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A Personalized & Multimodal Approach to Meditation Neurofeedback

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SHORT ON TIME? HERE'S THE SUMMARY

We decoded intra-session, online self-reports of **meditative depth** in expert Vipassana practitioners using source-localized EEG and **heartbeat evoked potential** (HEP) amplitudes. HEPs—neural responses to cardiac signals—proved to be particularly reliable biomarkers of meditative depth, with electrode C3 over left sensorimotor cortex showing the most pronounced sensitivity. Unlike traditional EEG markers reflecting non-specific relaxation states, HEPs capture **personalized heart-brain dynamics** inherent to each practitioner's embodied experience. Our next study introduces the first **real-time HEP cardio-neurofeedback system for meditation**. We will test a **gamified HEP neurofeedback intervention** for adolescents to improve **interoceptive sensibility** and psychological well-being, potentially leading to a scalable mobile neurofeedback framework for mindfulness training.

Identifying Gradations of the Meditative Experience

MOTIVATION

Neural signatures distinguish meditation from mind-wandering, but intra-meditative dynamics remained opaque: Is there linear amplification or distinct neural patterns across depth? Deepening meditation with neurofeedback mandates such insights

Neurophysiological heterogeneity invalidates one-size-fits-all protocols: Individual neural architectures demand more bespoke neurofeedback approaches.

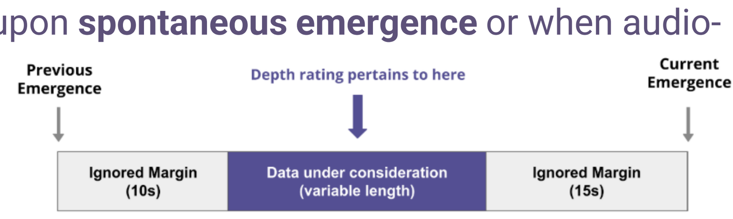
"Above the neck" metrics neglect meditation's embodied foundations: Interoceptive recalibration– not cortical activity alone– underlies meditation's transdiagnostic therapeutic efficacy.

METHODS

Participants: Expert Vipassana practitioners (n=34; μ=16.15 years experience, 6.53 days/week practice, 82.38 cumulative retreat days).

Sessions: 160 total minutes across 2 sessions (>1 week apart) with 64-channel EEG and bio peripherals

Depth reporting: Participants rated online meditative depth (1-5) and confidence via a series of button presses either upon **spontaneous emergence** or when audio-prom



Neural decoding: Multiple source estimation methods compared using spectral power/connectivity in theta, alpha, gamma bands. Leave-one-participant-out cross-validation

HEP analysis: EEG epochs time-locked to ECG R-peaks. Cluster-based permutation tests compared HEP amplitude across depth ratings.

HEP range: C3 (144-288ms) amplitude difference between high/low depths. Mixed linear models assessed its **prediction of post-session self-reports.**

RESULTS

EEG based ML classifiers can decode meditative depth

Table 1. Performance of Different Source Estimation Techniques Combined With Different Measures for Both Depth Scales

