Enhancing Meditative Development with Transcranial Focused Ultrasound: A Mixed-Methods Phenomenological Study of Neuromodulation in Experienced Meditators During a Ten-Day Retreat

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Abstract

Emerging research suggests some of the most profound meditation-induced psychological transformations require mastery of mental skills that enable access to advanced meditative states, stages, and endpoints. Such development, however, often demands years of sustained practice and expert guidance. Transcranial focused ultrasound (tFUS) offers a novel means of potentially supporting meditative development by modulating brain structures with high spatial precision. Suppression of the posterior cingulate cortex (PCC)—a hub of self-referential processing—may reduce stickiness in internal cognitions and self-interference, thereby fostering equanimity, a crucial meditative faculty. This pilot feasibility study investigated the effects of tFUS-based PCC inhibition during a ten-day silent retreat. Twenty-eight meditators received two stimulation sessions during the retreat and completed standardized questionnaires and daily phenomenological reports. Quantitative analyses revealed significant increases in trait mindfulness, both state–trait nondual awareness, and interoceptive body listening. Qualitative analyses identified consistent differences between stimulation and non-stimulation days: tFUS was associated with enhanced meditative phenomenology, including equanimity, concentration, and sensory clarity, as well as shifts in self-perception and cathartic emotional release. These experiential effects often unfolded in interaction with participants' ongoing psychological challenges, suggesting that tFUS may increase baseline equanimity and scaffold meditative capacities. Implementation was feasible but required logistical planning. Limitations include the quasi-experimental design, reliance on self-reports, and lack of long-term follow-up. Future studies should use randomized sham-controlled designs, neurophenomenological methods, and examine systematic dose–response parameters with MRI-guided targeting. Together, these findings highlight tFUS as a promising tool for augmenting meditation training and advancing the study of meditative development.

Keywords: transcranial focused ultrasound (tFUS), meditation retreat, non-invasive brain stimulation, advanced meditation, meditative development, neuromodulation

Introduction

A third wave of meditation research has emerged—the study of advanced meditation—which investigates deeper aspects of meditation, including soteriological constructs such as self-transcendence for promoting comprehensive well-being (Sacchet et al., 2024; Sparby & Sacchet, 2025a, 2025b). Unlike earlier meditation research that focused on broad psychological constructs such as mindfulness, and distinct from long-term meditation defined by duration rather than skill (Ehmann, et al., 2025b, 2025c), this newer focus of research emphasizes the multiplicity of antecedents and supporting conditions that enable access to distinct meditative states, stages, and endpoints that unfold with sustained practice and mastery (Sacchet et al., 2024). For millennia, contemplative traditions have maintained that proficiency in these skills is essential for realizing the deepest forms of human flourishing (Sparby & Sacchet, 2025b; Young, 2016), a view now supported by emerging empirical evidence (Ehmann et al., 2025e; Wright et al., 2023).

We refer to this process of systematically refining mental faculties and meditative techniques to access specific non-ordinary states of consciousness as *meditative development*. Meditative development is believed to be highly non-linear and multidimensional (Galante et al., 2023): the most profound existential transformations may require experiencing challenging aspects of the mind, during which practitioners cultivate new relations to suffering, thereby fostering psychological growth (Sparby & Sacchet, 2025a). Yet such later-stage development typically demands extensive training and expert guidance, often rendering accessibility to only a small subset of practitioners and limiting its broader impact.

To address this challenge, researchers are exploring novel technological applications, including non-invasive brain stimulation (NIBS) as a potential support for meditative development (Abellaneda-Pérez et al., 2024; Lord et al., 2024a). Among these, transcranial focused ultrasound (tFUS) is particularly promising: a safe NIBS modality that enables precise subcortical modulation with high spatial resolution (Blackmore et al., 2019). Unlike electrical or magnetic stimulation, tFUS uses low-intensity acoustic energy to penetrate the skull and modulate neural activity at millimeter scales, allowing access to deep brain structures without affecting intervening tissue. Proposed mechanisms include mechanical interactions with neuronal membranes—such as conformational state changes, activation of mechanosensitive ion channels, and intramembrane cavitation—that can alter excitability in a parameter-dependent manner (Dell'Italia et al., 2022). These properties position tFUS as a uniquely versatile tool for probing and augmenting the neurodynamics underlying meditative states.

Recent studies provide initial evidence for this potential, demonstrating that tFUS can enhance mindfulness (Lord et al., 2024b) and deepen meditative states (Cain et al., 2024). One neural target of particular relevance is the posterior cingulate cortex (PCC), a central hub of the default mode network (DMN) implicated in self-referential processing and mind-wandering, and shown to deactivate in long-term meditators across diverse practices (Brewer et al., 2011; Brewer & Garrison, 2014; Cooper et al., 2022). Reductions in PCC activation and within-DMN connectivity are thought to diminish entanglement in internally generated cognitions, thereby enabling more sustained, present-centered attention (Brewer et al., 2013). Preliminary work from our group suggests that tFUS can acutely reduce DMN functional connectivity when targeting the PCC (Lord et al., 2024b). Furthermore, using tFUS to support meditation training (Lord et al., 2025), we showed that tFUS increased resting-state DMN–CEN anticorrelation, which correlated with improvements in equanimity and subsequent self-chosen meditation sitting time. Building on this foundation, we thus propose that targeting the PCC with suppressive tFUS will directly reduce self-interference and promote equanimity—a core neurocognitive component of meditative development (Lord et al., 2024a; Young, 2016).

A contemporary unifying framework conceptualizes meditation practices as systematic training in cognitive, affective, and sensory processing skills (Young, 2016). These neurocognitive changes are argued to arise from three interrelated and mutually reinforcing factors: (1) flexible concentration—the capacity to sustain and direct attention while modulating attentional aperture; (2) equanimity—a non-interference with the natural flow of sensory experience (allowing sensations, emotions, or thoughts to arise and pass without suppressing, clinging, or resisting); and (3) sensory clarity—the resolution and detectability of sensory phenomena (Ehmann et al., 2025b, 2025c). Through structured practice, meditators are thought to develop these faculties, thereby increasing the likelihood of accessing more advanced meditative states, stages, and endpoints. Given that these outcomes are experiential in nature and meditation is by definition a mental activity, phenomenological methods are crucial to study the complex dynamics of meditative development (Sparby & Sacchet, 2022). Substantial research has highlighted the rigor and value of phenomenological approaches for investigating first-person experience and its causal dynamics, with meditators often considered ideal participants given their sustained and precise engagement with their own experiential content (Sparby, 2015, 2017, 2023, 2024).

Accordingly, this study employed a multimethod phenomenological approach to investigate the effects of PCC inhibition in expert meditators on equanimity and, more broadly, concentration and sensory clarity during a ten-day retreat. A central phenomenological construct was nondual awareness (NDA; Hanley et al., 2018)—a non-conceptual, non-representational reflexivity without a subject-object dichotomy (Josipovic, 2019, 2021, 2024; Young, 2016)—which is theorized to increase with ongoing meditative development (Cooper et al., 2022). In conjunction with measures of mindfulness, interoceptive awareness, and semi-structured response options, our goal was to provide a sufficiently comprehensive net of phenomenological assessments to capture how tFUS modulates mental factors such as equanimity and, in turn, influences the temporal dynamics of meditative states (e.g., acute nondual awareness), stages, and endpoints (e.g., trait-level nondual awareness)

Methods and Materials

Participants

Thirty-five participants (26 male, 9 female) enrolled in the study. Of these, 29 were recruited into the active tFUS condition and six into a non-equivalent comparison group. The comparison group consisted of individuals who were either ineligible for tFUS (n = 5) or declined participation (n = 1). During the retreat, three participants withdrew—one from the active condition and two from the comparison group—all for personal or scheduling reasons unrelated to the study.

For the quantitative analyses, the comparison group was excluded due to insufficient sample size and missing post-assessments. One additional participant from the active condition was excluded for missing post-retreat data, yielding a final quantitative analytic sample of 28. For the qualitative analyses, four participants (three from the active condition and one from the comparison group) were excluded for failing to complete the free-response prompt, resulting in a final qualitative sample of 28.

Exclusion criteria included: indication of pregnancy, history of head injury, epilepsy, migraines, cardiac problems, sleep disorders, or brain/mental illness (including drug or alcohol dependence); use of tobacco/nicotine or psychotropic drugs; current drug or alcohol intoxication; uncorrected hearing or vision impairment; and presence of metallic or magnetic implants or devices that would preclude MRI. Inclusion criteria were: age 18 and older, normal or corrected vision, ability to undergo MRI safely, and sufficient English proficiency to read the consent form.

The Meditation Retreat

Participants attended a nine-night retreat at Diamond Mountain, a Buddhist center in rural southeastern Arizona. This was the tenth consecutive year the retreat was held with the same teachers. The sample included both newcomers (eight participants attended this retreat for the first time, including one for whom it was their first retreat ever) and long-term attendees who had participated for many years. The meditation teachers leading the retreat were co-author TP and Upasaka Upali, who both trained primarily in the Southeast Asian lineage of Ananda Bodhi. Students on this retreat practiced a variety of techniques according to an individualized plan. The meditation practices fell into one of four categories: focused attention, insight, cultivation of positive mental qualities (such as lovingkindness), and “non-doing” practices such as *Shikantaza*.

Most of the retreat consisted of alternating periods of sitting meditation (45-60 mins) and walking meditation (generally 30 mins). There were three meals, and each evening the teachers gave a 90-minute lecture based on student questions. Students met individually with the teachers at least every other day, with the option to meet more frequently. The retreat was held in “Noble Silence,” meaning that while some necessary speech was permitted (such as talking with the teachers about practice or asking the chef about food allergies), students were silent nearly all of the time. The teachers let students know that it was acceptable to talk with the researchers when doing so was required for data collection.

Design and Procedures

The study was conducted in collaboration with two meditation teachers who regularly offer retreats. Participation was promoted through websites, social media, and teacher networks, where interested individuals could sign up. After registering, a research assistant contacted participants to confirm eligibility. Eligible participants (*n* = 29) received two 10-minute tFUS stimulation sessions during the 10-day retreat. For logistical reasons, stimulations were scheduled on nonconsecutive days with either three or four days between sessions, and no stimulations were conducted on the first or final day of the retreat.

This study was designed as a quasi-experimental feasibility and pilot trial, as no prior research has applied tFUS within a naturalistic retreat setting. The feasibility component evaluated recruitment, retention, and implementation logistics, while the pilot component provided preliminary data on study procedures and outcomes to inform future trials. All participants completed a standardized questionnaire, originally developed within clinical NIBS research, that assesses potential stimulation-related sensations and adverse effects (Schachtner et al., 2025), comprehensive phenomenological assessments at baseline and post-retreat, and a reduced set of daily assessments throughout the retreat, including semi-structured free response options.

