Natural music evokes correlated EEG responses reflecting temporal structure and beat

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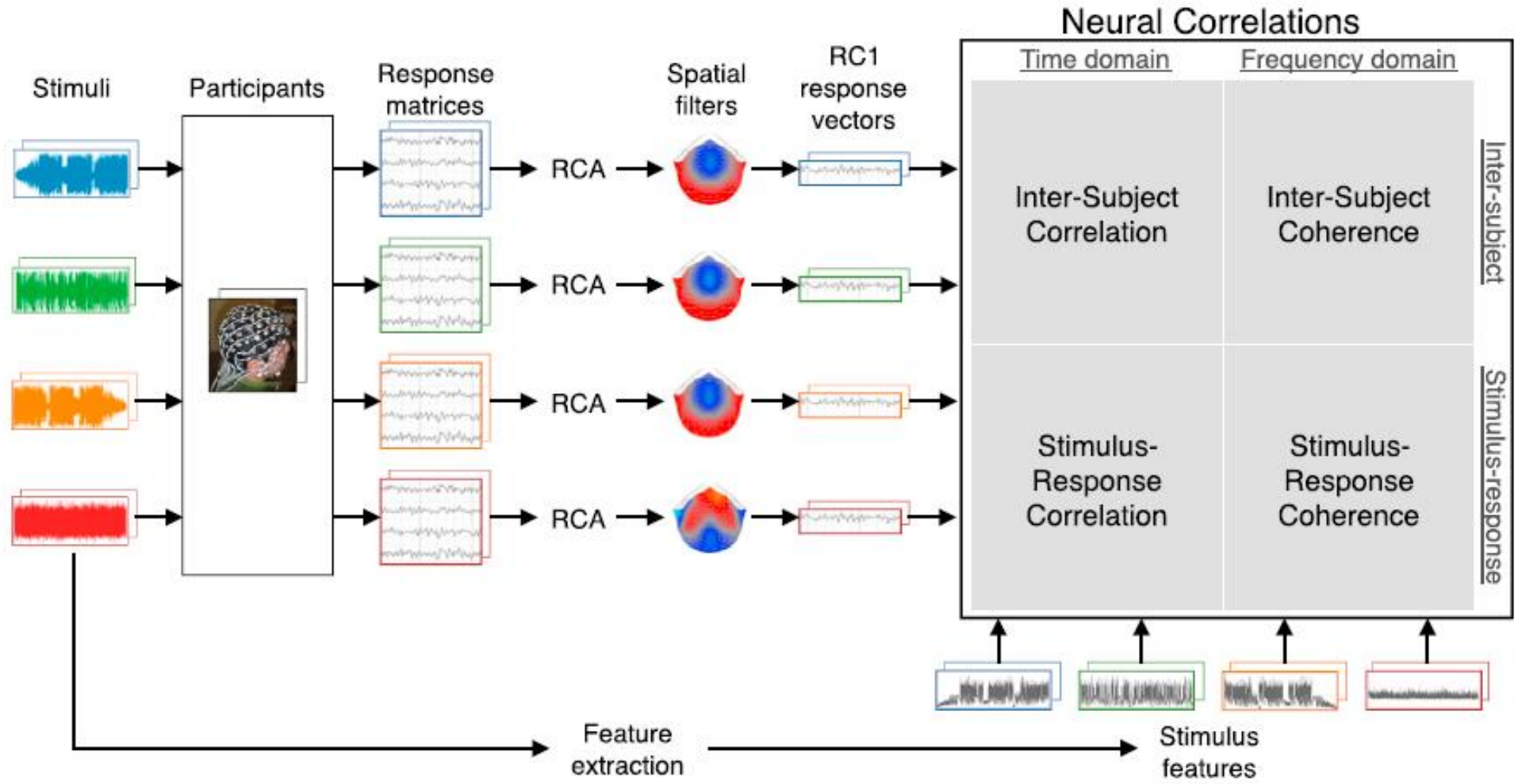
Summary

- Goal: neural correlation to the natural music
- Method: 48 subjects listen to real-world musical works, some are temporally disrupted. And measured correlation in the time and frequency domains.
- Result:
    - time-domain correlations were highest during measure-shuffled versions
    - Frequency-domain related to musical beat
    - natural music evokes significant inter-subject(ISC) and stimulus-response correlations(SRC).
    - neural correlates of musical ‘engagement’ may be distinct from enjoyment.

Pipeline


Stimuli
Participants
Response matrices
RCA
RCA
RCA
RCA
Spatial filters
RC1 response vectors
Neural Correlations
Time domain
Frequency domain
Inter-Subject Correlation
Inter-Subject Coherence
Stimulus-Response Correlation
Stimulus-Response Coherence
Inter-subject
Stimulus-response
Feature extraction
Stimulus features

Preparation

Participates

- N = 48 (25 males, 23 females), 18–34 years old (mean 24.58 years) with normal hearing.
- Recruited participants reported enjoying music, and listened to music at least 3h/week.
- No requirements for formal musical training or have absolute pitch.
- Not familiar but can understand the stimulus.