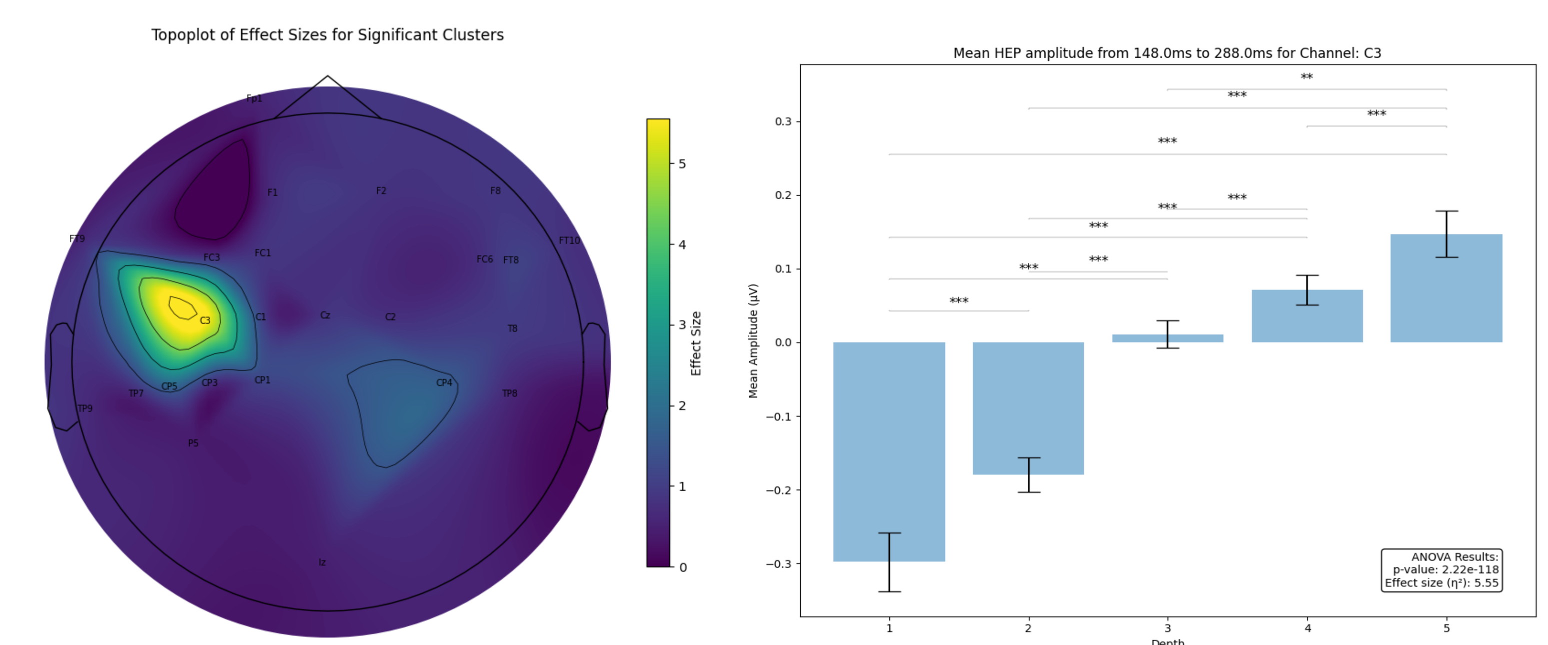
Source Estimation Method	Measure	Continuous Depth, MAE	Low/High Depth, AUC
Emergence Reporting			
Channel-Based—Subset	Variance	1.453 ± 0.363	0.629 ± 0.109
	Connectivity	1.478 ± 0.346	0.606 ± 0.115
Channel-Based—All	Variance	1.379 ± 0.344	0.667 ± 0.125
sLORETA	Variance	1.276 ± 0.288	0.683 ± 0.154
	Connectivity	1.372 ± 0.279	0.671 ± 0.141
Generalized Eigenvalue	Variance	1.303 ± 0.324	0.722 ± 0.147
	Connectivity	1.150 ± 0.263	0.770 ± 0.118
Deep Learning	Variance	1.265 ± 0.253	0.798 ± 0.108
	Connectivity	1.254 ± 0.239	0.765 ± 0.122
EEGNet	N/A	1.325 ± 0.264	0.766 ± 0.145
Probe Reporting			
Channel-Based—Subset	Variance	1.501 ± 0.372	0.634 ± 0.159
	Connectivity	1.522 ± 0.359	0.610 ± 0.135
Channel-Based—All	Variance	1.391 ± 0.302	0.724 ± 0.101
sLORETA	Variance	1.397 ± 0.350	0.714 ± 0.180
	Connectivity	1.457 ± 0.330	0.684 ± 0.150
Generalized Eigenvalue	Variance	1.426 ± 0.516	0.722 ± 0.150
	Connectivity	1.262 ± 0.300	0.754 ± 0.110
Deep Learning	Variance	1.289 ± 0.292	0.807 ± 0.117
	Connectivity	1.335 ± 0.313	0.798 ± 0.128
EEGNet	N/A	1.329 ± 0.385	0.756 ± 0.157
Emergence and Probe (Pooled) Reporting			
Channel-Based—Subset	Variance	1.450 ± 0.370	0.636 ± 0.157
Channel-Based—All	Variance	N/A	0.731 ± 0.115
Generalized Eigenvalue	Variance	1.309 ± 0.281	0.748 ± 0.149
	Connectivity	1.196 ± 0.269	0.807 ± 0.105
Deep Learning	Variance	1.239 ± 0.273	0.806 ± 0.117
	Connectivity	N/A	0.798 ± 0.128
EEGNet	N/A	1.237 ± 0.296	0.791 ± 0.142