TFUS Stimulation

Stimulation targeted the PCC using a custom-made single-channel low-intensity focused ultrasound system following the methods of Tufail and colleagues (Tufail et al., 2011; Blatek AT35246 transducer, 55 mm focus, BK Precision 4078 waveform generator). The signal was amplified by an E&I 210L Power Amplifier and monitored via a Tektronix TDS210 oscilloscope. Stimulation parameters—500 kHz acoustic frequency, 1000 Hz pulse repetition frequency, 5 ms pulse duration, and 5% duty cycle—were selected based on their suppressive effects on neural activity. During the 10-minute tFUS stimulation, the ultrasound device alternated between emitting sound waves for 5 seconds and pausing for 10 seconds. Targeting was guided by an MRI-based stereotactic system using a standardized brain (Visor2, ANT Neuro, Netherlands).

During stimulation, participants were seated comfortably. A depiction of the stimulation setup is provided in Figure 1.

After receiving tFUS, participants were advised to sit and relax in the immediate vicinity and follow their meditation practice, so that they could be monitored for any adverse events. Following this, a sensation report survey was administered (Schachtner et al., 2025), asking them to rate on a Likert scale of 1-5 sensations (from 1, “not present”, to 5, “severe”) of headache, unusual feelings on skin of the head, neck pain, tingling, itchiness, sleepiness, difficulty paying attention, unusual feelings/attitudes/emotions, tooth pain, change in hearing, nausea/sick to stomach, unusual twitches and movements in muscles, dizziness, anxious/worried/nervous, forgetful, difficulty with balance, change in movement in the stronger hand, abnormal sleep last night, seizure within the past 24 hours, and an open category for other; each of these sensations then had a prompt asking for a 1-5 rating of whether the participant attributed the reported sensation to tFUS.

Figure 1. Room setup for tFUS administration. Participants were seated in the chair while the transducer was manually positioned against the scalp and guided using a neuronavigation system.

Quantitative Data Analysis

Participants completed daily self-report surveys, as well as assessments administered before and after the retreat and following each tFUS session. The Nondual Awareness Dimensional Assessment–State (NADA-S; Hanley et al., 2018) was administered daily. Pre- and post-retreat assessments included the Five Facet Mindfulness Questionnaire (FFMQ; Baer et al., 2006), the Nondual Awareness Dimensional Assessment–Trait (NADA-T; Hanley et al., 2018), and the Multidimensional Assessment of Interoceptive Awareness, version 2 (MAIA-2; Mehling et al., 2012). The FFMQ includes five subscales (Observing, Describing, Acting with Awareness, Nonjudging, and Nonreactivity) and a Total score. The NADA-T comprises two subscales, Self-Transcendence and Bliss, along with a Total score. The MAIA-2 includes eight subscales: Noticing, Not-Distracting, Not-Worrying, Attention Regulation, Emotional Awareness, Self-Regulation, Body Listening, and Trusting, in addition to a Total score. All measures were scored according to their respective manuals or source papers, and double data entry was performed to ensure accuracy.

Pre-Post Surveys.

Given the small size of the comparison group and one participant missing post-retreat data, analyses focused on within-subject pre–post changes in the active condition (n = 28). Subscale and total scores were standardized (z-scores), and pre–post differences were evaluated using paired-samples t-tests. Because outcomes were z-scored within each subscale, effect estimates represent the mean change in standard deviation units, with positive values indicating increases from pre- to post-test. We denote mean change scores (post − pre) in z-units as Δ.

Assumption checks were conducted for normality, independence, and homoscedasticity. Shapiro–Wilk tests on residuals indicated significant departures from normality for the MAIA Noticing and Self-Regulation subscales, the NADA Total and NADA Bliss subscales, as well as the FFMQ Nonjudging subscale (all uncorrected $p < .05$); all other total scores and subscales did not deviate from normality. Residuals showed positive within-participant correlations across most subscales ($r \approx 0.19$–0.77; 13 of 18 tests $p < .05$), indicating violation of the independence assumption. Breusch–Pagan tests were non-significant for all subscales (smallest p = .065, MAIA

Total), suggesting approximate homoscedasticity. P-values for the paired-samples t-tests were adjusted for multiple comparisons using the Benjamini–Hochberg false-discovery-rate procedure.

Daily Surveys.

Daily NADA-S data were available for the same 28 participants as in the pre–post analysis. Scores were averaged across the three items within each day. Sonication day assignments were merged by participant, and dummy indicators marked sonication days and post-session periods. Assumption checks indicated slight departures from residual normality, although random intercepts were approximately normal. Residuals showed evidence of positive autocorrelation, consistent with the repeated-measures design, and variance appeared approximately homogeneous. Overall, these results supported the use of a linear mixed-effects model. The model was estimated with day, sonication day, and post-session indicators as fixed effects and participant as a random intercept, with p-values calculated using Satterthwaite approximations.

Qualitative Data Analysis

This study employed an inductive thematic analysis to identify experiential themes across participants without imposing a predefined conceptual framework (Braun & Clarke, 2006, 2023). Such exploratory approaches are particularly appropriate in areas with limited prior research (Hunter et al., 2019). Our approach drew on phenomenological epistemology, highlighting the ways in which meditators perceive, interpret, and express their own experiences (James & Busher, 2009). Methods and results are presented in accordance with the Consolidated Criteria for Reporting Qualitative Research (COREQ) guidelines (Tong et al., 2007). A completed COREQ checklist is provided in Supplement A.

Participants provided handwritten responses to a semi-structured prompt ("What were some memorable moments from your meditation today? Describe your experience.") on eight consecutive days of the retreat. Because the retreat followed a vow of silence, no interviews or focus groups were conducted. Responses were composed independently, typically in participants' cabins during the evening, which minimized researcher–participant interaction and reduced interviewer bias.

The research team was multidisciplinary, including psychologists, neuroscientists, meditation teachers, and students trained in qualitative analysis. Coding was conducted by two researchers (H.B.B., J.R.) with no direct relationship to participants, trained and supervised by S.E., who has several years of experience in qualitative and phenomenological analysis. Other team members provided oversight but did not code directly. While participants may have been indirectly aware of the team's interest in neuromodulation through public materials, no investigator disclosed personal beliefs about tFUS during the retreat.

Qualitative analysis followed a structured, iterative process. Two coders independently generated preliminary themes, which were refined through discussion with S.E. into a shared coding tree. Coding rounds continued until all themes reached strong inter-rater reliability ($\kappa \geq .80$; Landis & Koch, 1977). Themes were derived inductively with close attention to participants' terminology, while established contemplative frameworks (e.g., Buddhist concepts such as equanimity or meditative obstacles) informed inclusion and exclusion criteria. Meditative vocabulary that could not be independently verified was coded separately to preserve fidelity to first-person accounts.

Data management was performed using QualCoder (Version 3.6; Curtain, 2025). Themes were organized within a codebook, defined by inclusion and exclusion criteria, and illustrated with participant quotations identified by number. Given the large sample size relative to qualitative standards, and the high volume of reports (224 interviews), data saturation—conceptualized as the point where further data fail to generate substantially new themes or insights (Guest et al., 2020)—was not considered a limiting concern, as previous phenomenological studies have demonstrated full saturation after 9–17 interviews (Hennink & Kaiser, 2022). In presenting results, quotations were minimally edited for clarity. Minor disfluencies and filler words were removed when they did not affect meaning or tone. Ellipses (…) denote short omissions, bracketed ellipses […] longer ones, and square brackets were used sparingly to clarify meaning or complete fragments.

Results

TFUS Administration

Sensation Survey.

The median and mode for all sensations in the survey were 1 (“not present”), indicating that the most common report for all sensations was that they were not present. The most reported sensations were unusual feelings/attitudes/emotions (mean = 1.52; attribution to tFUS when present mean = 3.24), sleepiness (mean = 1.48; attribution to tFUS when present mean = 1.27), and difficulty paying attention (mean = 1.33; attribution to tFUS when present mean = 1.12). For a detailed visualization of the sensation survey results, see Figure 2.

One participant reported an incident following his first stimulation session, in which he felt light-headed and needed to lie down. After drinking water and eating food, he recovered and reported that he had not eaten all day, as he was affected by the higher elevation of the retreat site. The participant did not attribute these effects to the tFUS. He successfully completed the retreat, including the second stimulation session, without any adverse events. A second participant reported experiencing a strong non-ordinary state of consciousness following stimulation and chose to remain seated for approximately 10 minutes before resuming retreat activities. She did not consider these effects adverse but rather positive.

Implementation logistics.

TFUS administration and data collection proceeded without major difficulties; however, the study required extensive advance planning to prevent disruptions during the retreat. Given the remoteness of the retreat center and the rapid pacing between sessions, nearly all materials and equipment had to be transported in advance. Equipment setup was relatively straightforward, as the researchers’ cabin provided the necessary infrastructure (e.g., electricity, water). To preserve the vow of silence, both participants and staff received clear instructions beforehand, underscoring the importance of careful preparation to minimize interference with retreat structure.

The administration of tFUS placed some burden on the research team due to the sample size. Ten sessions were administered per day, with a 30-minute allotment for each. Sessions had to be staggered, such that each participant’s first and second administrations were spaced at consistent intervals but distributed across different days in three separate waves. Two researchers stayed overnight at the retreat site, which made the day-to-day running of sessions more feasible. While this scheduling strategy was necessary, it introduced complications for data entry and analysis because of the lack of uniform timing across participants. Nonetheless, advance scheduling with built-in flexibility proved effective in accommodating occasional errors or delays.

Data collection also proceeded smoothly overall. The structured retreat schedule provided a reliable framework for participants to remember and return their paper surveys, supporting the completeness of data capture. Most participants were punctual and respectful of the silence when moving to and from tFUS sessions, indicating that participant flow was generally smooth. At the same time, the need to monitor session timing required some participants to attend closely to logistics. In addition, one experience-tracing assessment produced limited usable data, suggesting that the overall number of assessments may have exceeded what participants could reliably complete within the retreat context.

