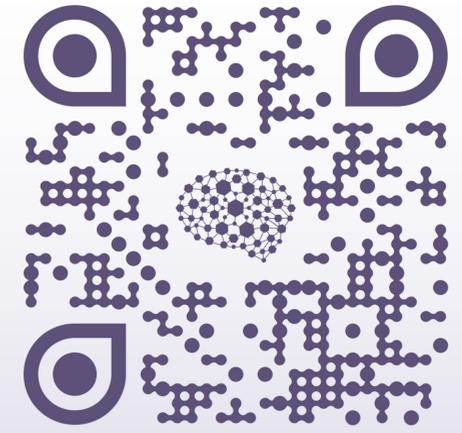




# Decoding Subtle Gradations in Phenomenology: EEG Predicts Meditative Depth Across Multiple Site Visits in Vipassana Experts

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## SHORT ON TIME? HERE'S THE SUMMARY

We decoded self-reported meditative depth across multiple sessions (weeks apart) in expert Vipassana practitioners (n=34) using source-localized EEG in theta, alpha, and gamma bands along with Heart Evoked Potential amplitudes. Conventional EEG channel-level methods and a priori chosen brain regions failed to capture the complex, non-linear neural dynamics associated with varying meditation depths. We also introduce "spontaneous emergence" as an ecologically valid phenomenological sampling method, creating potential for multivariate, personalized neurofeedback.

## 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, a high-dimensional, multivariate decoding approach is used to identify neural correlates of meditative gradations.
- Given the relationship between meditation and interoceptive awareness [1], this study also examines Heart Evoked Potentials as a function of meditative depth to further elucidate psychophysiological correlates.



## METHODS

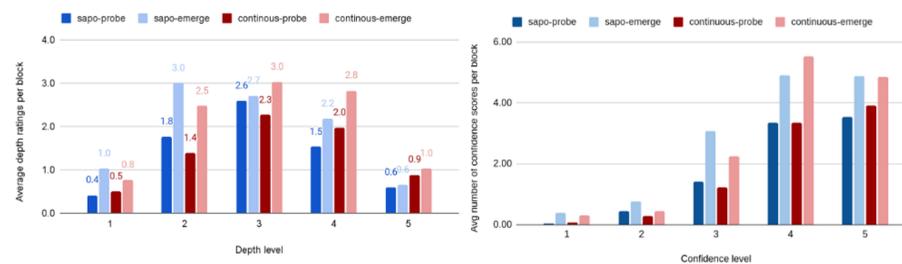
- **Expert Vipassana practitioners** (n=34;  $\mu_{\text{experience}}=16.15$  years, practicing  $\mu=6.53$  days/week, with  $\mu=82.38$  cumulative retreat days)
  - 160 total minutes of meditation **across 2 sessions** ( $\geq 1$  week apart) with 2 blocks per session with **64-Channel EEG** (BrainProducts) & **Bio Peripherals** (CGX)
  - Participants rated their meditative depth (1-5 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  $\sim 4$ -minute jittered intervals ("**probe**").
- For depth classification analyses, ratings with confidence  $\geq 4$  were included and epochs were extracted:
- 
- Multiple source estimation methods (channel-based, sLORETA, generalized eigendecomposition, and deep learning) were compared using either spectral power or connectivity features in theta, alpha, and gamma bands. Models were evaluated using leave-one-participant-out cross-validation, with mean absolute error (MAE) for the continuous 1-5 scale and area under the receiver operator curve (AUC) for the two-level scale (low: 0-2, high: 4-5) as accuracy measures.
  - For **Heart Evoked Potential** Analyses, EEG data were segmented into epochs **time-locked to the R-peak of the ECG**. One-way ANOVAs compared HEP amplitude across continual depth (1-5) and t-tests compared grouped depths (low: 1-2, high: 4-5).