Preparation

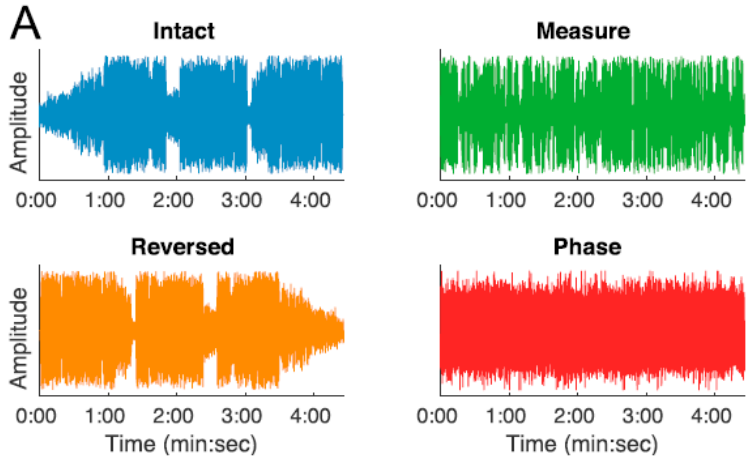
Stimulus

Recorded scalp EEG responses for four full-length Hindi-language ‘Bollywood’ songs, each prepared in four conditions:

- Intact : In original form (Intact)
- Measure : with its measures randomly rearranged across time
- Reversed : with the entire waveform reversed
- Phase : and with its phase spectrum randomized

Each participant would be assigned each song once, with a different stimulus condition for each song.

	Song 1	Song 2	Song 3	Song 4
Title	Ainvayi Ainvayi	Daaru Desi	Haule Haule	Malang
Film	*Band Baaja Baaraat*	*Cocktail*	*Rab Ne Bana Di Jodi*	*Dhoom 3*
Year	2010	2012	2008	2013
Length	4:27	4:30	4:24	4:33
Tempo	156	94	90	86



Preparation

Data acquisition

- Two recording blocks of around 20 min each, assigned stimulus once randomly.
- Participates listen attentively and watch a fixation.
- Rate Pleasantness, Musicality, Order, and degree of Interest on a scale of 1–9.
- Each participant heard their assigned stimuli twice, and 12 participants were assigned to each stimulus, a total of 24 trials for each of the 16 stimuli.

Data preprocessing

- EEG recordings filtered using bandpass filter (0.3–50 Hz)
- Downsampled by a sampling rate of 125 Hz
- Aggregated across trials on a per-stimulus basis, producing for each stimulus an electrode-by-time-by-trial matrix of size **125x T x 24**.

Method

Reliable Components Analysis

- RCA is a component analysis akin to PCA
- Computed to maximize covariance among multiple data records
- Focused subsequent analyses on the maximally correlated component, RC1.

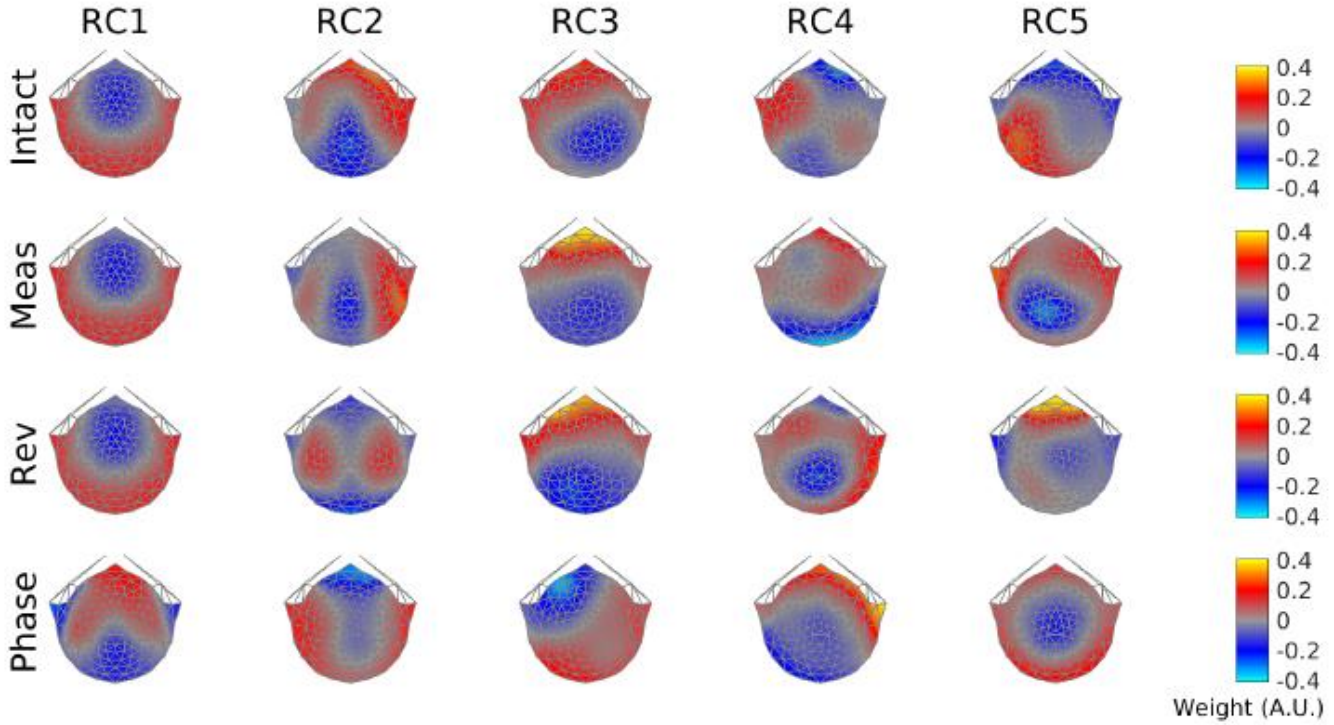


Figure S4: Forward-model projections of spatial filters, RCs 1–5.