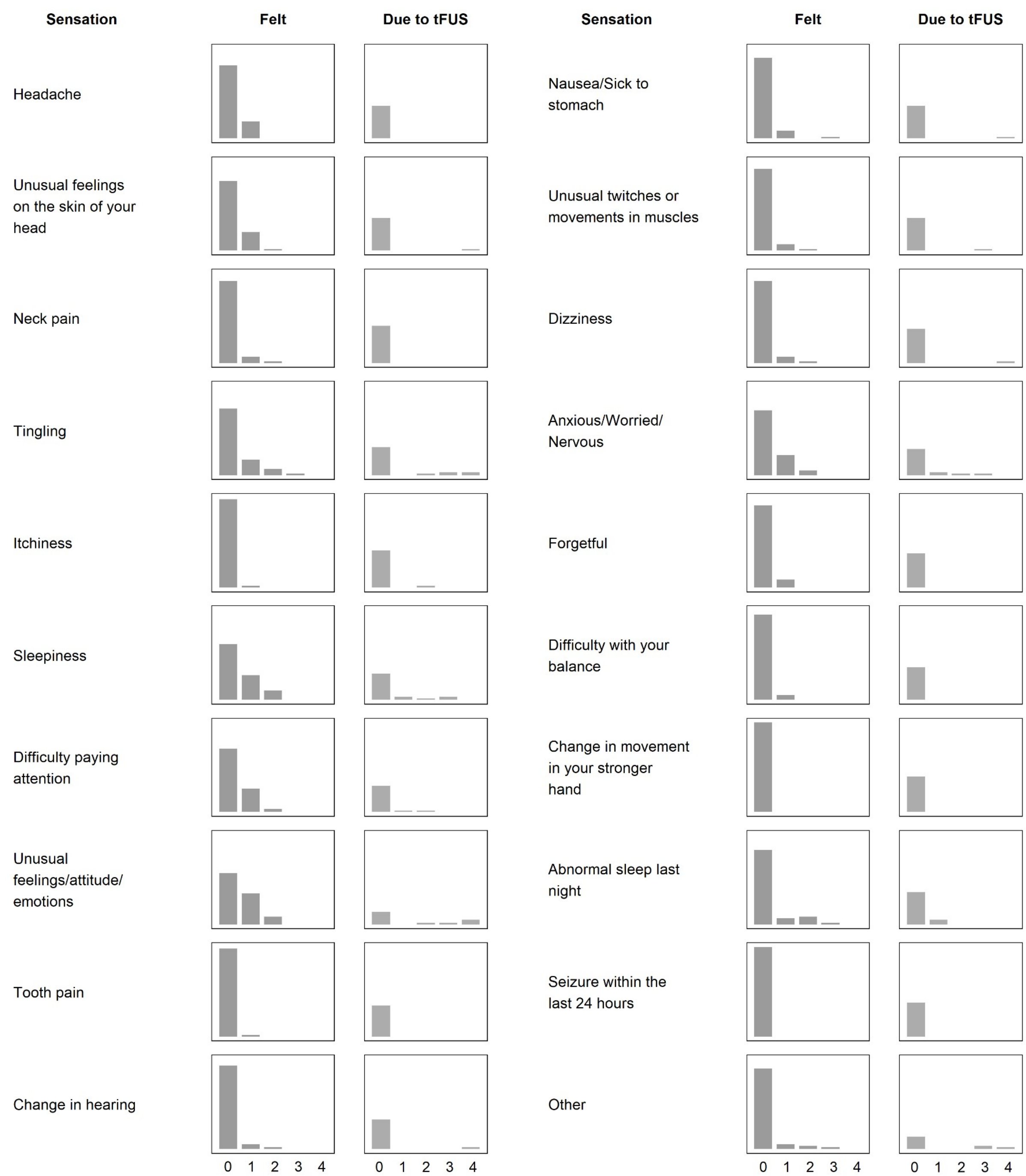


Figure 2. Sensation reports following active tFUS. For each symptom, histograms display ratings on a 1–5 scale. The “Felt” column shows the percentage of participants reporting the extent to which the symptom was experienced, from 1, “not present”, to 5, “severe”. The “Due to tFUS” column shows the percentage attributing the sensation to tFUS for those that were endorsed, from 1, “unrelated,” to 5, “definitely”.

Quantitative Results

Pre–Post Surveys.

Per subscale and total scale, mean change scores (post − pre, expressed in z-units) were tested using paired-samples t-tests with Benjamini–Hochberg false discovery rate (FDR) correction. After correction, eight outcomes showed significant increases: FFMQ Total (Δ = 0.758, p_{FDR} = 0.001), and the FFMQ subscales Acting with Awareness (Δ = 0.829, p_{FDR} = 0.001), Observing (Δ = 0.641, p_{FDR} = 0.001), Nonreactivity (Δ = 0.658, p_{FDR} = 0.011), and Describing (Δ = 0.480, p_{FDR} = 0.033); MAIA Body Listening (Δ = 0.434, p_{FDR} = 0.033); and NADA Self-Transcendence (Δ = 0.426, p_{FDR} = 0.021) and NADA Total (Δ = 0.383, p_{FDR} = 0.021). All other outcomes were non-significant after correction ($p_{FDR} \geq 0.111$). Spaghetti plots for the significant outcomes are shown in Figure 3, and the full set of effect estimates and adjusted *p*-values appears in Table 1.

Daily Surveys.

Linear mixed-effects models with day, sonication day, and post-session period as fixed effects and random intercepts for participants showed that NADA-S scores increased steadily across the retreat (β = 0.18 per day, *SE* = 0.03, $p < .001$; see Figure 4). Scores did not differ on the first sonication day (β = 0.10, *SE* = 0.12, p = .40) and showed only a trend toward higher values on the second (β = 0.22, *SE* = 0.12, p = .06). No reliable shift was observed in the days following the first session (β = −0.21, *SE* = 0.14, p = .15), but a modest decrease emerged after the second (β = −0.33, *SE* = 0.15, p = .027).

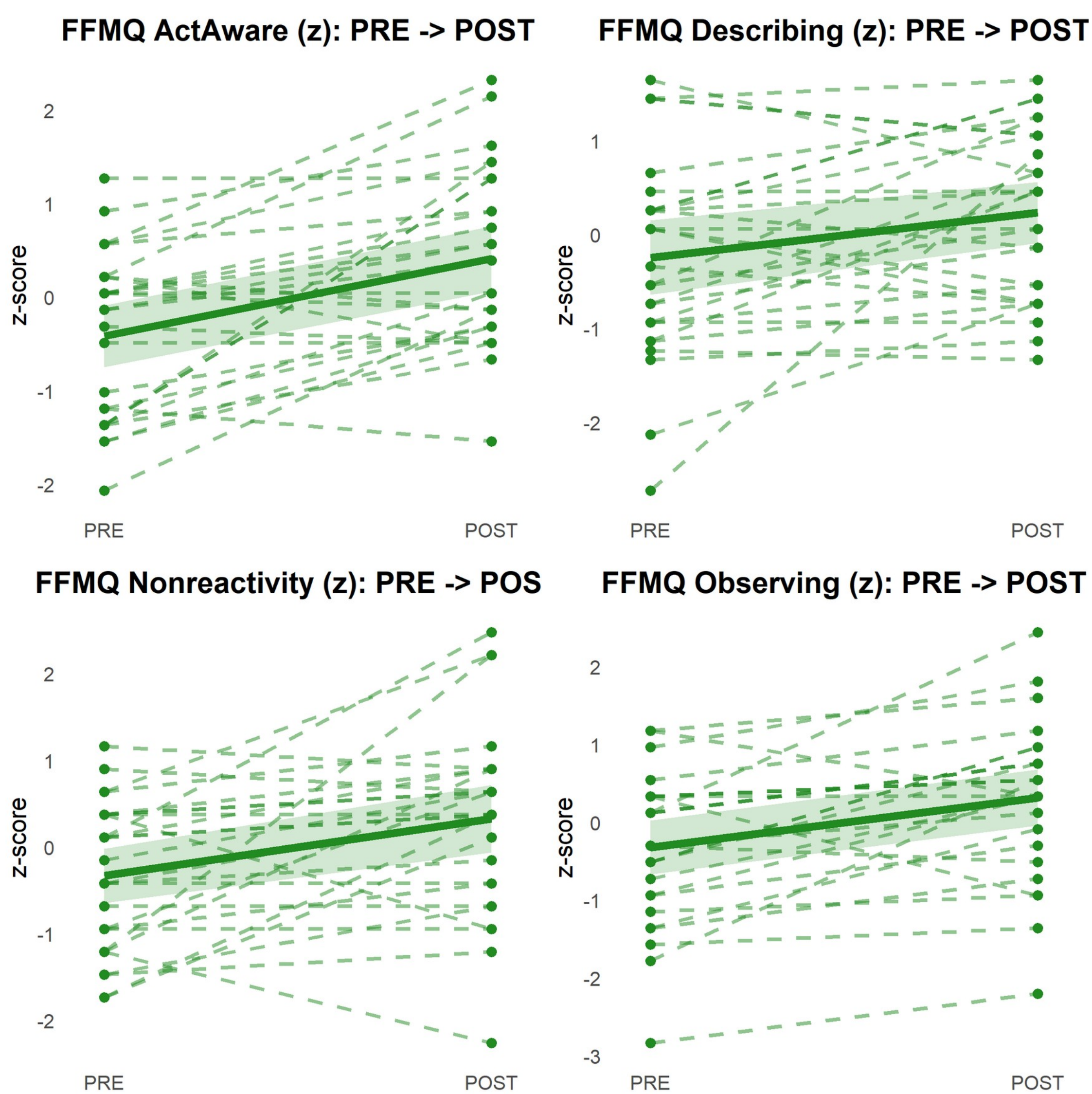
Table 1

Pre-Post Survey Results

Survey	Subscale	Estimate Δ (z-units)	*p*-value (uncorrected)	Corrected *p*-value (FDR)
FFMQ	**Acting with Awareness**	**0.829**	**< 0.001**	**0.001**
FFMQ	**Describing**	**0.480**	**0.015**	**0.033**
FFMQ	Nonjudging	0.284	0.133	0.184
FFMQ	**Nonreactivity**	**0.658**	**0.002**	**0.011**
FFMQ	**Observing**	**0.641**	**< 0.001**	**0.001**
FFMQ	**Total**	**0.758**	**< 0.001**	**0.001**
MAIA	Attention Regulation	0.402	0.068	0.111
MAIA	**Body Listening**	**0.434**	**0.015**	**0.033**
MAIA	Emotional Awareness	0.331	0.066	0.111
MAIA	Not Distracting	0.141	0.567	0.567
MAIA	Not Worrying	0.185	0.293	0.351

MAIA	Noticing	0.195	0.316	0.355
MAIA	Self-Regulation	0.149	0.495	0.524
MAIA	Total	0.402	0.086	0.128
MAIA	Trusting	0.311	0.153	0.197
NADA	Bliss	0.254	0.068	0.111
NADA	**Self-Transcendence**	**0.426**	**0.006**	**0.021**
NADA	**Total**	**0.383**	**0.007**	**0.021**

Note. The table presents pre–post survey results with FDR-corrected p-values. Significant results (p_{FDR} < .05) are shown in bold. Estimates represent mean pre–post change scores (*Δ*) expressed in z-units (SD units).