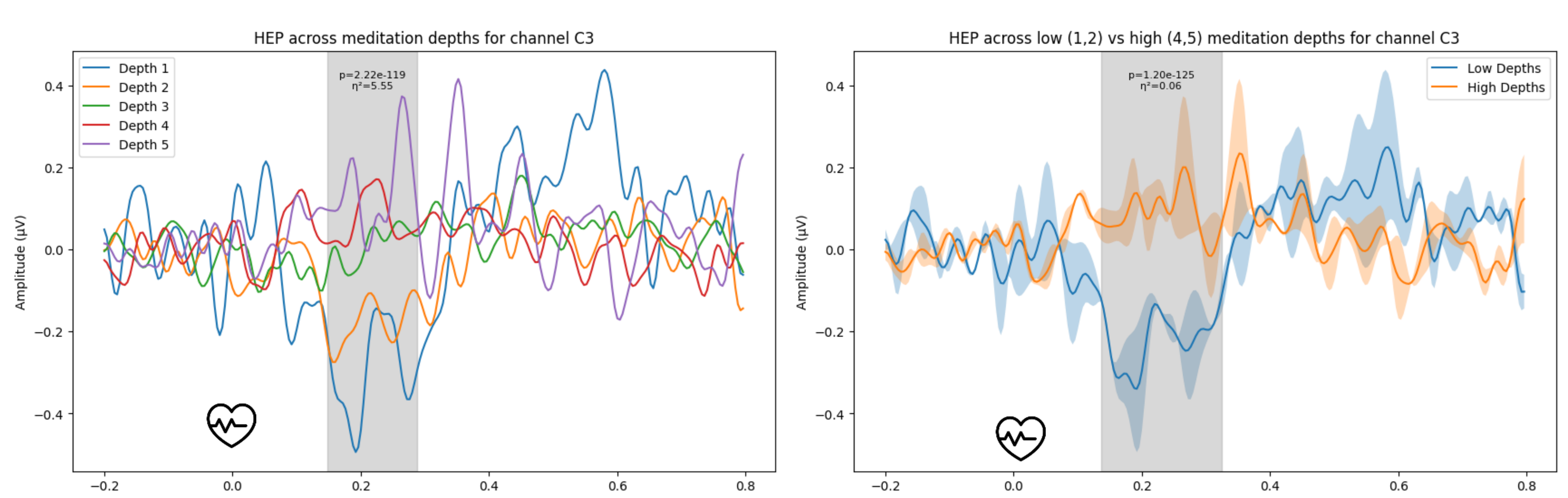
Deep learning-based source-localized ROIs using theta, alpha, and gamma band power achieved **81% depth decoding accuracy** for high (4,5) vs. low (1,2).

Generalized Eigendecomposition-informed source-localized ROIs using theta, alpha, and gamma connectivity achieved **1.2 Mean Absolute Error** in predicting continuous depth (1-5).

Standard EEG features (e.g., DMN activity, spectral power) **did not effectively capture** the nuanced changes that corresponded to varying meditative depth.

HEP amplitude over C3 increases with meditative depth





C3 HEP range significantly predicted post-session metrics

- **Toronto Mindfulness Scale (TMS):** Greater HEP range → **higher Decentering** (p <0.001).
- **Profile of Mood States (POMS):** Greater HEP range → **reduced total mood disturbance** (p = 0.03), **increased vigor** (p <0.001), **and decreased fatigue** (p <0.001).
- **Meditation Depth Index (MEDI):** Greater HEP range → **lower Personal Self** (p <0.001) and **higher Transpersonal Self** (p <0.001).