Time-domain analyses

inter-subject correlation (ISC) analysis

- Correlating RC1 time courses on a per-stimulus basis over the full duration of each stimulus.

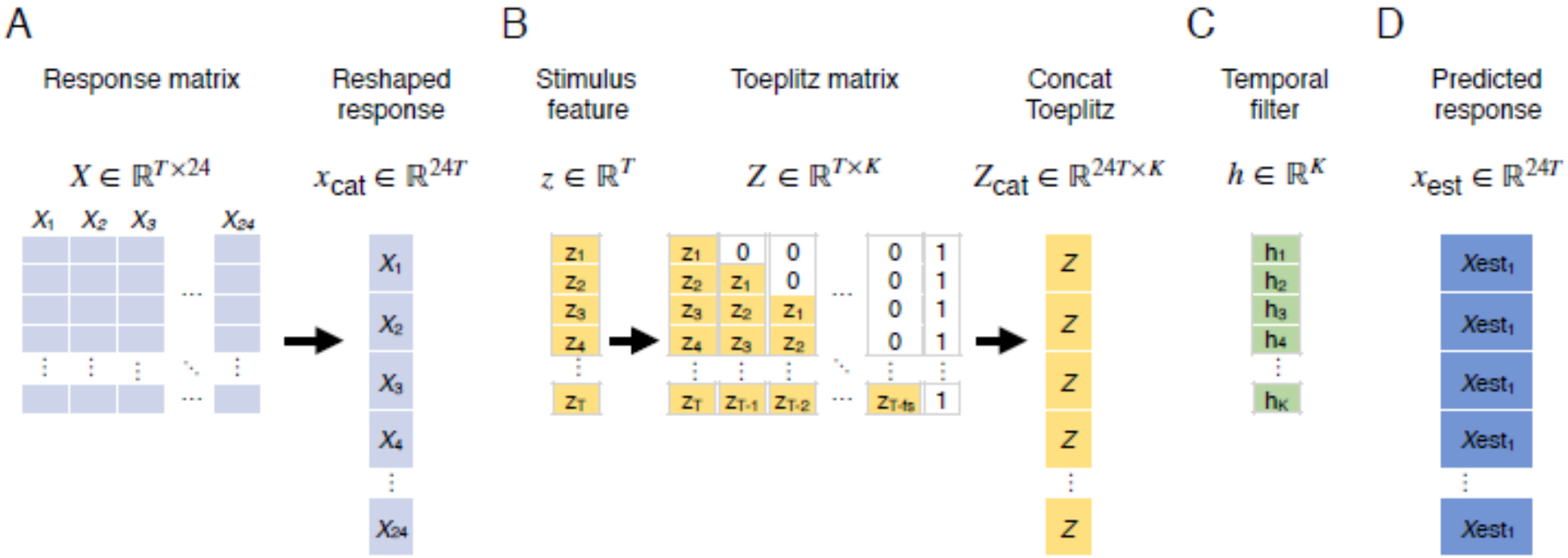
- Use a one-against-all procedure, reported correlation of each trial was the mean correlation of that trial with all other trials, refer as ISC.

- Additionally computed ISC over short (5s) time segments and correlated these values with the magnitude of the fluctuations in the stimulus envelope in the corresponding temporal windows.

Time-domain analyses

Stimulus-response correlation (SRC) analysis

- As a complement to ISC analyses, we computed SRC between each RC1 time course and the magnitude fluctuations of the corresponding stimulus envelope.
- Report mean correlation, and standard error of the mean, across the 24 stimulus-response correlations for each stimulus.
- The inter-subject and stimulus-response analyses described above produced one correlation per trial. 24*16=384 trials.



Frequency-domain analyses

- Reveal the relation between periodic stimuli, such as rhythms.
- Use a different approach based on coherence on Intact, Measure, and Reversed stimuli.

coherence

- DFT length of 1,024, a 5s Hamming window, and 50% overlap between windows.
- Output coherence magnitudes over frequencies 0–62.5 Hz with a resolution of 0.122 Hz.
- Observed low-frequency (< 12 Hz) peaks, identified for each song the frequency corresponding to the most prominent coherence peak across stimulus conditions.

- inter-subject : one-against-all
- stimulus-response : between RC1 and stimulus envelope fluctuations

Cross power spectral density (CPSD)

