

Heartbeat Evoked Potentials Increase With Meditative Depth: Implications for Personalized, Multimodal Neurofeedback

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SHORT ON TIME? HERE'S THE SUMMARY

This study examined **Heartbeat Evoked Potentials (HEPs)** during meditation in expert Vipassana practitioners, revealing progressive amplitude increases **tracking self-reported meditative depth in real-time**. While traditional EEG markers often reflect non-specific states like relaxation or drowsiness, HEPs capture the heart's direct influence on brain activity—a neurophysiological marker **inherently personalized to each practitioner's embodied experience**. This heart-brain coupling, robust over the C3 region, serves as a precise indicator of interoceptive processing, addressing a core dysfunction across mental health conditions that meditation ameliorates. The specificity of HEPs as a marker of meditative depth, combined with their accessibility via single-channel EEG, makes them **ideal for neurofeedback interventions** fostering heightened embodied awareness. By quantifying the heart's causal influence on neural signatures during meditation, this approach offers a tractable pathway toward personalized meditation training, illuminating mechanisms underlying its broad therapeutic effects.



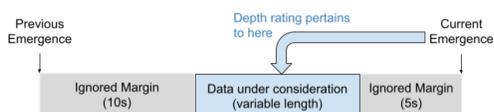
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MOTIVATION

- To enhance EEG specificity for meditation neurofeedback, this study explores **nuances within the meditative experience**, going beyond differentiating meditation from other states (e.g., mind-wandering).
- Focusing on moment-to-moment "meditative depth" reporting in expert Vipassana practitioners, this study investigates HEPs as neurophysiological correlates of meditative gradations, revealing how **heart-brain interactions** shift with varying depths of meditation.
- Given the relationship between **meditation and interoceptive awareness** [1], HEPs are examined to provide insight into how these neural correlates can be leveraged as a neurofeedback tool, further elucidating psychophysiological connections in meditation.

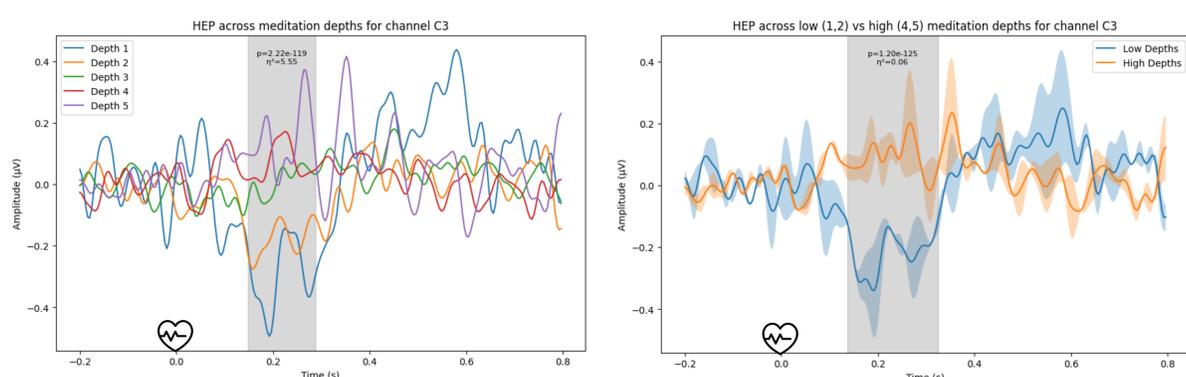
METHODS

- Expert Vipassana practitioners (n=34; $\mu_{\text{experience}}=16.15$ years, practicing $\mu=6.53$ days/week, with $\mu=82.38$ cumulative retreat days)
- 160 total minutes of meditation across 2 sessions (≥ 1 week apart) with 2 blocks per session with 64-Channel EEG (BrainProducts) & Bio Peripherals (CGX)
- During 45-minute sessions, participants rated their meditative depth (1-5 button presses; shallow to deep) since their last report and confidence (1-5; low to high) using a finger-mounted clicker in separate blocks: spontaneously upon noticing mind-wandering ("spontaneous emergence") or when prompted by audio cues at ~4-minute jittered intervals ("probe"). Epochs were extracted as follows and ensured no overlap with reporting periods:

