Beyond Univariate Envelope Brain Modeling: Increasing EEG response accuracy with the multivariate Amplitude-Binned TRF model

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Introduction

Naturalistic soundscapes evoke more complex neural dynamics than synthetic sounds, challenging simple modeling approaches.[6] Traditional standard envelope models assume a linear relationship between stimulus and EEG response, which may overlook important nonlinear neural processing[5].

Amplitude-Binned (AB) envelopes offer a promising alternative by capturing these nonlinearities through segmenting the audio envelope into discrete amplitude ranges. Temporal Response Function (TRF) modeling enables us to link these stimulus features directly to EEG signals.[3]

Objective:

- Evaluate AB envelope's ability to improve EEG modelling in complex soundscape compared to standard envelopes.

Hypotheses:

- **H1**: AB envelope will outperform the standard envelope in prediction accuracy
- **H2**: Combining AB envelope with the onset envelope will further enhance prediction performance.

Materials & Methods

Dataset and Experiment Design

- **EEG Data Acquisition:** 24-channel SMARTING EEG used to get continuous brain the data. EEG synced with audio via Lab Streaming Layer.
- **Participants:** N= 20 (14 Female, aged 20-30)
- **Task:** Complex audio-visual-motor (3D Tetris) task with naturalistic soundscape in different attention instructions.
- **Conditions:** Narrow vs. Wide attention (Alarm vs. Beep).

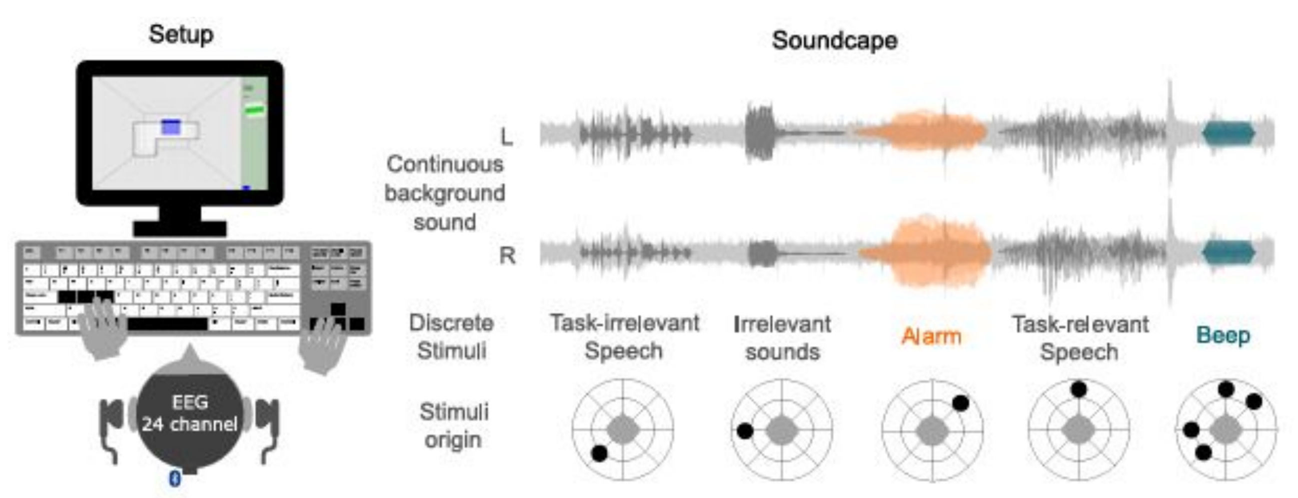


Fig 1. Task and soundscape from Rosenkranz et al., 2023[2]

Naturalistic Soundscape: speech, alarms, beeps, and background noise.