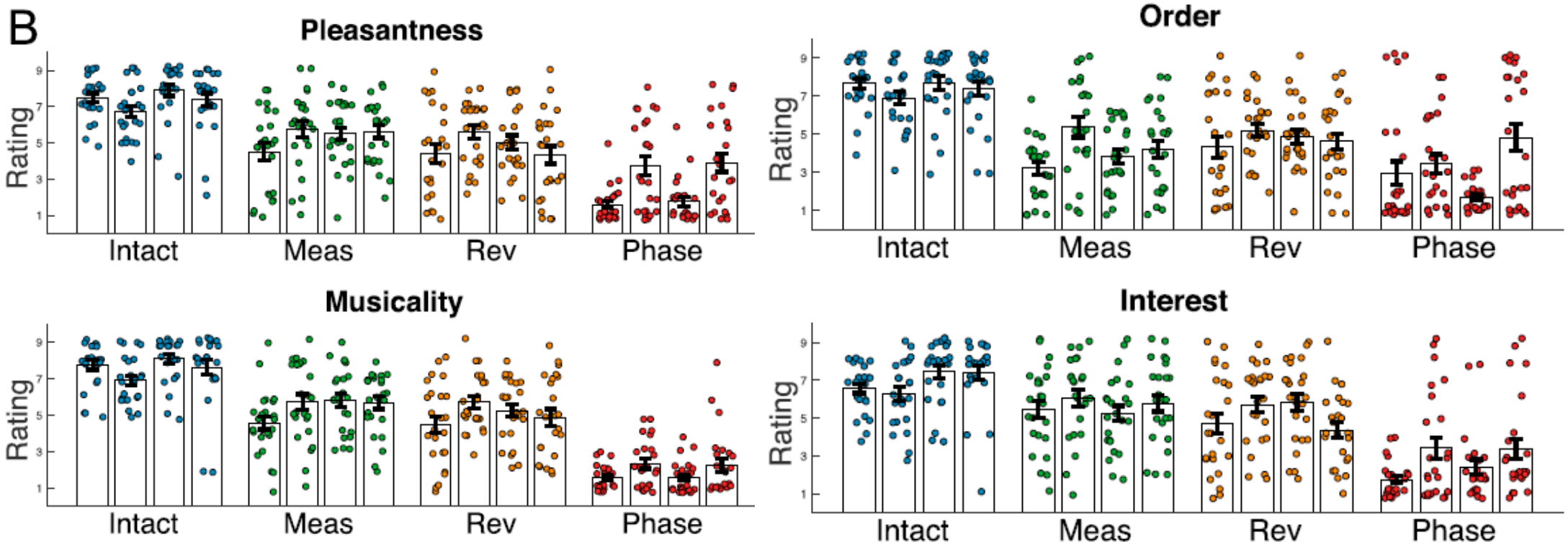
phase angles using the same DFT and windowing

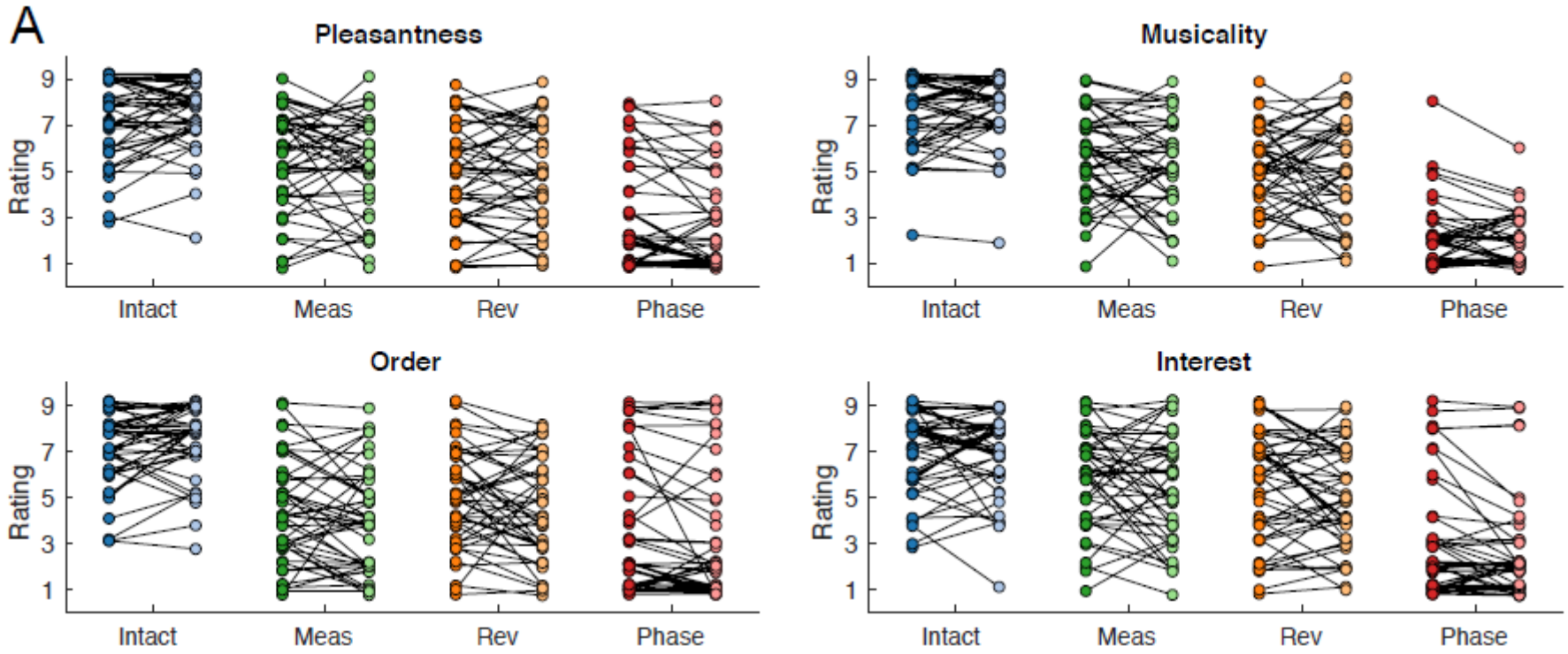
Result

Intact stimuli elicit highest behavioral ratings

- Previous findings suggest ISC indexes emotional arousal or engagement with narrative stimuli
- Hypothesized both behavioral measures of enjoyment and ISC would be highest for the Intact stimuli, to show successfully engagement
- Overall, behavioral ratings aligned with our expectations of highest ratings for Intact stimuli, and lowest ratings for Phase stimuli, which are perceived as modulated noise.

