Cortical PCA: Exploring Potential Tempo and Transient Locking to Musical Stimuli

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Abstract

We explore whether dynamic principal component analysis (PCA) of cortical EEG amplitude or power envelopes reveals tempo and/or transient locking to musical stimuli. Using log-transformed, z-scored amplitude or power envelopes across a range of frequency bands, we project whole-cortex EEG dynamics into a low-dimensional PCA space and track trajectories over time. These trajectories exhibit stable rotations, song-specific attractors (with occasional overlap between songs), and orbit structures that vary systematically with PCA parameters (e.g., window size, Gaussian taper shape) and frequency band. We compared the tempo of several songs with the natural oscillatory tempo of PCA ring trajectories in the first three dimensions of PCA space, finding that PCA ring rate held steady around 5.14 Hz invariant to song tempo. We also explored whether transients align with sharp directional changes in PCA space, considering a wide range of spectral bands.

1 Introduction

In a previous study[**1**], we observed that electrodes Fz and O1 showed potential locking of beta/gamma amplitude crests to musical transients. Here, we extend this preliminary study by exploring potential tempo and transient locking across the entire EEG-recordable cortex, as seen through the lens of dynamic PCA.

The basic pipeline is as follows (CMW = Complex Morlet Wavelet convolution):

$$\textbf{EEG} \xrightarrow{\textbf{CMW}} \textbf{Band Power Envelopes} \xrightarrow{\textbf{PCA}} \textbf{Trajectories}$$

It is noted that our methodology and results deviate from traditional PCA in three key ways:

1. **Dynamic and Quasi-Dynamic PCA** are employed, wherein PCA is computed across sliding windows in time, rather than performed once across the entire session ("static" PCA).
2. **Spectral amplitude- and power-modulation (AM, PM) at the macroscale (LFP/EEG)** are analyzed in place of the more commonly studied **frequency-modulation (FM) of individual neuron firing,** as emphasized in prior work (e.g., Churchland et al.[**2**]). Incidentally, **voltage modulation**—i.e., applying PCA directly to raw EEG signals—yields weak results and appears largely uninformative in this context.
3. **5.14 Hz, rather than 0.5–2 Hz, rings are noted.** The emergence of PCA rings at this faster rate may reflect an ability of musical stimuli to trigger periodicity (in PC1-3 space) at a sort of cortical resonant frequency. It is possible, though, that the rings emerge from closing one's eyes at a certain point into the music or due to some other reason.

The stimulus list for this EEG session, conducted on June 1, 2025, is as follows:

- *Threshold* — Sungazer (first listen)
- *Smells Like Teen Spirit* — Nirvana
- *A Horse with No Name* — America

- *Espresso* — Sabrina Carpenter
- *Ocean Eyes* — Billie Eilish
- *Physical* — Dua Lipa
- *I Could Fall in Love* — Selena Quintanilla
- *Dreaming of You* — Selena Quintanilla
- *An Old Fashioned Love Song* — Three Dog Night
- *Ordinary World* — Duran Duran
- *Alone* — Heart

In a previous study[**1**] conducted on September 17, 2024—focused on examining 3D time-frequency-amplitude (TFA) fabrics for locking to musical transients—the following stimuli were used:

- *Use Me* — PVRIS
- *Smoke* — PVRIS
- *Reeling in the Years* — Steely Dan
- *Crystal Ball* — Styx
- *Aja* — Steely Dan

In this study, we briefly explore time-frequency-log(power) (TFP) plots below—an extension of the time-frequency-amplitude (TFA) fabrics described in the previous paper[**1**]. As demonstrated in Figure 1 (see full video: Dreaming of You TFP Fabric), these plots reveal structured dynamics in the gamma range (52.5–62.5 Hz). Note the arch-like behavior around 60 Hz, with Pz's peak aligning with Fz's trough, briefly converging at a shared power level. This pattern reflects periodic modulation in gamma-band power across these sites (close to, but consistently 0.32 Hz slower than, song tempo).

It is worth noting that two longstanding challenges in neuroscience are:

1. Identifying a unitary locking mechanism for perceptual events in a brain whose EEG channels often display profound apparent disunity.
2. Determining the precise temporal lag between external stimuli and the corresponding emergence of perception or consciousness.

The findings presented in this paper may offer insight into both problems, particularly if transient events along PCA ring trajectories represent a unitary perceptual lock (with no evidence of echo or duplication) and occur consistently 40–60 ms after the stimulus—suggesting a stable perceptual lag.

2 Methods

Participant: Male, 42 years old, familiar with all chosen songs (except Threshold by Sungazer).

Materials: OpenBCI 16-channel EEG cap with sintered Ag/AgCl electrodes; Cyton + Daisy Biosensing Board (125 Hz sampling rate) transmitting wirelessly to a MacBook Pro; Fender Acoustasonic amp playing songs via the YouTube Music app on an iPhone using aux input; Canon 5D Mark IV DSLR camera used to align timestamps between OpenBCI software and musical onsets (a lag of 40–60 ms was applied in most videos for aesthetic alignment of transients and PCA brain response).