Narrow Condition: **Alarm**
Wide Condition: **Beep**

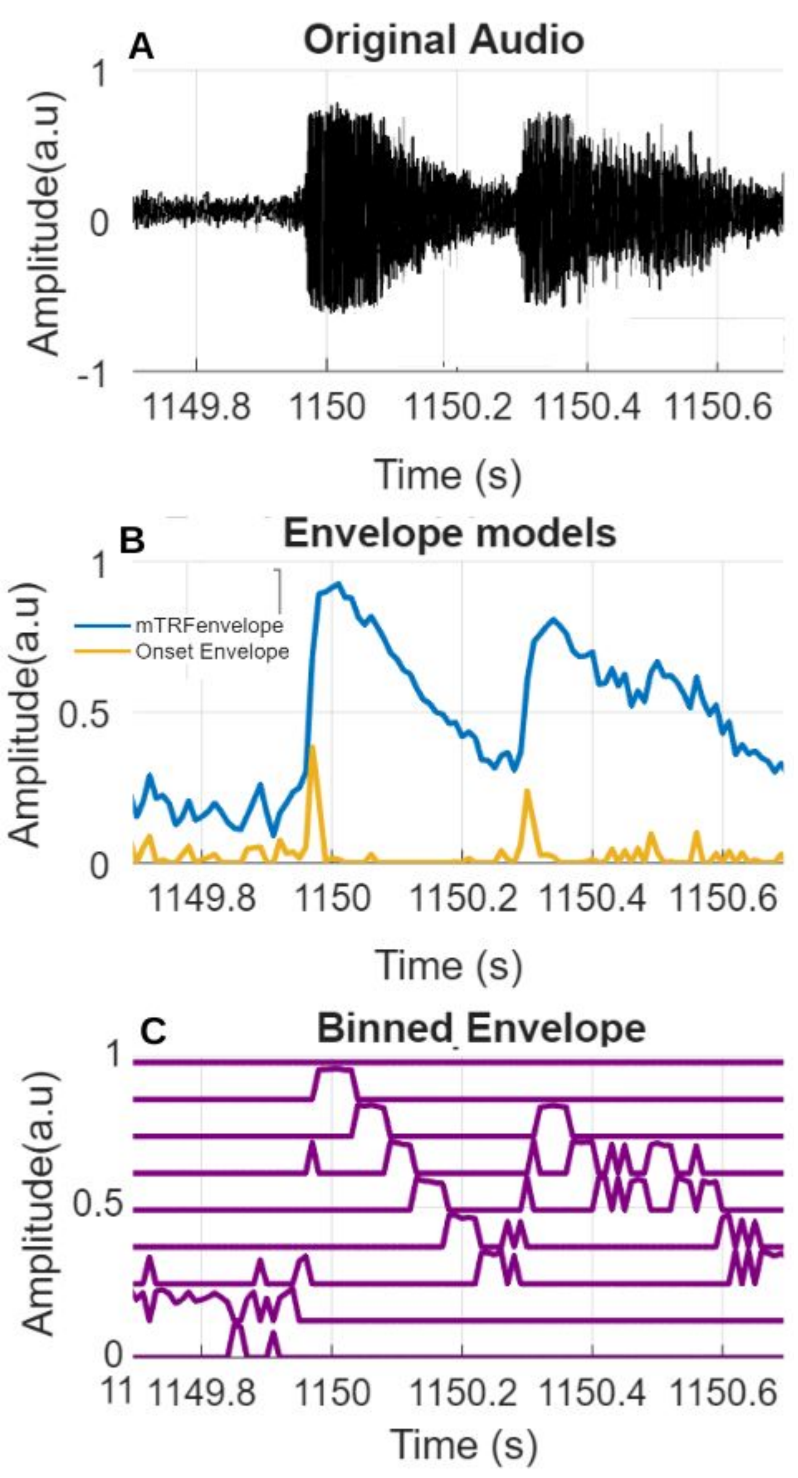


Fig 2. Sound Features
A - Stereo Audio sample waveform
B - *Univariate*: Standard and Onset Envelopes
C - *Multivariate*: Amplitude-Binned envelope.

Statistics

- Pearson correlation for model fit.
- Paired t-tests, Wilcoxon signed-rank tests (α = 0.05).
- Permutation testing (n = 100) for null comparison.
- Permutation and bin-shuffle tests for validation.

Feature Extraction

- **Standard Envelope (Fig 2.B):**
  - Using mTRF envelope, the amplitude values of the sound waveform
  - univariate RMS, log-scaled, normalized.
- **Onset Envelope (Fig 2.B):**
  - Derivative of standard envelope; positive peaks (detects sharp changes in amplitude) only.
- **AB Envelope (Fig 2.B):**
  - Multivariate representation with 8 bins
  - across 0–62.72 dB
  - log-converted
  - normalized [0–0.98]
- **Combined Model:**
  - AB envelope + Onset envelope.