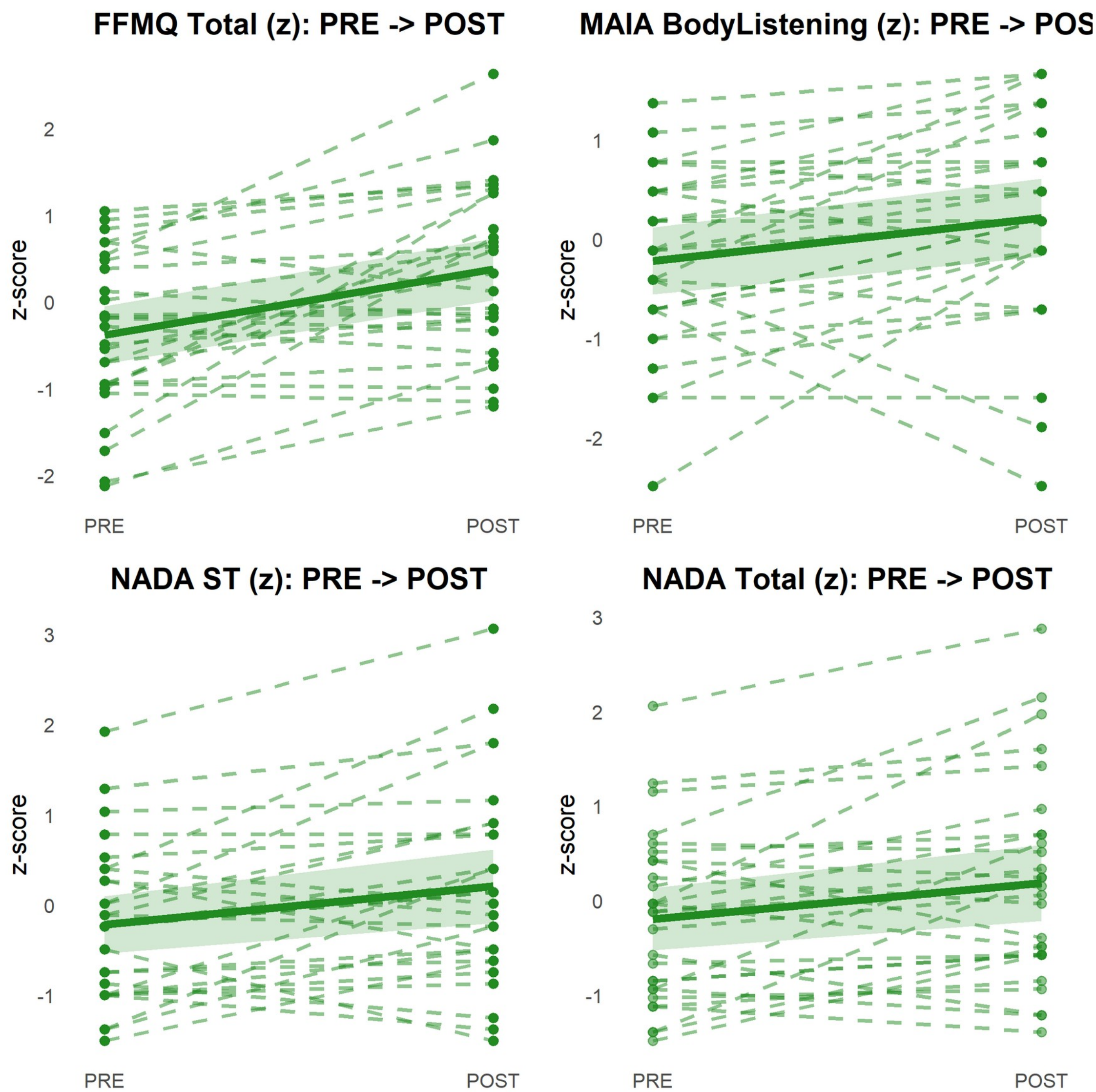


Figure 3. Change in FFMQ subscales (*Acting with Awareness, Describing, Nonreactivity,* and *Observing*), FFMQ Total, NADA Total, NADA *Self-Transcendence*, and MAIA *Body Listening* scores from pre- to post-assessment. Each dashed line represents an individual participant (n = 28), with points showing z-scored values at each timepoint. The ribbon plot shows the mean, with a 95% confidence interval. Positive slopes indicate increases from pre to post.

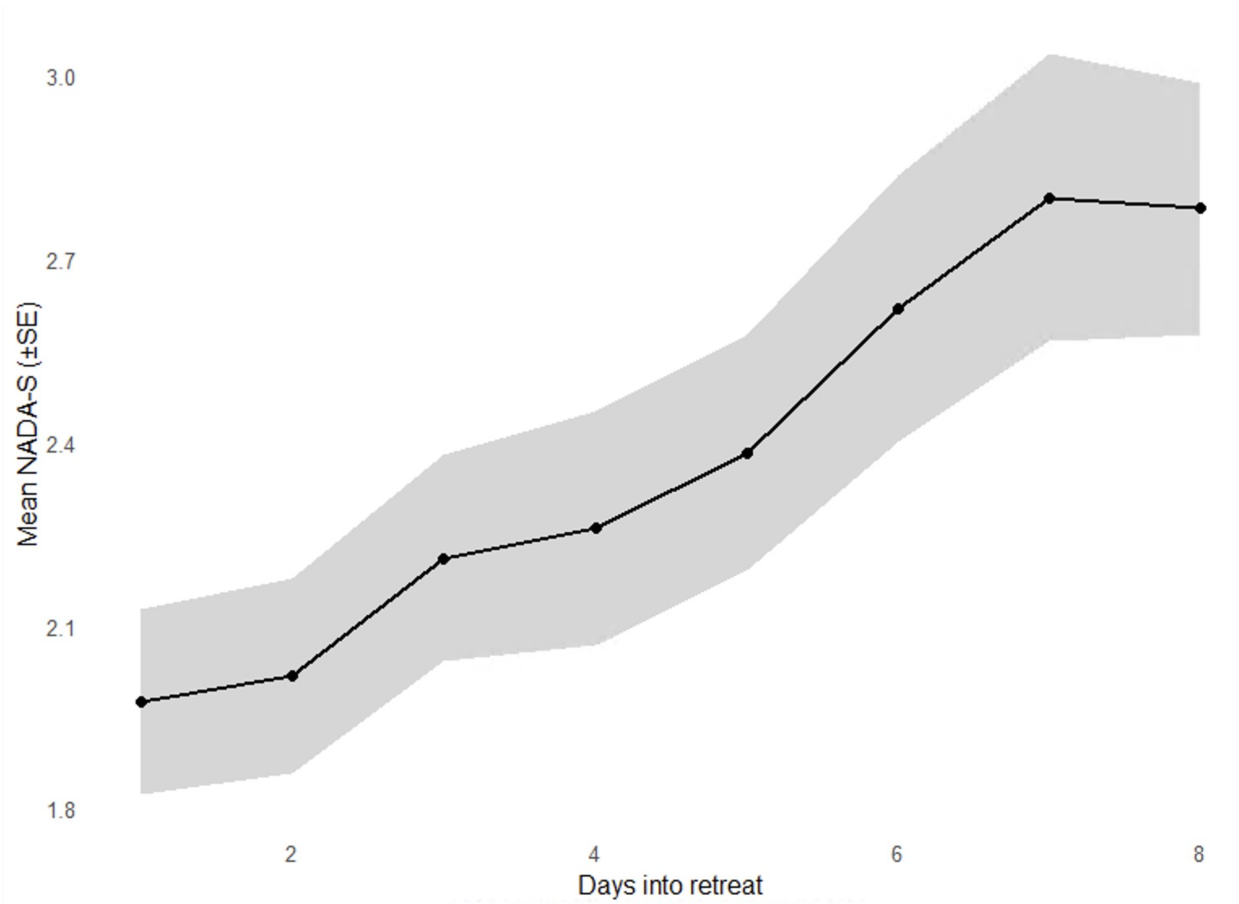


Figure 4. Daily NADA-S scores across the retreat. The solid line depicts the mean score, and the shaded area indicates the standard error of the mean. Scores increased steadily across retreat days.

Qualitative Reports

Qualitative findings indicated marked differences in thematic patterns on days when participants received tFUS stimulation compared to non-stimulation days (see Figure 5 for a visualization). For clarity, the results are summarized by contrasting themes that emerged between stimulation and non-stimulation days, although participants' reports also suggested potent non-linear interaction effects between their ongoing retreat practice and the tFUS intervention. These interaction effects are addressed in greater detail in the discussion section.

Thematic analysis of 224 interviews from 28 participants yielded 13 themes reflecting the experiential changes reported across the retreat. The primary themes included: (1) Catharsis, (2) Effortlessness, (3) Equanimity, (4) Insight, (5) Meditative Barriers, (6) Meditative States, (7) Negative Experience, (8) Positive Experience, (9) Negative Practice Judgments (10) Positive

Practice Judgements, (11) Shift in Self Perception, (12) Spaciousness, and (13) Qualities of Meditative States. A summary of all identified themes, together with their definitions and a sample quote, is provided in Table 2. For a more detailed overview, including inclusion and exclusion criteria, see Supplement B (codebook).

Table 2

Themes Identified Across All Retreat Participants, Independent of Stimulation Day

Themes	Definition	Sample quote
1) Catharsis/ Emotional Release [35]	Release of an emotional knot/entanglement	“After that, I was able to experience [full bodied] sadness and find peace.” (Participant 120)
2) Effortlessness [41]	A reduced sense of mental or physical strain when engaging with practice	“The experience of "things just happening" without much effort or intervention on my side, e.g. my mind can "decide" to do vipassana or body scanning on particular body parts without me prompting it.” (Participant 106)
3) Equanimity [49]	A non-interference with sensory experience	“While there was some conflict that arose from this experience, I didn't get wrapped up in rumination and was generally able to see the thoughts as transient and impermanent.” (Participant 129)
4) Insight [38]	A mental realization of sudden new understanding of something previously unclear or unknown	“I discovered that this emotional blockage I have worked on is actually [a] reaction of the mind against a sense of separateness with experience.” (Participant 114)
5) Meditative Barriers [117]	A mental factor or condition that obstructs the deepening of practice	“Today the mind was very chatty. During meditation I experienced over-efforting.” (Participant 107)
	The report of previously mapped or described	“I think I've been able to do the 2nd formless jhana.” (Participant 112)

6) Meditative States [39]	meditative states or stages	
7) Negative Experience [92]	Any cognitive, emotional, or somatic states of negative character	“I was extremely annoyed over the discussion of temperature in the dharma hall. I was pretty absorbed in feeling bad.” (Participant 203)
8) Positive Experience [114]	Any cognitive, emotional, or somatic states of positive character	“Warm loving joy radiated upwards from my heart area and gradually come to fill my chest and shoulders/neck.” (Participant 101)
9) Negative Practice Judgments [27]	Any negative evaluative judgments towards the quality of one’s practice	“None of my sits felt very productive.” (Participant 124)
10) Positive Practice Judgments [45]	Any positive evaluative judgments towards the quality of one’s practice/sits	“Had an extremely nice sit late at night.” (Participant 121)
11) Shift in Self Perception [34]	Any reported changes to the self	“Had a sit in the morning where I stopped perceiving sensations as being perceived by someone and just being perceived and there was nothing else than what was there moment to moment, so "myself" was changing moment to moment and "I" was the sensations every moment.” (Participant 108)
12) Spaciousness	A sense of openness/expansion or spatial boundlessness.	“I felt like [...] I was holding a rapidly increasing vast space between my arms and hands which were heavy like boulders.” (Participant 101)

[24]		
13) Qualities of Meditative States [142]	Factors or qualities of meditative experiences	"I did [have] a sense of bodily calm that I could rest into and a very pleasant high sensory clarity."