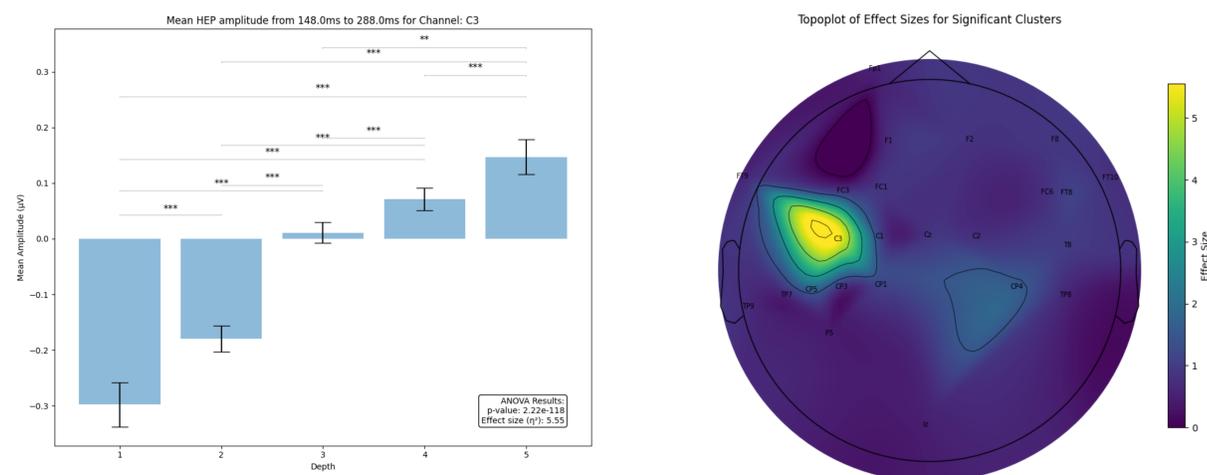


- EEG data were segmented into epochs time-locked to the R-peak of the ECG. Each epoch spanned from -200 ms to +800 ms relative to the R-peak. The EEG data were preprocessed through band-pass filtering (0.5-30 Hz), automated artifact rejection, and manual correction via independent component analysis (ICA). Baseline correction was applied using the pre-R-peak interval (-200 to 0 ms).
- The primary analysis involved comparing HEP amplitudes across the self-reported meditative depths (1-5) using one-way ANOVAs. Additionally, t-tests were conducted to compare grouped depths (low: 1-2, high: 4-5). Cluster-based permutation tests with 1000 permutations were employed to control for multiple comparisons across EEG channels and time points. The significance level for all tests was set at $p < 0.05$, with correction using the false discovery rate (FDR). Post-hoc comparisons using Tukey's HSD were performed for pairwise analysis across different depths.

RESULTS



When using HEP-amplitude data, a Random Forest classifier achieved .63 MAE (1-5) and 91% Accuracy (High vs. Low)



HEP range: defined as the difference in mean HEP amplitude (channel 'C3', 144-288 ms) between high meditative depths (4, 5) and low depths (1, 2).

- **Toronto Mindfulness Scale (TMS):** A larger HEP range significantly predicted **greater Decentering**, reflecting increased emotional regulation and mindfulness (Coef = 6.79, $p = 1.25E-06$).
- **Profile of Mood States (POMS):** Higher HEP ranges were associated with better post-session mood, including **reduced total mood disturbance** (Coef = -2.221, $p = 0.035$), as well as **increased vigor and decreased fatigue**, indicating enhanced emotional and physical well-being.
- **Meditation Depth Index (MEDI):** In the MEDI, larger HEP ranges were linked to a **decrease in Personal Self** (Coef = -0.315, $p = 6.93E-03$) and an **increase in Transpersonal Self** (Coef = 0.65, $p = 1.00E-138$), highlighting deeper meditative states and a shift toward a transpersonal awareness.

CONCLUSIONS

- HEPs provide a precise index of meditative depth using minimal hardware—single-channel EEG and ECG—outperforming complex multivariate approaches[2] and enabling scalable neurofeedback applications.
- HEPs' direct link to interoceptive awareness and their suitability for real-time tracking make them ideal for enhancing meditation practices. Their **relationship with both mindfulness depth and emotional states** suggests powerful applications in personalized meditation training, helping practitioners deepen their practice while improving emotional regulation.
- The specificity and responsiveness of HEPs enable precise adjustments in neurofeedback protocols, potentially improving the effectiveness of meditation training and outcomes in mindfulness-based interventions. Future research might explore how **real-time HEP modulation** could guide practitioners towards deeper meditative states.

ACKNOWLEDGEMENTS

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