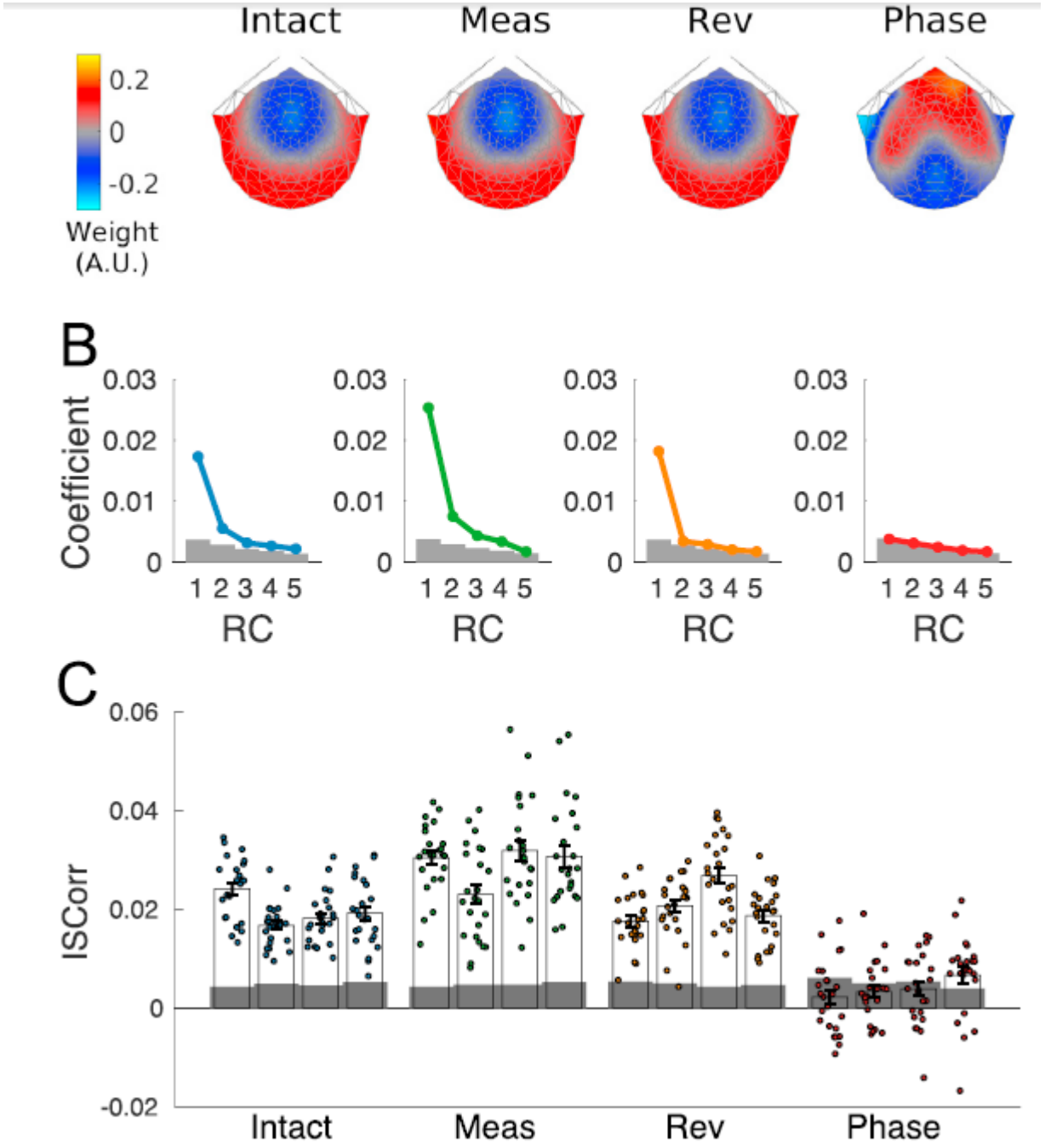
Result


B
Pleasantness
Order
Musicality
Interest
Rating
Intact
Meas
Rev
Phase



Perform one-tailed paired t-tests on a per-question, to determine whether behavioral ratings dropped during the second stimulus presentation. In no case did behavioral ratings drop significantly during the second stimulus presentation

Result


Intact
Meas
Rev
Phase
0.2
0
-0.2
Weight
(A.U.)
B
Coefficient
0.03
0.02
0.01
0
1 2 3 4 5
RC
C
ISCorr
0.06
0.04
0.02
0
-0.02
Intact
Meas
Rev
Phase

Result

Stimuli retaining musical features produce consistent EEG components

Projected spatial filter weights can be visualized as topographic scalp maps. RC1 topographies for Intact, Measure, and Reversed.

Fig. 3B, shows the RC1 correlation coefficient was well above permutation test significance thresholds for responses to Intact, Measure, and Reversed stimuli , but not Phase.

Mean RC1 ISC was significant for all songs in Intact, Measure, and Reversed conditions but not for Phase.

ISC varied significantly by stimulus condition, with highest ISC for Measure stimuli and lowest ISC for Phase.