Note. Numbers in brackets represent the total number of coded segments assigned to each theme.

Non-Stimulation Days.

On non-stimulation days, participants reported a wide range of experiences that varied from positive states of bliss, clarity, and insight to more challenging states, including emotional distress, mental agitation, and fatigue. While some participants remained more constant than others, generally, the occurrence of positive and negative themes for each participant oscillated back and forth over the course of the retreat. Several days of positive themes such as effortlessness or positive practice judgments were typically followed by 1-2 days of reported barriers to meditation or negative experience, and vice versa, reflecting the non-linearity of meditative development. When participants described a more positive day, reported themes included: happiness, compassion, insight into the nature of mind and experience, and enhanced sensory or emotional clarity. For example, Participant 113 (day 5) described: "*Some very wonderful moments [and] sits that were very pleasant. Flying high most of the day*." And Participant 107 noted: "*In the last meditation there was a good focus and sensory clarity.*"

Conversely, on more challenging meditation days, participants reported difficulty accessing meditative states, pervasive mind-wandering, restlessness, and discouragement regarding barriers to meditation.

For instance, participant 103 (day 4) noted significant emotional distress: "*Off the cushion, extremely distracted by thoughts and stresses related to personal life -- really struggled to set that aside to focus on practice today. Very pronounced and ongoing feelings of anger which have been hard to work with or around.* [He concluded that he experiences] *frustration and self-judgment about that*."

Participant 129 (day 5) also highlighted salient difficulties, describing a perceived lack of meditative development and corresponding negative emotions: "*The first half of the day was difficult—boredom mixed in with discouragement brought in from the lack of progress.*" Participant 119 described similar discouragement on day 2, stemming from an inability to cultivate and sustain a productive meditative practice: "*Led to a lot of effort that burned me out super quickly and led to a lot of mind wandering*."

Stimulation Days.

During tFUS stimulation days, participants frequently reflected on the effects of the neuromodulation on their practice, often contrasting their pre-stimulation experiences with post-stimulation experiences. Broadly, participants described marked shifts in multiple dimensions of their practice. Compared to before stimulation, participants reported a heightened presence of meditative qualities including sensory clarity, non-dual awareness, and tranquility; more positive evaluations of their own practice; and an increased sense of equanimity. In several cases, stimulation also appeared to catalyze shifts in self perception and cathartic emotional releases, allowing participants to reframe their view on themselves and to process difficult emotions inhibiting the deepening of practice.

One participant (129, day 9) described a substantial change in their experience before and after ultrasound, noting improved tranquility and concentration: "*I got so much mind chatter and kept getting distracted. I was feeling disappointed that I had lost progress and that I was leaving in such a state. But then I got sonicated [tFUS] and wow! The change in my meditation and mental state was so noticeable. I was more calm, more present, more in the moment and more content. I wanted to just stay in your cottage and meditate.*"

Enhanced attentional control and perceptual clarity were also commonly reported. As Participant 120 (day 3) noted: "*The ultrasound experience was significant. Time felt slower, concentration was 5x-10x stronger and able to be placed wherever I wanted. Some normal thoughts came up but it was easy to drop them and focus elsewhere. I was able to experience my emotions in more detail, especially difficult ones. My meta-awareness was very high.*"

Participants also indicated profound enhancements of meditative absorption and reduced identification with and solidification of mental phenomena on stimulation days. Following their ultrasound on day 3, participant 119 noted: "*Sonification immediately improved single pointed-ness. Did a 45 min sit afterward that caused a level of de-reification I had never experienced before.*"

Another common difference to non stimulation days were reports of an increased sense of equanimity, as in participant 129's description of how, after their second ultrasound session on day 9, they experienced an increased acceptance towards negative thoughts and emotions which they had previously been ruminating over: "*While there was some conflict that arose from* [addressing these emotions]*, I didn't get wrapped up in rumination and was generally able to see the thoughts as transient and impermanent.*"

Also present were reports of participants experiencing a shifting sense of the boundaries of the self, as in one description by participant 121 on day 4: "*During the ultrasound I was able to "accept" many feelings and experiences very rapidly. So there was a cascade of acceptance and falling away of phenomena that I was experiencing & identifying with*."

Additionally, several meditators highlighted substantial cathartic moments following the ultrasound, in which previously described negative emotions were processed and released leading to a sense of relief. Demonstrating a strong emotional shift on day 8, participant 121 stated: "*[I'm] experiencing some of the most discomfort and suffering I ever have. That transitioned into anger. The most significant change was the sonication. After that, I was able to experience full-bodied sadness and find peace. Today was the first time I have been able to notice emotions go all the way up to the front of my neck instead of just being in my torso because of the ultrasound.*"

In addition to meditation-related themes, an increase in reports of negative experiences was noted on stimulation days. Many of these instances (*n* = 9, 40.9%) were highlighted by participants prior to the administration of ultrasound. These occurrences were assessed as unrelated to the stimulation and appeared to be more due to the participants' natural day-to-day emotional fluctuations. Several of these occurrences resolved later in the day, while others did not. Although tFUS was generally well tolerated, transient sensations were reported in some instances (*n* = 5, 22.7%), such as apprehension about neuromodulation, minor headaches, or tingling and itching of the scalp. These effects were short-lived and typically resolved after the first session, suggesting that initial nervousness about what to expect may have contributed to their occurrence. Another 5 instances (22.7%) were mentioned following the ultrasound, with some being related to stimulation (e.g. unmet expectations) and others appearing unrelated. Some of the increased reporting of negative experiences also appeared to result from participants deliberately emphasizing pre-stimulation meditative challenges in order to highlight contrasts with subsequent effects (*n* = 3, 13.6%). These contrasts often involved strong state shifts, including cathartic releases, the dropping of resistances through enhanced equanimity, and reductions in mind-wandering or rumination that gave way to greater ease and stillness.

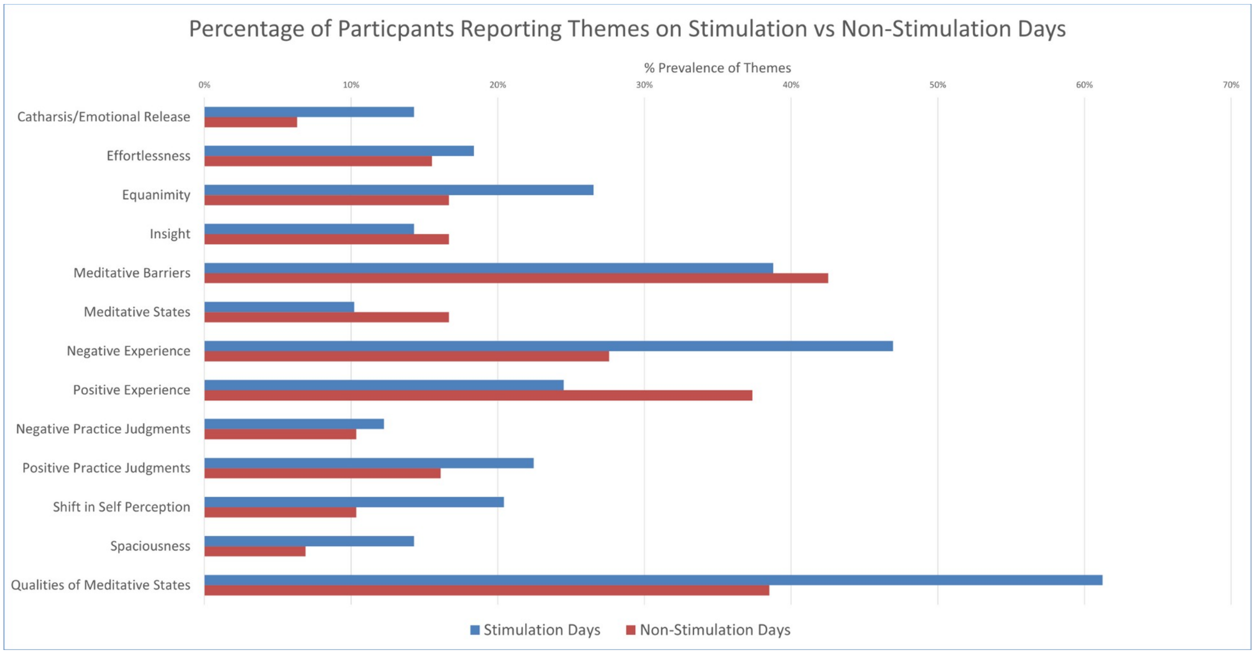


Figure 5. Percentage of participants reporting themes on stimulation vs non-stimulation days.

Discussion

This study investigated the feasibility and preliminary effects of tFUS, a NIBS technology, on meditative development in a naturalistic meditation retreat setting. Results from 28 participants indicated that tFUS was generally well tolerated with minimal adverse effects. Implementation was feasible but required careful logistical planning to avoid interference with the retreat schedule and to ensure standardized data collection. Pre–post analyses of trait measures revealed increases in canonical mindfulness, particularly in the subfacets Acting with Awareness, Observing, Nonreactivity, and Describing, as well as trait-level increases in NDA and its subfacet Self-Transcendence. For interoception, only the Body Listening subfacet showed a significant change, while the remaining seven subscales and the total score were nonsignificant. Consistent with the trait-level increases in NDA, daily surveys of state NDA showed incremental gains across the retreat. These increases were not specifically associated with tFUS days, although a significant decline in state NDA emerged following the second tFUS session. Qualitative findings revealed substantial variability in experiential content both across participants and over time. Nevertheless, we identified consistent differences in themes between tFUS days and non-tFUS days. Specifically, participants reported a greater presence of meditative experiential qualities on tFUS days, including clarity, non-dual awareness, tranquility, as well as increases in equanimity, shifts in self-perception, and moments of emotional catharsis.

These results suggest that tFUS can be effectively implemented in a naturalistic retreat environment with minimal adverse effects. Findings point to a progression in deeper meditative development consistent with recent research on cognition in long-term practitioners, reflecting a unified neurophenomenological gestalt of mindfulness characterized by enhanced emotion regulation, improved self-regulation, and greater access to self-transcendence, but more variable effects on interoception (Ehmann et al., 2025c). Although the study design did not permit the quantification of tFUS-specific effects on meditative phenomenology due to a lack of a sham control group, the considerable effect sizes and simultaneous increases in both state and trait constructs related to advanced meditation—particularly NDA—suggest meaningful progression in meditative development that may have been supported by stimulation sessions, a conclusion reinforced by the qualitative findings.