HeartBEAM: Heart-Brain Engagement for Adolescent Meditation

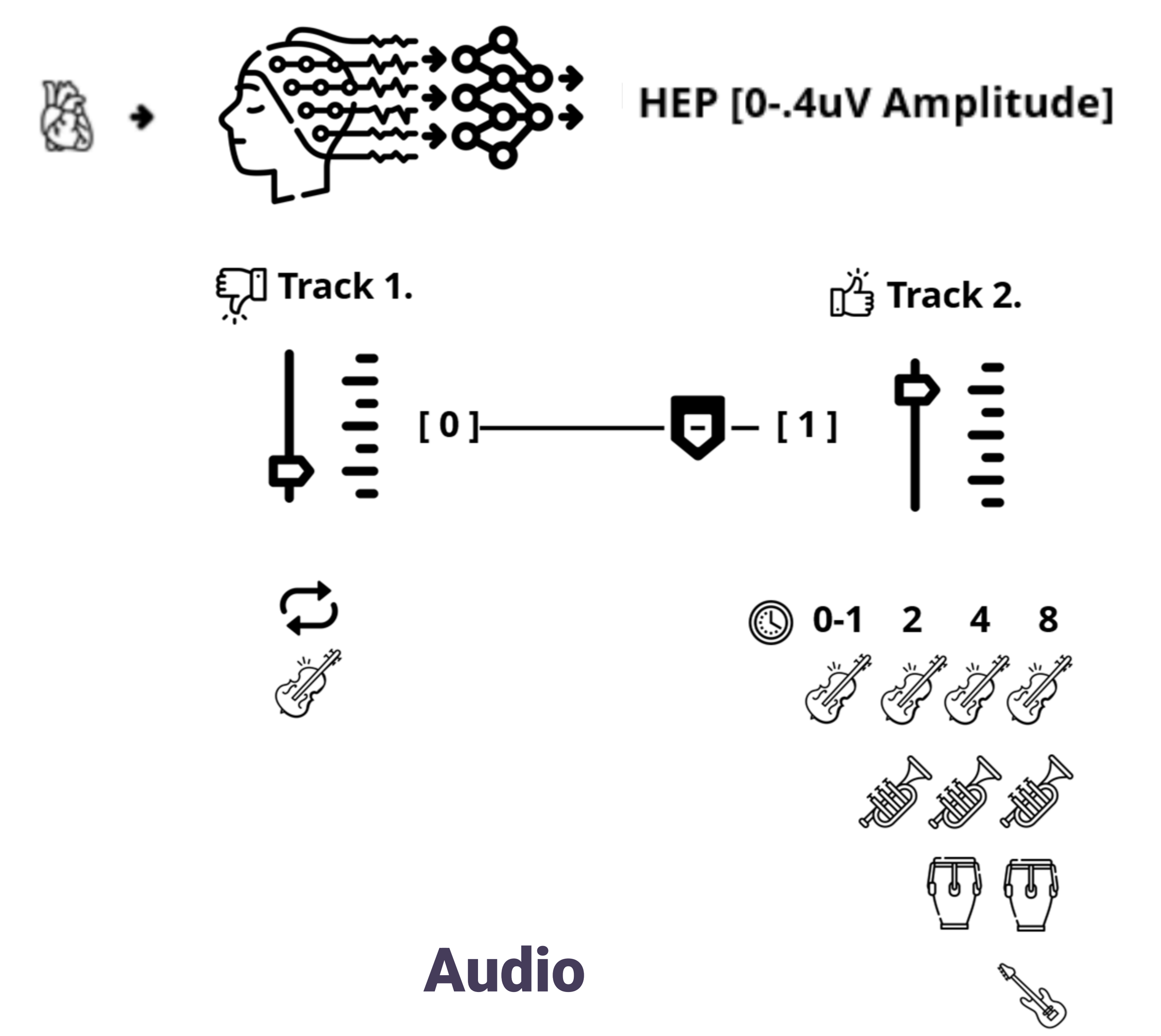
MOTIVATION

HEP tracks meditative depth using **minimal hardware (single-channel EEG and ECG)**, outperforming complex multivariate approaches. Traditional neurofeedback targets indirect downstream correlates; HEP tracks a much more **fundamental feature of meditation — interoception**.

