



Heartbeat-Evoked Potentials Track Depth of Meditation

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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 upcoming 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



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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 neglects meditation's embodied foundations:** Interoceptive recalibration— not cortical activity alone— underlies meditations 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-prompted (~4-minute intervals)
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- ❖ **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

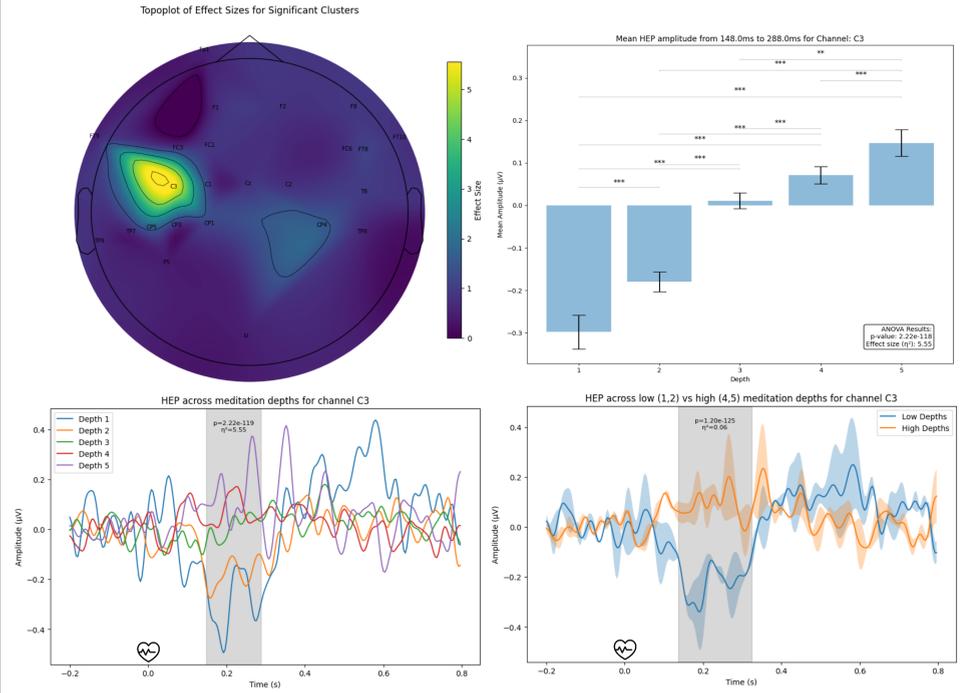
EEG based ML classifiers can decode meditative depth

Table 1. Performance of Different Source Estimation Techniques Combined with Different Measures for Both Depth Scores

Source Estimation Method	Measure	Continuous Depth, WA	Lengthy Depth, ACC
Emergence Reporting			
Channel-Based-Spatial	Valence	1.453 ± 0.343	0.629 ± 0.109
	Connectivity	1.478 ± 0.346	0.608 ± 0.116
Channel-Based-At	Valence	1.295 ± 0.344	0.607 ± 0.109
	Connectivity	1.278 ± 0.298	0.608 ± 0.104
uMRETA	Valence	1.285 ± 0.319	0.617 ± 0.102
	Connectivity	1.262 ± 0.274	0.617 ± 0.102
Generalized Eigenvalue	Valence	1.302 ± 0.324	0.702 ± 0.147
	Connectivity	1.182 ± 0.263	0.702 ± 0.148
Deep Learning	Valence	1.282 ± 0.255	0.708 ± 0.109
	Connectivity	1.258 ± 0.239	0.702 ± 0.102
EEGNet	Valence	1.302 ± 0.294	0.708 ± 0.109
	Connectivity	1.282 ± 0.255	0.702 ± 0.102
Probe Reporting			
Channel-Based-Spatial	Valence	1.450 ± 0.372	0.624 ± 0.109
	Connectivity	1.425 ± 0.358	0.612 ± 0.109
Channel-Based-At	Valence	1.302 ± 0.302	0.714 ± 0.131
uMRETA	Valence	1.282 ± 0.302	0.714 ± 0.130
Generalized Eigenvalue	Valence	1.427 ± 0.330	0.688 ± 0.130
	Connectivity	1.429 ± 0.316	0.707 ± 0.102
Deep Learning	Valence	1.282 ± 0.300	0.704 ± 0.110
	Connectivity	1.282 ± 0.282	0.697 ± 0.102
EEGNet	Valence	1.302 ± 0.315	0.708 ± 0.109
	Connectivity	1.282 ± 0.282	0.708 ± 0.109
Emergence and Probe (Mixed) Reporting			
Channel-Based-Spatial	Valence	1.450 ± 0.372	0.624 ± 0.109
	Connectivity	1.425 ± 0.358	0.612 ± 0.109
Channel-Based-At	Valence	N/A	N/A
uMRETA	Valence	1.302 ± 0.302	0.714 ± 0.130
	Connectivity	1.282 ± 0.282	0.707 ± 0.102
Generalized Eigenvalue	Valence	1.427 ± 0.330	0.688 ± 0.130
	Connectivity	1.429 ± 0.316	0.707 ± 0.102
Deep Learning	Valence	1.282 ± 0.300	0.704 ± 0.110
	Connectivity	1.282 ± 0.282	0.697 ± 0.102
EEGNet	Valence	N/A	N/A
	Connectivity	1.278 ± 0.298	0.708 ± 0.109
	Connectivity	1.258 ± 0.239	0.702 ± 0.102

- **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 **1.1 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

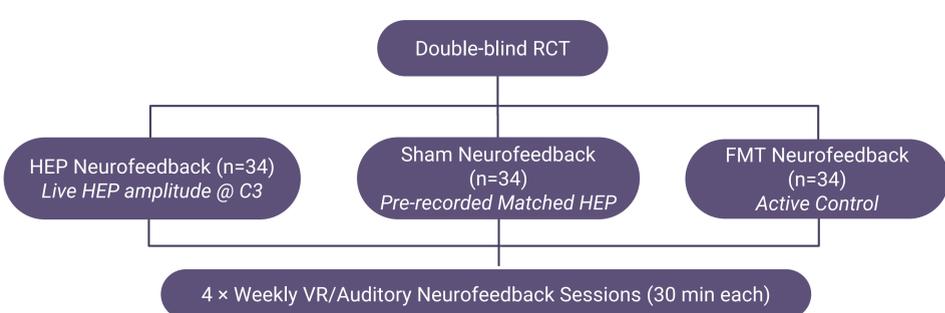
- ★ **Toronto Mindfulness Scale (TMS):** Greater HEP range → **higher Decentering** ($p < 0.001$).
- ★ **Profile of Mood States (POMS):** Greater HEP range → **reduced total mood disturbance** ($p = 0.03$), **increased vigor** ($p < 0.001$), and **decreased fatigue** ($p < 0.001$).
- ★ **Meditation Depth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

HeartBEAM: Heart-Brain Engagement for Adolescent Meditation

MOTIVATION

- ❖ HEPs track 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.

PLANNED STUDY



NEUROFEEDBACK DESIGN

- Transition from dissonant to consonant as a function of HEP amplitude.
- Additional stems for maintaining high HEP.

Visual (VR)

Move toward "Vipassana" by clearing the fog and discovering artifacts (rewarded) as a function of increased and sustained HEP amplitudes.

ACKNOWLEDGEMENTS

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