TRF Modeling

- **Before TRF, EEG and Audio preprocessed:**
  - Synching Audio and EEG using Events. Applying ICE, Filtering, Removing and Interpolating data.
- **Time Window:**
  - −100 to +400ms
- **Design Matrix: (Bins, Time Points, Channels)**
  - Standard: **1×51×22**
  - AB: **8×51×22**
  - Combined: **9×51×22**
- 10-fold cross-validation
- Regularization optimized per subject and feature.

Results

Channel selection

- EEG accuracy varies by channel;
- Across conditions highest in **frontocentral** & **temporal** areas
- 5 Channels (**FC2, FC1, C3, C4, Cz**) used for analysis;

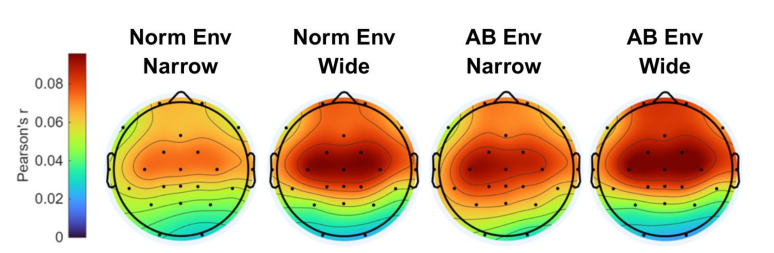


Fig 3. Topoplot.

Search Grid - Bin Optimization

- **Linear binning > Logarithmic** in complex soundscapes
- **Optimal setup:** 8 bins, normalized [0–0.98], over 0–62.72 dB *(Fig4,A)*.
- **Normalization timing** & binning method critically affect performance *(Fig4,B)*.
- **Shuffled bin order** → no effect → AB mTRF model **not bin-sequence dependent**

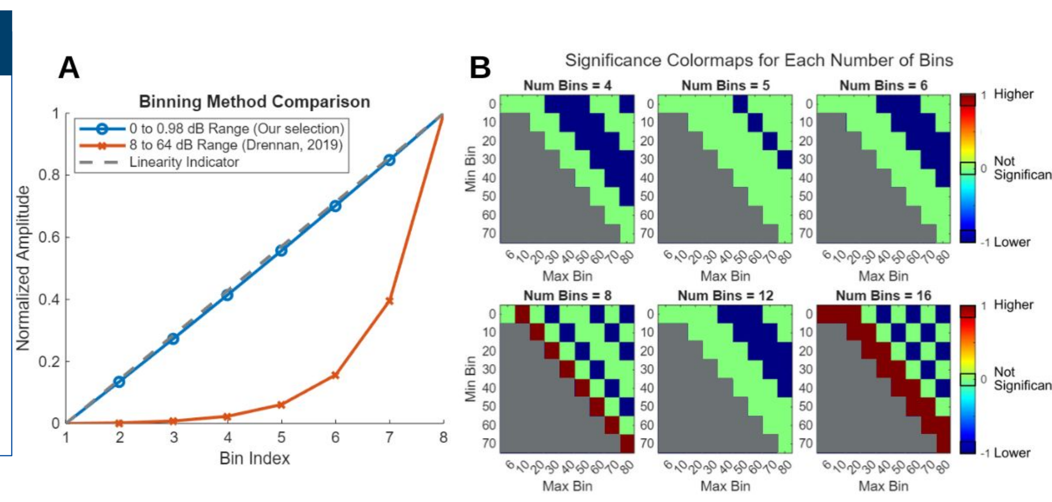


Fig 4.
A - Binning methods,
B - Search Grid

AB Envelope vs. Standard Envelope Model

- **Both models** (Standard & AB) predict EEG **above chance** (null = 0.05). *(Fig 5,A)*
- **AB envelope outperforms Standard** overall (p = 0.0191, d = 0.57). *(Fig 5,A.)*
- **Narrow condition:** AB significantly better (p < 0.0006, d = 0.92). *(Fig 5,B.)*
- **Wide condition:** No significant difference (p > 0.6). *(Fig 5,B.)*
- Reflects **stronger attention effects** in narrow focus.