The shaded gray area denotes the 95th percentile of the null distribution. Bar height represents the mean value, error bar height represents twice the standard error of the mean, and colored points represent single trials (N= 24 trials per stimulus)

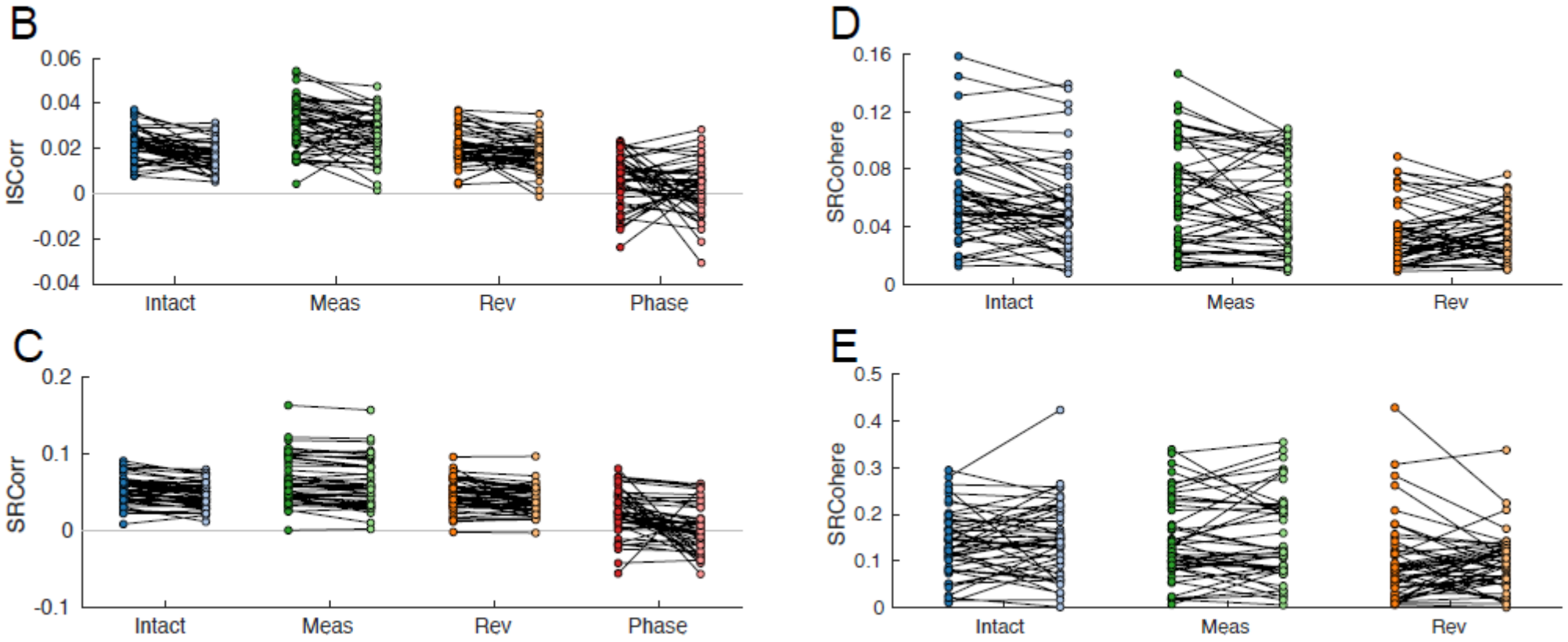
Result

EEG ISC Conclusion

focused our analyses on RC1.

However, Intact stimuli always received the highest behavioral ratings, the most-correlated neural responses were evoked by the Measure stimuli

One-tailed paired t-tests for repetition



One-tailed paired t-tests indicated that for all stimulus conditions, ISC dropped significantly during the second stimulus presentation