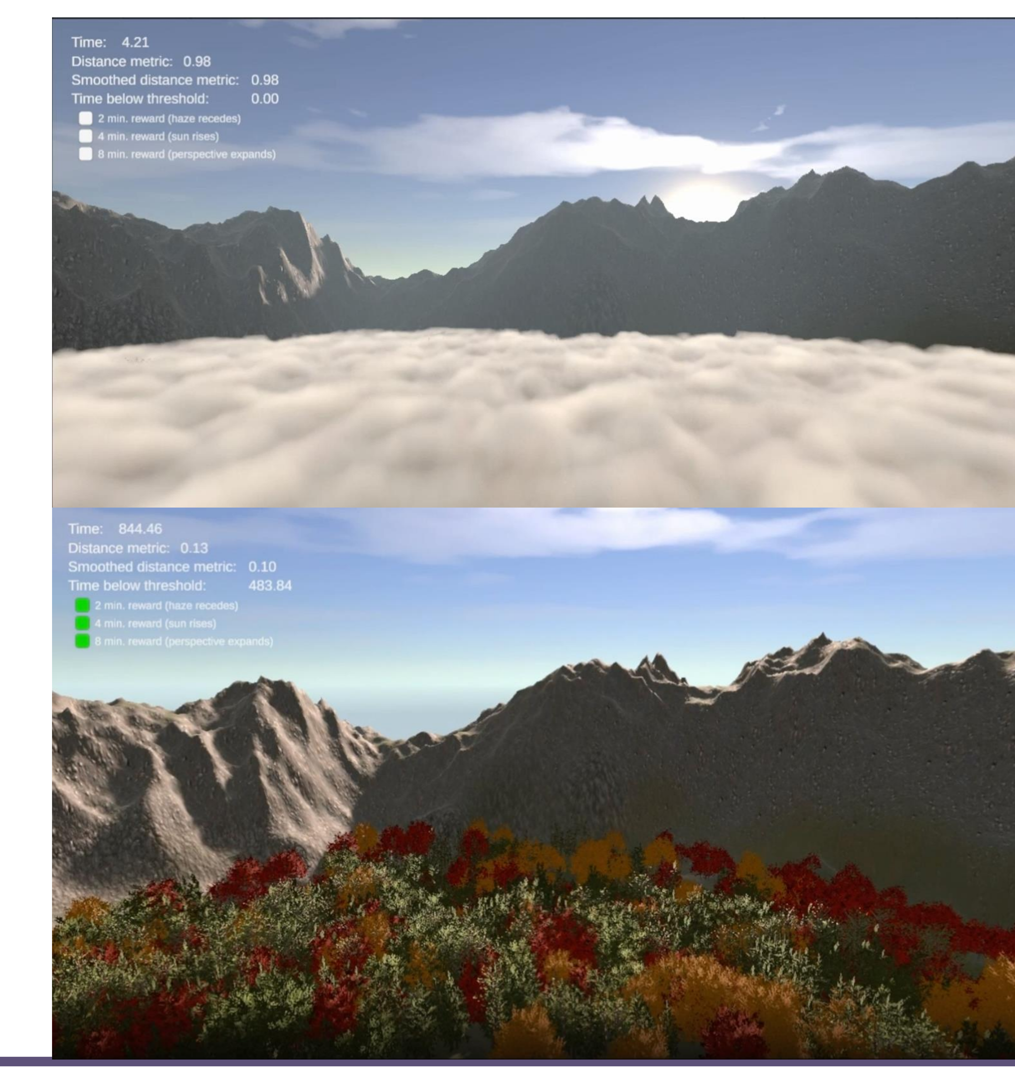
The relationship between HEP and meditative depth and outcomes that downregulate egoic emphasis suggests potential markers of **self-transcendent experiences** that can be cultivated non-pharmacologically, helping **democratize these states**, especially for youth populations.

The adolescent developmental window represents an **optimal intervention period** as interoceptive networks undergo significant refinement prior to typical affective disorder emergence. Enhancing HEP through reward-based neurofeedback in familiar settings (e.g., virtual games) may encourage interoceptive sensitivity to translate into sensibility, thus equipping adolescents with robust tools for adaptive emotional regulation.

NEUROFEEDBACK DESIGN



VR



PLANNED STUDY

Double-blind RCT

- HEP Neurofeedback (n=34) — *Live HEP amplitude @ C3*
- Sham Neurofeedback (n=34) — *Pre-recorded Matched HEP*
- FMT Neurofeedback (n=34) — *Active Control*

4 × Weekly VR/Auditory Neurofeedback Sessions (30 min each)

ACKNOWLEDGEMENTS

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