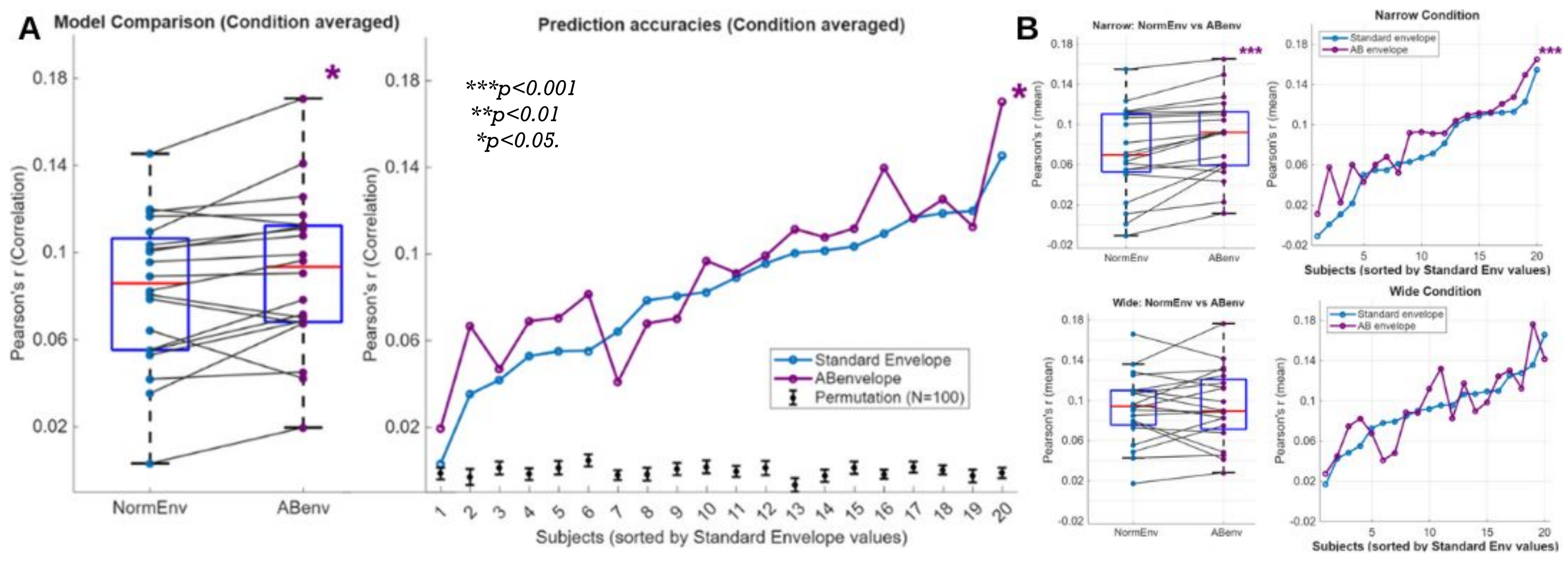
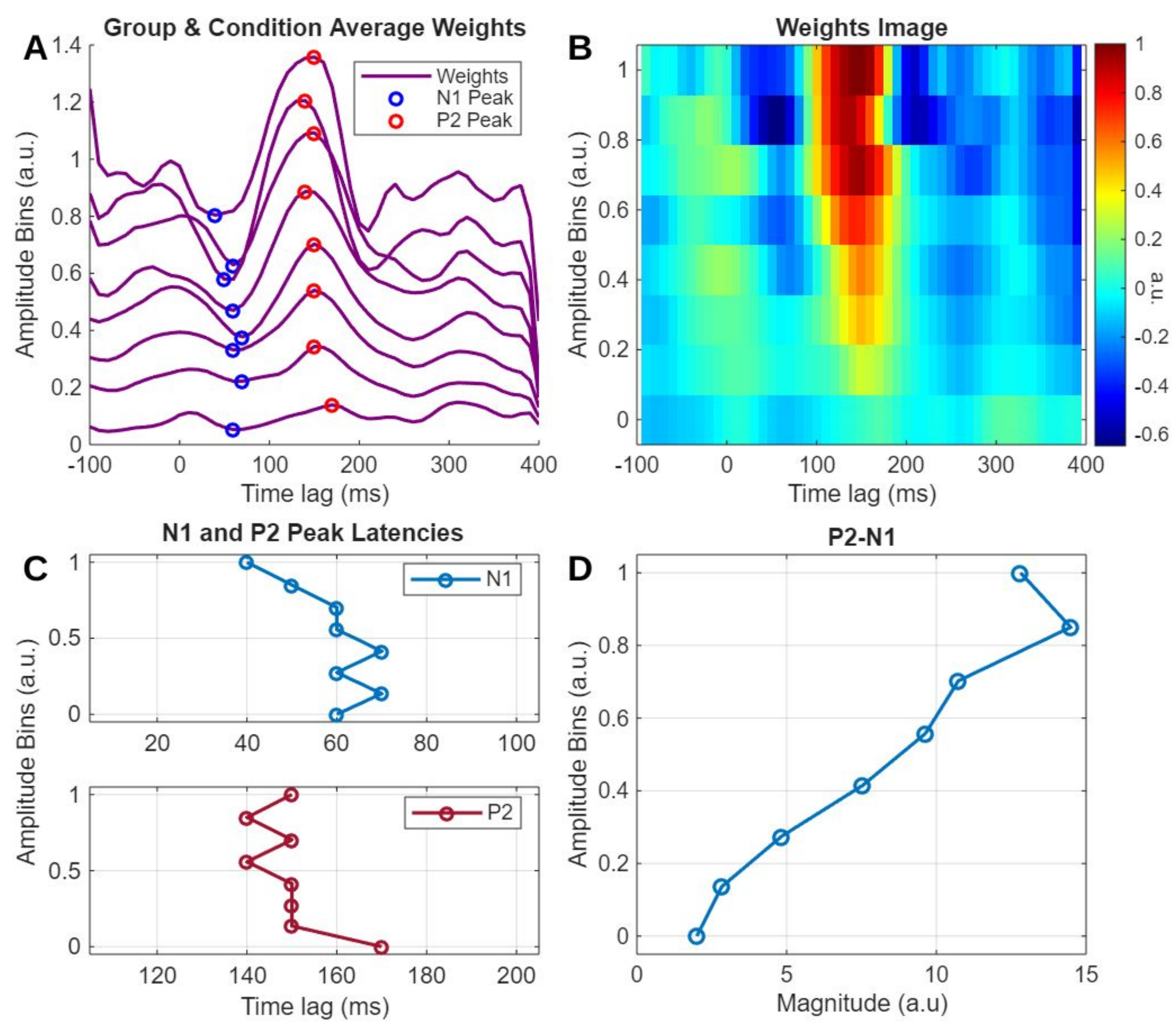