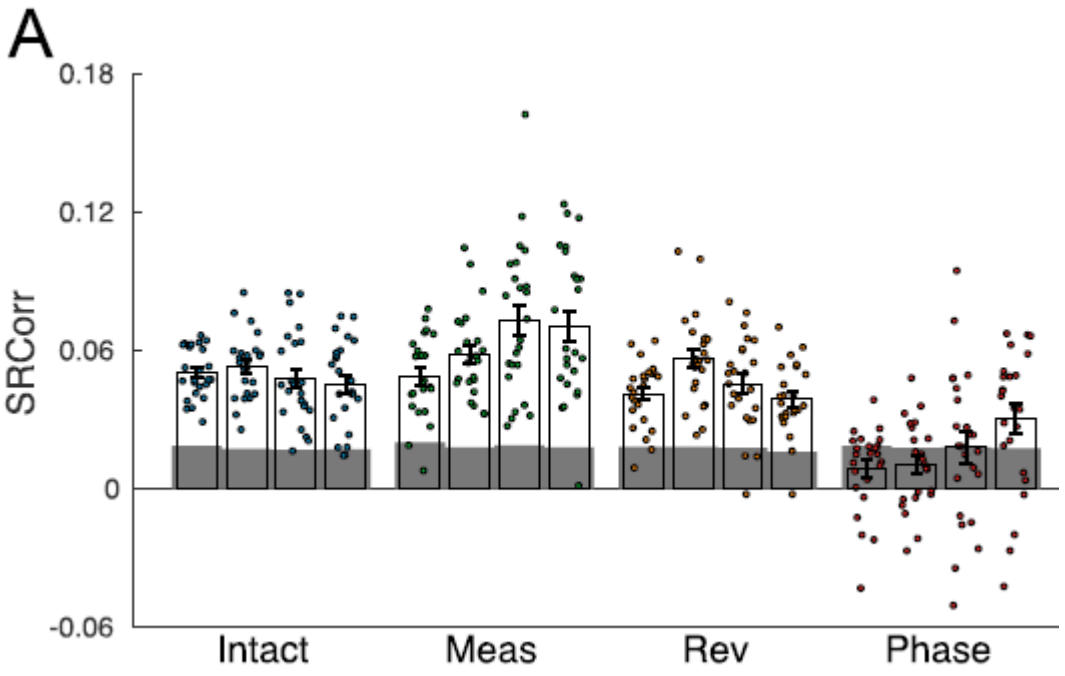
Result

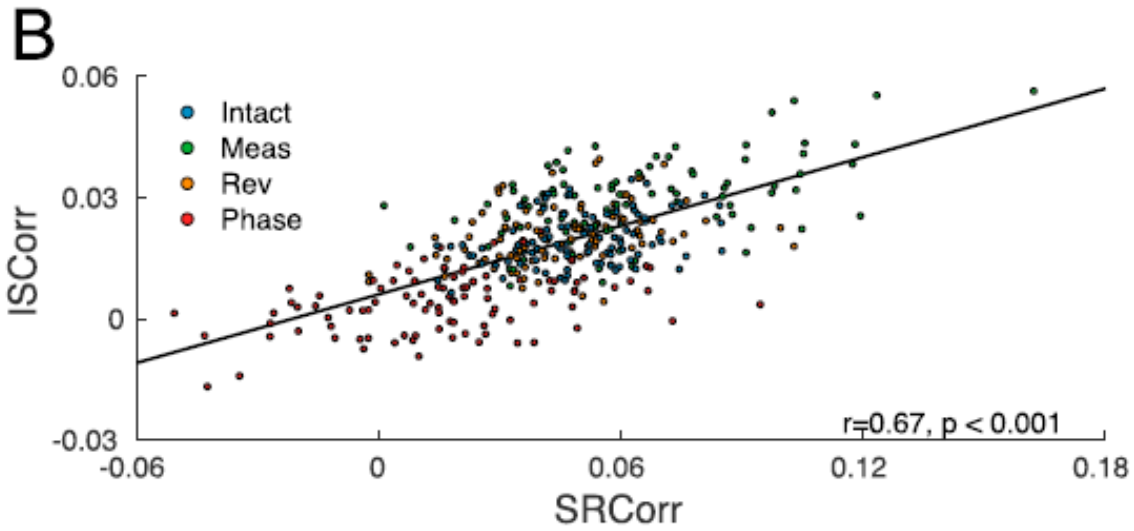
ISC correlates with envelope SRC

measured correlations between envelope fluctuations and RC1 EEG—the stimulus-response correlation (SRC)

SRC results were similar to ISC results.

As ISC and SRC results were broadly similar, we computed their correlation on a per-trial basis; with 24 trials per stimulus and 16 stimuli, this procedure involved 384 trials.