## EEG Based Classifiers Can Decode Meditative Depth

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

Source Estimation Method	Measure	Continuous Depth (MAE, lower is better)	Low/High Depth (AUC, higher is better)
Channel-based (subset)	Power	1.501 +/- 0.372	0.634 +/- 0.159
	Connectivity	1.522 +/- 0.359	0.610 +/- 0.135
Channel-based (all)	Power	1.391 +/- 0.302	0.724 +/- 0.101
	Connectivity	1.397 +/- 0.350	0.714 +/- 0.180
sLORETA	Power	1.457 +/- 0.330	0.684 +/- 0.150
	Connectivity	1.426 +/- 0.516	0.722 +/- 0.150
Gen. Eigval	Power	<b>1.262 +/- 0.300</b>	0.754 +/- 0.110
	Connectivity	1.289 +/- 0.292	<b>0.807 +/- 0.117</b>
Deep Learning	Power	1.335 +/- 0.313	0.798 +/- 0.128
	Connectivity	1.329 +/- 0.385	0.756 +/- 0.157
EEGNet	N/A		

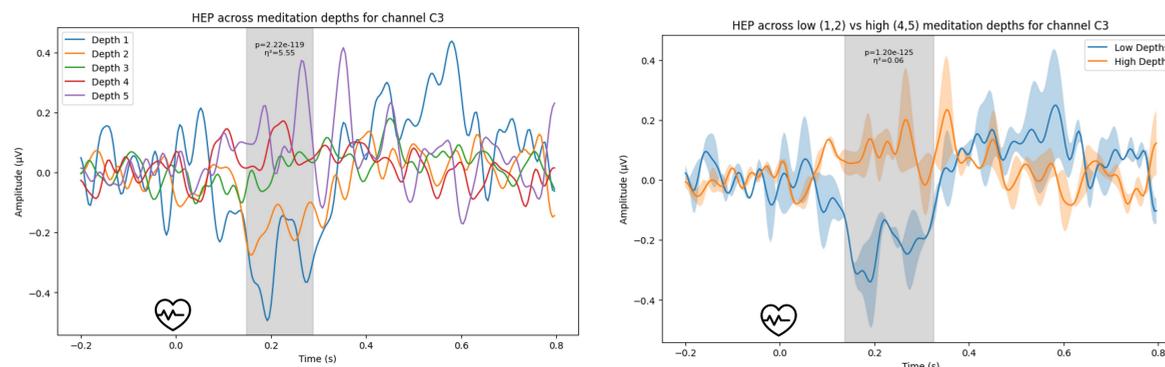
Generalized Eigendecomposition informed source-localized ROIs using theta, alpha, and gamma connectivity achieved **1.2 Mean Absolute Error** in predicting continuous depth (1-5)



Participants provided **45% more ratings (with more confidence) in the "spontaneous emergence" blocks** with equivalent accuracy values to "probe".

## Heart Evoked Potential Amplitude Increases With Meditative Depth

Is this increased sensitivity to endogenous signals a mechanism underlying the increased interoceptive awareness and well-being accompanying meditation practice?

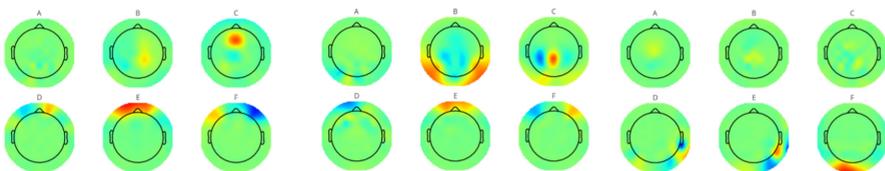


When using HEP-amplitude data, a Random Forest classifier achieved .63 MAE (1-5) and 91% Accuracy (High vs. Low)

## CONCLUSIONS

- Source-localized EEG, Heart Evoked Potential amplitudes, and connectivity measures outperformed conventional methods in decoding self-reported meditative depth, revealing complex neural dynamics and heart-brain interactions.
- "Spontaneous emergence" proved to be a more ecologically valid and effective method for capturing self-reported depth compared to probing that yielded more responses and equivalent decoding accuracies..
- Decoding meditative depth feasibility is a critical step towards developing sophisticated, **multivariate neurofeedback** for effective meditation practice

### Theta (4-7 Hz) Alpha (8-12 Hz) Gamma (31-42 Hz)



Scalp forward projections of learned EEG sources corresponding to the node connectivity weights between six spatial components estimated using the Generalized Eigendecomposition.

## ACKNOWLEDGEMENTS

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