Prior studies have reported improvements in state NDA following mindfulness-based interventions (Garland et al., 2024; Hanley et al., 2023), higher trait NDA in experienced meditators relative to novices (Hanley et al., 2018), and increases in both trait NDA and trait mindfulness during a nine-month traditional Tibetan mind–body program (Ehmann et al., 2025a). Yet links between trait mindfulness and trait NDA (Hanley, et al., 2018) remain inconsistent

(Ehmann & Gawrysiak, 2025), and some studies report that trait mindfulness measures fail to reliably distinguish advanced from novice meditators (Christopher et al., 2009). Against this background, the observed state–trait increases in NDA are particularly promising, given ongoing concerns about the construct validity of canonical mindfulness questionnaires for capturing long-term meditative development (Sacchet et al., 2024).

Beyond concerns about the construct validity of meditative developmental measures, future research should address the dynamic interplay of meditative states and traits across developmental trajectories. Meditative development is inherently circular and nested; that is, a practitioner's baseline or current stage of skill shapes the quality of present training, while the intensity and dose of training, in turn, influence subsequent stage progression (Ehmann et al., 2025c, 2025d). With tFUS adding a further dimension to this already complex process, computational models that formalize meditative phenomenology may help capture the multiplicity of interactions between traditional practices and novel tools (Tal et al., 2025). Systematic investigations of these circular dynamics, supported by standardized training frameworks that track meditative variables longitudinally and across stages, could provide deeper insights into how states and traits co-evolve over time (Ehmann et al., 2025d).

These considerations also underscore the value of qualitative methodologies for uncovering nuanced individual changes in meditative development (Sparby, 2015, 2017, 2023, 2024). Our qualitative results suggest substantial acute tFUS-related enhancements in key meditation-related faculties (Young, 2016). Consistent with our hypothesis that PCC suppression would promote greater openness, acceptance, and non-interference toward sensory phenomena, tFUS appeared to notably increase equanimity while also enhancing concentration and sensory clarity (Lord et al., 2024a). These improvements likely facilitated greater access to experiential meditative qualities, such as ease, stillness, and spaciousness, as well as cathartic emotional releases and shifts in self-perception. However, the exact effects of tFUS remained strongly dependent on the meditator's experiential context. For example, psychological or meditative breakthroughs frequently emerged in relation to prior challenges or blockages, with cathartic moments tied to the resolution of unresolved emotional resistance. From a theoretical standpoint, one might understand this as suggesting that tFUS enhances baseline equanimity in ways that potentially scaffold the cultivation of other mutually reinforcing meditative skills, thereby fostering development across multiple domains and enhancing access to advanced meditative states and stages (Ehmann et al., 2025d; Young, 2016). In this way, tFUS-supplemented meditation practice may not only induce technology-facilitated state shifts but also provide conditions conducive to profound psychological transformation through meditative endpoints, including what have been referred to as, for example, enlightenment, *nibbana*, *nirvana*, salvation, or awakening (Shinozuka et al., 2025; Sparby & Sacchet, 2025b; Yang et al., 2025a, 2025b). At the same time, prior research has underscored the benefits—and even the necessity—of difficult or challenging experiences for psychological growth (Sparby & Sacchet, 2025a). Thus, future work is needed to determine whether tFUS-induced equanimity shifts are universally beneficial for meditative development, or whether there may be contexts in which unsupported engagement with raw, challenging experience is more supportive of growth. Assessing meditative development within specific frameworks of advanced meditation—such as investigative insight stages or deep concentration (absorption) states—could clarify tFUS's role in supporting developmental shifts toward advanced meditative states, stages, and endpoints, as well as illuminate how such transitions relate to the cultivation of core meditative faculties like equanimity, concentration, and sensory clarity.

When considering the interaction between tFUS and meditative practice, it is important to emphasize that the aim is to integrate the technology with the practice—facilitating both the experience of equanimity and the learning of equanimity—rather than to use it as a replacement. Previous research has demonstrated tFUS-induced increases in neuroplasticity (Kronberg et al., 2020; Niu et al., 2022; Yaakub et al., 2023), suggesting that the technology may open windows for enhanced learning and skill acquisition (Ashcroft et al., 2020; Clark et al., 2012; Reis et al., 2009; Veldman et al., 2018; Wessel et al., 2016). If appropriately incorporated into the intentions and context of meditation, such effects could foster more effective meditative development (Galante et al., 2023; Sparby & Sacchet, 2022). Future research should therefore adopt interdisciplinary approaches in which specific meditative practices are strategically paired with tFUS to optimally support skill acquisition and growth. This endeavor will require deeper phenomenological insight into the experiential dynamics and mechanisms of combining both tFUS and selected meditative activities, in order to identify synergies that meaningfully support meditative development.

Beyond the specific practices, as with psychedelic experiences, the mental *set* or orientation of the practitioner and the environmental *setting* are crucial for effectively integrating tFUS into meditative development (Carhart-Harris et al., 2018). While tFUS may induce transient experiential states, an exclusive focus on these states risks fostering grasping and distraction from practice. By contrast, cultivating equanimity—the capacity to meet all arising experiences with balance and acceptance—supports the integration of such states into a stable meditation practice. In this framework, ultrasound is not valued for the transient states it produces, but for its potential to serve as a training ground for equanimity and deeper contemplative growth. In addition to emphasizing mental *set*, we sought to create a supportive physical environment. The "tFUS room" was designed to minimize clinical sterility, with soft lighting and comfortable cushions, to encourage productive practice. As the technology advances and systems require fewer screens and wires, the sense of intimidation or unfamiliarity will likely diminish. Collectively, these considerations and adjustments help mitigate the risk of disappointment from unfulfilled expectations, ensuring that the technology supports rather than disrupts practitioners' developmental trajectories.

Limitations and Future Directions

Several limitations should be noted. First, given its open-label, repeated-sampling design, this study cannot support causal inferences regarding the effects of tFUS on meditative development. A viable, more rigorous future design could involve a randomized waitlist crossover block design with an active sham condition, in which all participants are informed that they will receive tFUS. Random assignment to active or sham conditions at the outset would allow for causal inferences, while the cross-over structure would make it possible to examine the effects of active tFUS at different stages of a meditation retreat. Additionally, expectancy and placebo effects may have contributed to participants' reports, given the novelty and perceived promise of ultrasound stimulation. Future studies employing double-blinding and active sham stimulation will be crucial to disentangle genuine neurostimulation effects from expectancy-driven changes. Furthermore, given the pilot and feasibility design of this study, power and sample size were not specifically controlled, which limits the ability to draw firm statistical conclusions.

Second, because participants self-selected into this retreat and most were long-term meditators, there is a likely selection bias that may limit the generalizability of the findings. Future studies could investigate the effects of tFUS in novice meditators to examine whether equanimity-enhancing effects extend beyond highly trained practitioners, and whether such effects might facilitate more rapid meditative development at earlier stages of practice.

Third, although the retreat was structured, it is not known which specific meditative techniques participants practiced at any given time, or in what dose. This enhances on the one hand the real-world applicability of the findings but simultaneously reduces the ability to examine possible interactions between specific meditative practices and tFUS.

Fourth, because this study did not longitudinally assess the influence of the retreat on participants' meditation practice, it remains unclear whether ultrasound stimulation altered meditative skills in a sustainable way. Further phenomenological research is needed to assess the complex, skill-based development that characterizes advanced meditation once the retreat has concluded.

Fifth, given the limited structure and self-reported nature of the qualitative data, future research could incorporate more systematic pre–post assessments to deepen the analysis of experiential changes. Methods such as micro-phenomenological interviews (Petitmengin, 2006; Petitmengin et al., 2019) or interpretative phenomenological analysis (Smith et al., 2009; Eatough & Smith, 2017) may provide clearer insights into experiential details and the meaning of the practitioners. In addition, short-answer structured diaries (Lutz et al., 2015) could capture the moment-to-moment unfolding of tFUS-mediated states, yielding richer and more precise phenomenological data.

Sixth, although this study focused primarily on phenomenological outcomes, the underlying neural mechanisms of tFUS in the context of longitudinal meditation interventions remain unclear. Future research could integrate multimodal neuroimaging approaches—such as fMRI and EEG—with first-person reports to more directly link phenomenological changes to underlying neural dynamics. Such neurophenomenological data could then be compared with emerging findings on advanced meditators (Chowdhury et al., 2023, 2025; Demir et al., 2025; Potash et al., 2025a, 2025b; Shinozuka et al., 2025; Treves et al., 2024; van Lutterveld et al., 2024, 2025; Yang et al., 2025a, 2025b) to assess whether ultrasound stimulation produces changes consistent with those observed in this population.

Lastly, optimal dosing parameters of tFUS in meditative contexts—such as frequency, intensity, and duration—are not yet established, and stimulation targeting may have been imprecise. Future research should systematically investigate dose–response relationships and incorporating T1 MRI–guided neuronavigation could enhance targeting accuracy, thereby improving both reproducibility and the interpretability of results.

Conclusion

This pilot study demonstrates the feasibility of implementing tFUS during a ten-day meditation retreat and provides preliminary evidence for its potential to support meditative development. Quantitative findings revealed improvements in trait mindfulness, both state and trait NDA, and the interoception subscale Body Listening, while qualitative reports highlighted more pronounced experiential shifts on stimulation days, including enhanced meditative phenomenology, cathartic emotional release, and altered self-perception. These effects appeared to be facilitated by improvements in meditation-related faculties—particularly equanimity, consistent with the hypothesized role of PCC inhibition—alongside concentration and sensory clarity. At the same time, the changes depended strongly on participants' experiential context, underscoring the importance of qualitative phenomenological methods in studying meditative development. Practical considerations further suggest that tFUS should be integrated into ongoing contemplative practice to support skill cultivation, rather than applied as a stand-alone intervention producing transient states. Collectively, these findings position tFUS as a promising, though still exploratory, tool for augmenting meditation. More rigorous designs, systematic neurophenomenological approaches, and improved targeting strategies will be essential to clarify its role in supporting advanced meditation and meditative development, and ultimately its full transformative potential.

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Data availability.

Data not publically available.

Conflict of Interest Statement.

M.D.S. serves as a consultant for Vielight Inc., a company that develops brain stimulation technology. J.L.S. receives salary and is a shareholder in Sanmai Technologies, PBC. S.Y. receives consulting fees from Sanmai Technologies, PBC. T.P. received financial compensation for running the retreat from the participants. The remaining authors report no biomedical financial interests or other potential conflicts of interest.

Author Contributions (CRediT).

S.E.: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing.

B.L.: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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H.B.B.: Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing.

J.R.: Data curation, Formal analysis, Investigation.

T.P.: Conceptualization, Project administration, Writing – original draft, Writing – review & editing.

M.D.S.: Conceptualization, Methodology, Supervision, Writing – review & editing.

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J.L.S.: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process.