Fig 5. AB Envelope Model Performance: Boxplots and individual subject accuracies with permutation test baseline. **A:** Condition-averaged performance, **B:** Narrow vs. wide attention conditions,

TRF Morphology

- **P2–N1 magnitude** ↓ with decreasing amplitude (R^2 = 0.95, p < 0.001) .,*(Fig. 6D)*
- **N1 latency** ↑ slightly with lower amplitude (R^2 = 0.55)., *(Fig. 6C)*
- **P2 latency** ↑ (R^2 = 0.39) — weak trend., *(Fig. 6C)*
- Confirms: **AB envelope captures amplitude-driven TRF dynamics**

Fig 6. mTRF Model EEG Weights - Amplitude-Dependent Changes
A- TRF weights by amplitude bin,
B - Image plot of TRF weights,
C - N1/P2 latency shifts
D - P2–N1 magnitude difference across bins.



Combined Models

- **AB + Onset > AB alone**
  - (p = 0.0252, d = 0.54)
- **AB + Onset > Onset alone**
  - (p < 0.0001, d = 1.38)

Discussion

AB Envelope Improves Prediction

- Adds structural info via **amplitude segmentation**, without altering the signal
- Outperforms Standard envelope, especially in **narrow attention**
- AB model captures nonlinear neural tracking via amplitude segmentation.
- **No improvement** in wide condition (likely due to attention/masking effects)

Combined Model Improves Further

- **AB + Onset envelope** = highest prediction accuracy
- Captures **complementary dynamics**: AB → continuous amplitude; Onset → fast transients (Matches findings from **Drennan et al., 2019**[1])

Future Directions

- Separate **speech vs. non-speech** in natural soundscapes
- Build **3D TRF models** combining **amplitude + frequency binning**
- Integrate **attention markers & cognitive features** into modeling

Conclusion

- ✅ **H1 confirmed**: AB envelope is a stronger EEG predictor under focused attention
- ✅ **H2 confirmed**: Combining AB + Onset enhances performance
- **Binning strategy** & **normalization timing** are critical for model success.
- Future models should consider **attention, masking**, and **sound type distinctions** to better decode EEG in complex environments

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