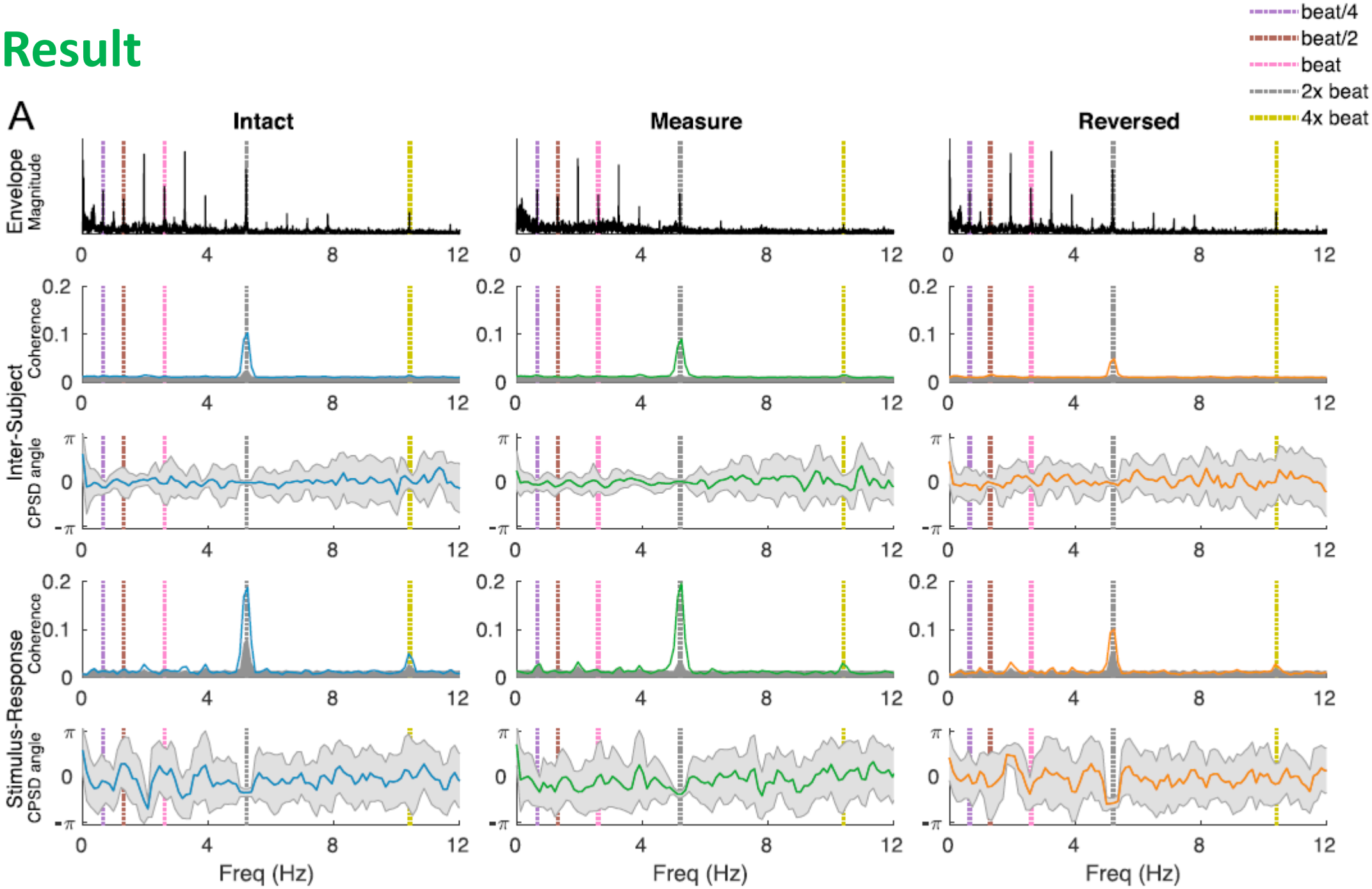
Result

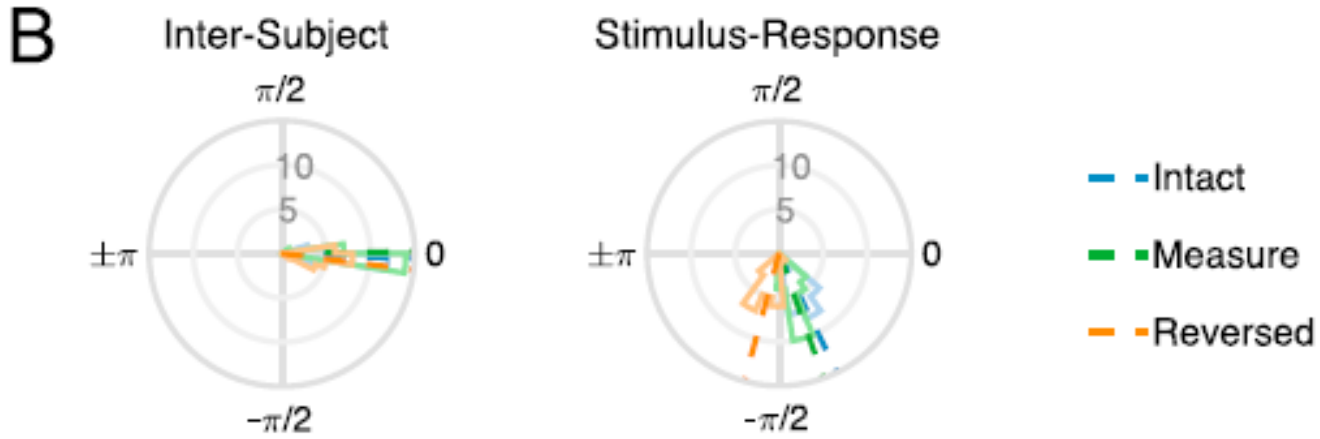
Frequency-domain EEG correlations implicate musical beat

Determine whether correlated temporal activations implicated perceptually relevant frequencies, we computed the magnitude-squared coherence spectrum

We observed prominent peaks in the low-frequency coherence spectrum (0–12 Hz).

Result


beat/4
beat/2
beat
2x beat
4x beat
A
Intact
Measure
Reversed
Envelope
Magnitude
Inter-Subject
Coherence
CPSD angle
Stimulus-Response
Coherence
CPSD angle
0
4
8
12
0.2
0.1
π
-π
Freq (Hz)



We next compared the distributions of phase angles at the frequency of interest implicated by coherence peaks by visualizing them as polar histograms

However, follow-up pairwise comparisons did not align with time-domain correlation results:
While the highest time-domain correlation was observed for responses to Measure stimuli, coherence did not differ significantly between Intact and Measure stimuli

Discussion

Stimuli retaining basic (particularly rhythmic and melodic) musical features produced statistically significant ISC and SRC, while Phase excerpts did not

We additionally found that natural music excerpts need not be in their original, intact form in order to elicit significant ISC. However, we note that among the musical features removed by phase scrambling are amplitude envelope fluctuations characteristic to music

Contrary to our expectation that Intact stimuli would produce the most-correlated brain activity, results indicated that brain responses to the Measure condition were most correlated in both ISC and SRC contexts.

Therefore, engagement here may point to a heightened state of attention associated with anticipating and processing continually surprising musical events of the Measure condition, even if listeners do not equate this state with enjoyment.

Future work could consider additional dimensions along which to collect behavioral ratings, such as mood, arousal, and valence.

We interpret this correlation to be the confluence of two factors:
The preservation of metrical structure and the deviation of harmonic and melodic consequence across metrical units.

Thus, on one hand there was a consistent level of temporal organization, preserving metrical expectations, while on the other hand, disjunctions at metric segmentation boundaries violated melodic and harmonic expectations.

Conclusion

Inter-subject and stimulus-response EEG correlation techniques can be employed in the time and frequency domains to study natural music processing.

Propose an analysis pipeline which enables these techniques to be deployed on a common set of spatially filtered EEG activations.

Results suggest a state of listener engagement can be disassociated from behavioral reports of enjoyment.

These findings enrich the interpretation of elevated neural correlation as engagement and compel future studies to clarify the relationship between neural correlation, engagement, and enjoyment.

Thank you!