During the preparation of this work, the authors (S.E., B.L., E.N.C., and H.B.B) used ChatGPT-5 (OpenAI, 2025) to enhance clarity and style in the written text and to assist with code refinement and troubleshooting for data analyses. The tool was not used to generate novel content, ideas, or citations. All outputs were critically reviewed and edited by the authors, who take full responsibility for the integrity and accuracy of the manuscript.

References

Abellaneda-Pérez, K., Potash, R. M., Pascual-Leone, A., & Sacchet, M. D. (2024). Neuromodulation and meditation: A review and synthesis toward promoting well-being and understanding consciousness and brain. *Neuroscience and Biobehavioral Reviews*, *166*, 105862. https://doi.org/10.1016/j.neubiorev.2024.105862

Ashcroft, J., Patel, R., Woods, A. J., Darzi, A., Singh, H., & Leff, D. R. (2020). Prefrontal transcranial direct-current stimulation improves early technical skills in surgery. *Brain Stimulation*, *13*(6), 1834–1841. https://doi.org/10.1016/j.brs.2020.10.013

Baer, R. A., Smith, G. T., Lykins, E., Button, D., Krietemeyer, J., Sauer, S., Walsh, E., Duggan, D., & Williams, J. M. G. (2008). Construct Validity of the Five Facet Mindfulness Questionnaire in Meditating and Nonmeditating Samples. *Assessment*, *15*(3), 329–342. https://doi.org/10.1177/1073191107313003

Blackmore, J., Shrivastava, S., Sallet, J., Butler, C. R., & Cleveland, R. O. (2019). Ultrasound Neuromodulation: A Review of Results, Mechanisms and Safety. *Ultrasound in Medicine and Biology*, *45*(7), 1509–1536. https://doi.org/10.1016/j.ultrasmedbio.2018.12.015

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Braun, V., & Clarke, V. (2023). Toward good practice in thematic analysis: Avoiding common problems and be(com)ing a knowing researcher. *International Journal of Transgender Health*, *24*(1), 1–6. https://doi.org/10.1080/26895269.2022.2129597

Brewer, J. A., & Garrison, K. A. (2014). The posterior cingulate cortex as a plausible mechanistic target of meditation: Findings from neuroimaging. *Annals of the New York Academy of Sciences*, *1307*(1), 19–27. https://doi.org/10.1111/nyas.12246

Brewer, J. A., Worhunsky, P. D., Gray, J. R., Tang, Y.-Y., Weber, J., & Kober, H. (2011). Meditation experience is associated with differences in default mode network activity and connectivity. *Proceedings of the National Academy of Sciences*, *108*(50), 20254–20259. https://doi.org/10.1073/pnas.1112029108

Brewer, J., Garrison, K., & Whitfield-Gabrieli, S. (2013). What about the "Self" is Processed in the Posterior Cingulate Cortex? *Frontiers in Human Neuroscience*, *7*, 647. https://doi.org/10.3389/fnhum.2013.00647

Cain, J., Brandmeyer, T., Simonian, N., Sanguinetti, J., Young, S., Sacchet, M., & Reggente, N. (2024). *Facilitating Meditation with Focused Ultrasound Neuromodulation: A First Investigation in Experienced Practitioners* [Preprint]. PsyArXiv. https://doi.org/10.31234/osf.io/3bzg6

Carhart-Harris, R. L., Roseman, L., Haijen, E., Erritzoe, D., Watts, R., Branchi, I., & Kaelen, M. (2018). Psychedelics and the essential importance of context. *Journal of Psychopharmacology*, *32*(7), 725–731. https://doi.org/10.1177/0269881118754710

Chowdhury, A., Bianciardi, M., Chapdelaine, E., Riaz, O. S., Timmermann, C., van Lutterveld, R., Sparby, T., & Sacchet, M. D. (2025). Multimodal neurophenomenology of advanced concentration absorption meditation: An intensively sampled case study of Jhana. *NeuroImage*, *305*, 120973. https://doi.org/10.1016/j.neuroimage.2024.120973

Chowdhury, A., van Lutterveld, R., Laukkonen, R. E., Slagter, H. A., Ingram, D. M., & Sacchet, M. D. (2023). Investigation of advanced mindfulness meditation "cessation" experiences using EEG spectral analysis in an intensively sampled case study. *Neuropsychologia*, *190*, 108694. https://doi.org/10.1016/j.neuropsychologia.2023.108694

Christopher, M. S., Christopher, V., & Charoensuk, S. (2009). Assessing "western" mindfulness among Thai Theravāda Buddhist monks. *Mental Health, Religion and Culture*, *12*(3), 303-314. https://doi.org/10.1080/13674670802651487

Clark, V. P., Coffman, B. A., Mayer, A. R., Weisend, M. P., Lane, T. D., Calhoun, V. D., Raybourn, E. M., Garcia, C. M., & Wassermann, E. M. (2012). TDCS guided using fMRI significantly accelerates learning to identify concealed objects. *NeuroImage*, *59*(1), 117–128. https://doi.org/10.1016/j.neuroimage.2010.11.036

Cooper, A. C., Ventura, B., & Northoff, G. (2022). Beyond the veil of duality—Topographic reorganization model of meditation. *Neuroscience of Consciousness*, *2022*(1), niac013. https://doi.org/10.1093/nc/niac013

Curtain, C. (2025). *QualCoder* (Version 3.6) [Computer software]. Colin Curtain. https://qualcoder.wordpress.com/how-to-use/

Dell'Italia, J., Sanguinetti, J. L., Monti, M. M., Bystritsky, A., & Reggente, N. (2022). Current State of Potential Mechanisms Supporting Low Intensity Focused Ultrasound for Neuromodulation. *Frontiers in Human Neuroscience*, *16*, 872639. https://doi.org/10.3389/fnhum.2022.872639

Demir, U., Yang, W. F. Z., & Sacchet, M. D. (2025). Advanced concentrative absorption meditation reorganizes functional connectivity gradients of the brain: 7T MRI and phenomenology case study of jhana meditation. *Cerebral Cortex*, *35*(4), bhaf079. https://doi.org/10.1093/cercor/bhaf079

Eatough, V., & Smith, J. A. (2017). Interpretative phenomenological analysis. In C. Willig & W. Stainton-Rogers (Eds.), *The SAGE handbook of qualitative research in psychology* (2nd ed., pp. 193–211). SAGE.

Ehmann, S., & Gawrysiak, M. (2025). Unveiling the pathways: The effects of mindfulness and recreational psychedelic experiences on well-being—The mediating roles of nondual awareness, prosociality, and meaning in life. *Psychology of Consciousness: Theory, Research, and Practice.* Advance online publication. https://doi.org/10.1037/cns0000443

Ehmann, S., Pohlig, R. T., Chaoul, A., Cuzzupe, J., Vaughn, M., Rocco, G., Wangyal, T., Gawrysiak, M. (2025a). Bridging the Soteriological-Secular Divide: A 9-Month Online Tibetan Mind-Body Practice Program Enhances Eudaimonic Well-Being and Non-Dual Awareness. https://doi.org/10.31219/osf.io/6cze8_v1

Ehmann, S., Sezer, I., Keller, A., Treves, I., & Sacchet, M. (2025b). *Attention and Meditative Development: A Review and Synthesis of Long-Term Meditators and Outlook for the Study of Advanced Meditation*. OSF. https://doi.org/10.31219/osf.io/fh3py_v1

Ehmann, S., Sezer, I., Treves, I. N., Gabrieli, J. D. E., & Sacchet, M. D. (2025c). Mindfulness, cognition, and long-term meditators: Toward a science of advanced meditation. *Imaging Neuroscience*, *3*, IMAG.a.82. https://doi.org/10.1162/IMAG.a.82

Ehmann, S., Sparby, T., Ingram, D. M., & Sacchet, M. D. (2025d). A Framework for the Systematic Quantified Training of Meditation across Meditative Development. Retrieved from osf.io/2dm53

Ehmann, S., Sparby, T., Naughton, V. R., & Sacchet, M. (2025e). *Mental Health, Well-Being, and Meditative Development: A Phenomenological Study of Advanced Meditators*.

Galante, J., Grabovac, A., Wright, M., Ingram, D. M., Van Dam, N. T., Sanguinetti, J. L., Sparby, T., van Lutterveld, R., & Sacchet, M. D. (2023). A Framework for the Empirical Investigation of Mindfulness Meditative Development. *Mindfulness*, *14*(5), 1054–1067. https://doi.org/10.1007/s12671-023-02113-8

Garland, E. L., & Jinpa, T. (2024). Mindfulness-induced self-transcendence promotes universal love with consequent effects on opioid misuse. *Behaviour Research and Therapy*, *175*, 104494. https://doi.org/10.1016/j.brat.2024.104494

Guest, G., Namey, E., & Chen, M. (2020). A simple method to assess and report thematic saturation in qualitative research. *PLOS ONE*, *15*(5), e0232076. https://doi.org/10.1371/journal.pone.0232076

Hanley, A. W., Nakamura, Y., & Garland, E. L. (2018). The Nondual Awareness Dimensional Assessment (NADA): New Tools to Assess Nondual Traits and States of Consciousness Occurring Within and Beyond the Context of Meditation. *Psychological Assessment*, *30*(12), 1625–1639. https://doi.org/10.1037/pas0000615

Hanley, A. W., Dorjee, D., & Garland, E. L. (2023). Mindfulness training encourages self-transcendent states via decentering. *Psychology of Consciousness: Theory, Research, and Practice, 10*(4), 431–440. https://doi.org/10.1037/cns0000262

Hennink, M., & Kaiser, B. N. (2022). Sample sizes for saturation in qualitative research: A systematic review of empirical tests. *Social Science & Medicine*, *292*, 114523. https://doi.org/10.1016/j.socscimed.2021.114523

Hunter, D. J., McCallum, J., & Howes, D. (2019). Defining exploratory-descriptive qualitative (EDQ) research and considering its application to healthcare. *GSTF Journal of Nursing and Health Care*, *4*(1). https://portal.issn.org/api/search?search[]=MUST=default=GSTF+Journal+of+Nursing+and+Health+Care&search_id=18224449

James, N., & Busher, H. (2009). ONE Epistemological Dimensions in Qualitative Research: The Construction of Knowledge Online. In *Online Interviewing* (pp. 5–18). SAGE Publications Ltd. https://doi.org/10.4135/9780857024503

Josipovic, Z. (2019). Chapter 12 - Nondual awareness: Consciousness-as-such as non-representational reflexivity. In N. Srinivasan (Ed.), *Progress in Brain Research* (Vol. 244, pp. 273–298). Elsevier. https://doi.org/10.1016/bs.pbr.2018.10.021

Josipovic, Z. (2021). Implicit–explicit gradient of nondual awareness or consciousness as such. *Neuroscience of Consciousness*, *2021*(2), niab031. https://doi.org/10.1093/nc/niab031

Josipovic, Z. (2024). Reflexivity gradient—Consciousness knowing itself. *Frontiers in Psychology*, *15*. https://doi.org/10.3389/fpsyg.2024.1450553

Kronberg, G., Rahman, A., Sharma, M., Bikson, M., & Parra, L. C. (2020). Direct current stimulation boosts hebbian plasticity in vitro. *Brain Stimulation*, *13*(2), 287–301. https://doi.org/10.1016/j.brs.2019.10.014

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, *33*(1), 159–174.

