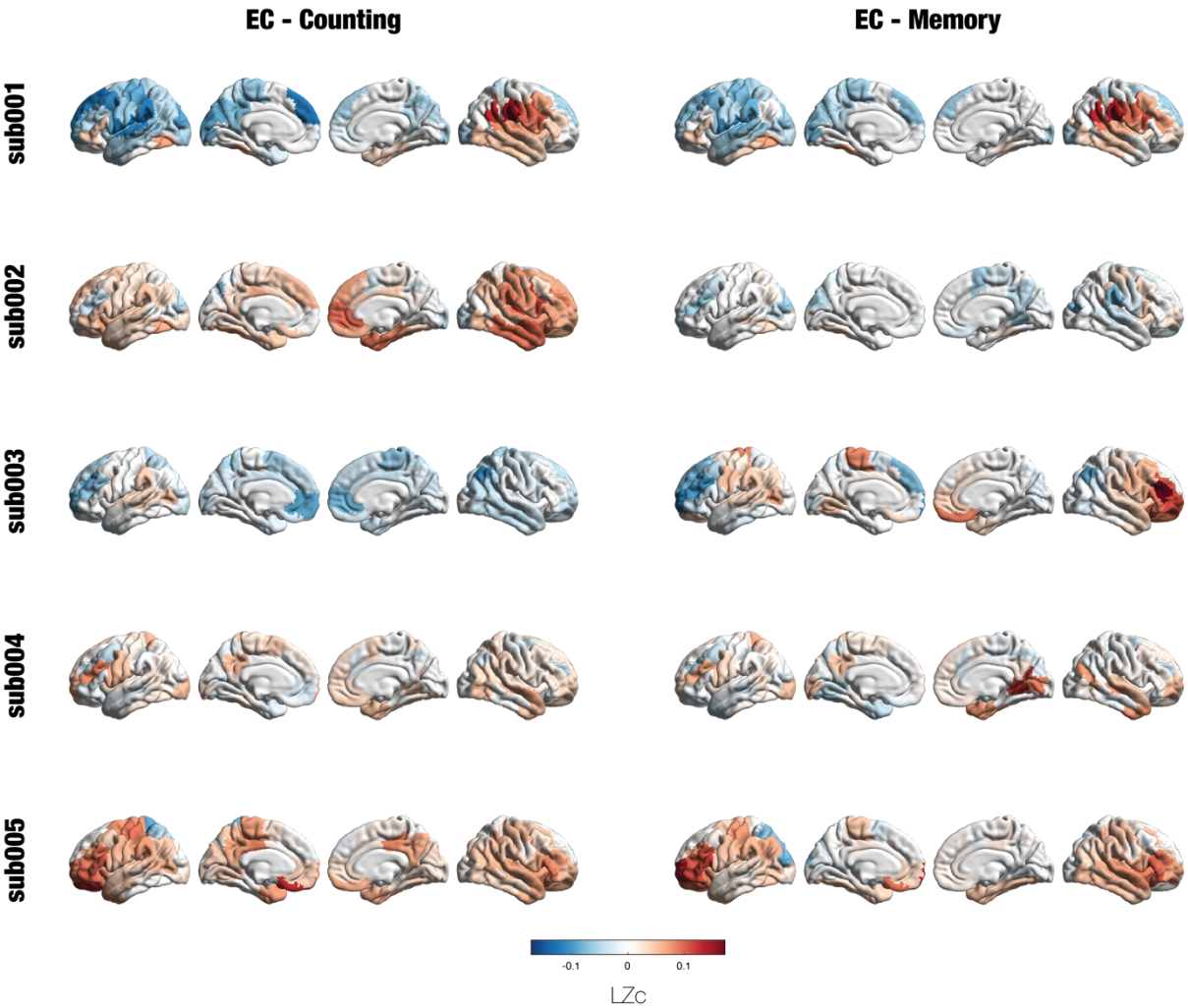

Figure 4. EC significantly increases LZc in the right insula and right precentral gyrus in all participants. *Blue colors reflect reduced LZc on EC relative to the control conditions, whereas red colors reflect increased LZc. White regions are brain areas for which there was no significant difference in LZc between EC and the respective control task. The same color scale was used for all comparisons. In all comparisons except EC vs. Counting in sub003, LZc (not phase-normalized) in the right insula and precentral gyrus significantly increased during EC. Generally speaking, EC significantly raised LZc in regions within the limbic cortex. Increases in LZc tended to occur in more anterior cortical regions, whereas decreases tended to take place in more posterior cortical regions.*