Lord, B., Allen, J. J., Young, S., & Sanguinetti, J. (2024a). Enhancing Equanimity with Non-Invasive Brain Stimulation: A Novel Framework for Mindfulness Interventions. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*. https://doi.org/10.1016/j.bpsc.2024.12.005

Lord, B., Sanguinetti, J. L., Ruiz, L., Miskovic, V., Segre, J., Young, S., Fini, M. E., & Allen, J. J. B. (2024b). Transcranial focused ultrasound to the posterior cingulate cortex modulates default mode network and subjective experience: An fMRI pilot study. *Frontiers in Human Neuroscience*, *18*. https://doi.org/10.3389/fnhum.2024.1392199

Lord, B., Cook, E., Schachtner, J., Beaman, L., Young, S., Allen, J.J.B., Sanguinetti, J. (2025, in prep). Facilitating Mindfulness Training with Ultrasonic Neuromodulation.

Lutz, A., Jha, A. P., Dunne, J. D., & Saron, C. D. (2015). Investigating the phenomenological matrix of mindfulness-related practices from a neurocognitive perspective. *American Psychologist, 70*(7), 632–658. https://doi.org/10.1037/a0039585

Mehling, W. E., Acree, M., Stewart, A., Silas, J., & Jones, A. (2018). The Multidimensional Assessment of Interoceptive Awareness, Version 2 (MAIA-2). *PLoS ONE*, *13*(12), e0208034. https://doi.org/10.1371/journal.pone.0208034

Niu, X., Yu, K., & He, B. (2022). Transcranial focused ultrasound induces sustained synaptic plasticity in rat hippocampus. *Brain Stimulation*, *15*(2), 352–359. https://doi.org/10.1016/j.brs.2022.01.015

OpenAI. (2025). *ChatGPT* [Large language model].

Petitmengin, C. (2006). Describing one's subjective experience in the second person: An interview method for the science of consciousness. *Phenomenology and the Cognitive Sciences, 5*(3–4), 229–269. https://doi.org/10.1007/s11097-006-9022-2

Petitmengin, C., van Beek, M., Bitbol, M., Nissou, J. M., & Roepstorff, A. (2019). What is it like to meditate? Methods and issues for a micro-phenomenological description of meditative experience. *Journal of Consciousness Studies, 26*(7–8), 232–270.

Potash, R. M., van Mil, S. D., Estarellas, M., Canales-Johnson, A., & Sacchet, M. D. (2025a). Integrated Phenomenology and Brain Connectivity Demonstrate Changes in Nonlinear Processing in Jhana Advanced Meditation. *Journal of Cognitive Neuroscience*, 1–24. https://doi.org/10.1162/jocn.a.50

Potash, R. M., Yang, W. F. Z., Winston, B., Atasoy, S., Kringelbach, M. L., Sparby, T., & Sacchet, M. D. (2025b). Investigating the complex cortical dynamics of an advanced concentrative absorption meditation called jhanas (ACAM-J): A geometric eigenmode analysis. *Cerebral Cortex (New York, N.Y.: 1991)*, *35*(2), bhaf039. https://doi.org/10.1093/cercor/bhaf039

Reis, J., Schambra, H. M., Cohen, L. G., Buch, E. R., Fritsch, B., Zarahn, E., Celnik, P. A., & Krakauer, J. W. (2009). Noninvasive cortical stimulation enhances motor skill acquisition over multiple days through an effect on consolidation. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(5), 1590–1595. https://doi.org/10.1073/pnas.0805413106

Sacchet, M. D., Fava, M., & Garland, E. L. (2024). Modulating self-referential processing through meditation and psychedelics: Is scientific investigation of self-transcendence clinically relevant? *World Psychiatry: Official Journal of the World Psychiatric Association (WPA)*, *23*(2), 298–299. https://doi.org/10.1002/wps.21214

Schachtner, J. N., Dahill-Fuchel, J. F., Allen, K. E., Bawiec, C. R., Hollender, P. J., Ornellas, S. B., Konecky, S. D., Achrol, A. S., & Allen, J. J. B. (2025). Transcranial focused ultrasound targeting the default mode network for the treatment of depression. *Frontiers in Psychiatry*, *16*, 1451828. https://doi.org/10.3389/fpsyt.2025.1451828

Shinozuka, K., Yang, W. F. Z., Potash, R. M., Sparby, T., & Sacchet, M. D. (2025). *Neuroelectrophysiological correlates of extended cessation of consciousness in advanced meditators: A multimodal EEG and MEG study*. bioRxiv. https://doi.org/10.1101/2025.09.19.677455

Smith, J. A., Flowers, P., & Larkin, M. (2009). *Interpretative phenomenological analysis: Theory, method and research.* SAGE.

Sparby, T. (2015). Investigating the Depths of Consciousness Through Meditation. *Mind and Matter*, *13*(2), 213–240.

Sparby, T. (2017). The Nature of Contemplative Science and Some Prospects for its Future Development. *Journal of Consciousness Studies*, *24*(5–6), 226–250.

Sparby, T. (2023). Micro-phenomenological self-inquiry. *Phenomenology and the Cognitive Sciences*, *22*(1), 247–266. https://doi.org/10.1007/s11097-022-09815-9

Sparby, T. (2024). Researching causal relationships from the first-person perspective. An Expansion of the micro-phenomenological method. *New Ideas in Psychology*, *75*, 101105. https://doi.org/10.1016/j.newideapsych.2024.101105

Sparby, T., & Sacchet, M. D. (2022). Defining Meditation: Foundations for an Activity-Based Phenomenological Classification System. *Frontiers in Psychology*, *12*. https://doi.org/10.3389/fpsyg.2021.795077

Sparby, T., & Sacchet, M. D. (2025a). The Third Wave of Meditation and Mindfulness Research and Implications for Challenging Experiences: Negative Effects, Transformative

Psychological Growth, and Forms of Happiness. *Mindfulness*. https://doi.org/10.1007/s12671-025-02607-7

Sparby, T., & Sacchet, M. D. (2025b). Toward a Unified Model of Advanced Meditation, Human Development, Meditation Maps, and Transtradition Metaphors: Facing Impermanence, Suffering, and Death. *Mindfulness*. https://doi.org/10.1007/s12671-025-02632-6

Tal, H., Wright, M., Prest, S., Sandved-Smith, L., & Sacchet, M. (2025). Active Inference, Computational Phenomenology, and Advanced Meditation: Toward the Formalization of the Experience of Meditation. https://doi.org/10.31234/osf.io/pm5y2_v2

Tong, A., Sainsbury, P., & Craig, J. (2007). Consolidated criteria for reporting qualitative research (COREQ): A 32-item checklist for interviews and focus groups. *International Journal for Quality in Health Care: Journal of the International Society for Quality in Health Care*, *19*(6), 349–357. https://doi.org/10.1093/intqhc/mzm042

Treves, I. N., Yang, W. F. Z., Sparby, T., & Sacchet, M. D. (2024). Dynamic brain states underlying advanced concentrative absorption meditation: A 7T fMRI intensive case study. *Network Neuroscience*, 1–55. https://doi.org/10.1162/netn_a_00432

Tufail, Y., Yoshihiro, A., Pati, S., Li, M. M., & Tyler, W. J. (2011). Ultrasonic neuromodulation by brain stimulation with transcranial ultrasound. *Nature Protocols*, *6*(9), Article 9. https://doi.org/10.1038/nprot.2011.371

van Lutterveld, R., Cahaly, T., Ingram, D., & Sacchet, M. D. (2025). *Brain Criticality and Advanced Meditation "Cessation" Events: An Intensively Sampled Electroencephalography Case Study* (SSRN Scholarly Paper No. 5296987). https://doi.org/10.2139/ssrn.5296987

van Lutterveld, R., Chowdhury, A., Ingram, D. M., & Sacchet, M. D. (2024). Neurophenomenological investigation of mindfulness meditation "cessation" experiences using eeg network analysis in an intensively sampled adept meditator. *Brain Topography*. https://doi.org/10.1007/s10548-024-01052-4

Veldman, M. P., Maurits, N. M., Zijdewind, I., Maffiuletti, N. A., van Middelkoop, S., Mizelle, J. C., & Hortobágyi, T. (2018). Somatosensory electrical stimulation improves skill acquisition, consolidation, and transfer by increasing sensorimotor activity and connectivity. *Journal of Neurophysiology*, *120*(1), 281–290. https://doi.org/10.1152/jn.00860.2017

Wessel, M. J., Zimerman, M., Timmermann, J. E., Heise, K. F., Gerloff, C., & Hummel, F. C. (2016). Enhancing Consolidation of a New Temporal Motor Skill by Cerebellar Noninvasive Stimulation. *Cerebral Cortex (New York, N.Y. : 1991)*, *26*(4), 1660–1667. https://doi.org/10.1093/cercor/bhu335

Wright, M. J., Sanguinetti, J. L., Young, S., & Sacchet, M. D. (2023). Uniting contemplative theory and scientific investigation: Toward a comprehensive model of the mind. *Mindfulness, 14,* 1088–1101. https://doi.org/10.1007/s12671-023-02101-y

Yaakub, S. N., White, T. A., Roberts, J., Martin, E., Verhagen, L., Stagg, C. J., Buhle, J., Bhandari, R., & Fouragnan, E. F. (2023). Transcranial focused ultrasound–mediated neurochemical and functional connectivity changes in deep cortical regions in humans. *Nature Communications, 14*(1), 5318. https://doi.org/10.1038/s41467-023-41079-2

Yang, W. F. Z., Kadambi, A., Abellaneda-Perez, K., Mackin, G., Beslic, I., Potash, R., Sparby, T., & Sacchet, M. D. (2025b). *Endogenous suspension and reset of consciousness: 7T fMRI brain mapping of the extended cessation meditative endpoint*. bioRxiv. https://doi.org/10.1101/2025.09.06.674021

Yang, W. F. Z., Chowdhury, A., Sparby, T., & Sacchet, M. D. (2025a). Deconstructing the self and reshaping perceptions: An intensive whole-brain 7T MRI case study of the stages of insight during advanced investigative insight meditation. *NeuroImage*, *305*, 120968. https://doi.org/10.1016/j.neuroimage.2024.120968

Young, S. (2016). What Is Mindfulness? A Contemplative Perspective. In K. A. Schonert-Reichl & R. W. Roeser (Eds.), *Handbook of Mindfulness in Education* (pp. 29–45). Springer New York. https://doi.org/10.1007/978-1-4939-3506-2_3