Procedure: The EEG cap was fitted and electrodes filled with conductive gel. Impedances were reduced to 3–22 kΩ. The participant remained as still as possible during recording, with eyes mostly closed and attention focused on the music. After the session, timestamps marking the onset of silence and the beginning of each song were recorded as precisely as possible for later use in MATLAB-based TFP fabric and PCA

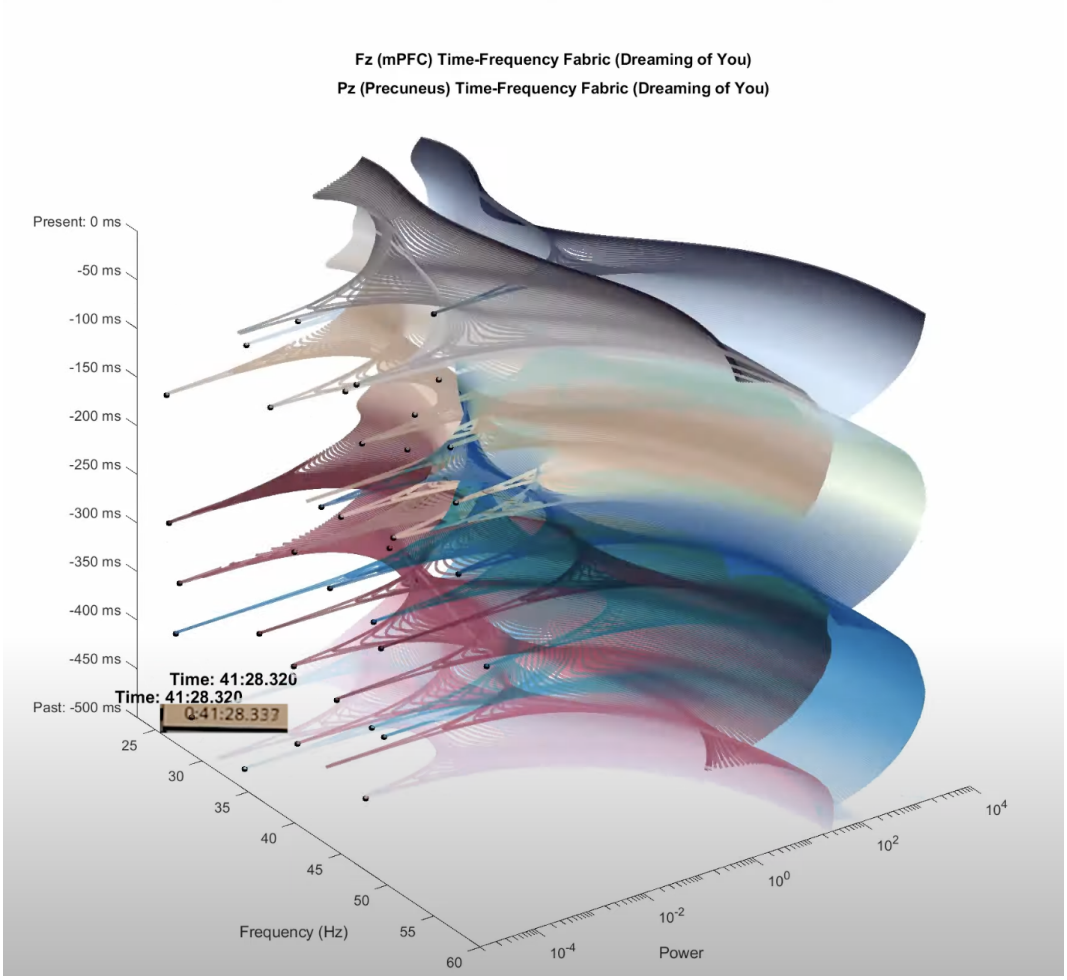

Figure 1: TFP (time-frequency-log(power)) fabric showing periodic gamma-band structure at Fz and Pz electrodes.

ring video generation. Clean audio was synchronized with the Matlab-generated videos in Adobe Premiere Pro, with an alignment precision of approximately ±10 ms. After alignment, an artificial offset lag of 40-60 ms was induced, which aligned PCA transients with musical transients, and might reflect brain processing lag. This EEG session was recorded on June 1, 2025.

Data Analysis: EEG voltage data were timestamped at approximately 8 ms intervals (125 Hz sampling). However, minor timing irregularities were observed (ranging from 5 to 11 ms between samples). Timestamps were therefore used to interpolate voltage levels at precise 1 ms intervals, and the data were upsampled to 1000 Hz. Interpolated signals were then convolved with varying numbers of complex Morlet wavelets in MATLAB to produce detailed arrays of complex-valued analytic signals, providing high-resolution frequency decomposition of the EEG data.

3 Results

3.1 Background and Exploring Potential Tempo Locking

We begin by reviewing the hour-long PCA video, which featured dynamic PCA with a broad window (see Figure 2). In this analysis, a new PCA was computed once every millisecond. This created a smooth trajectory through 3D PCA space that preserved the evolving shape of attractors while allowing for some fine-grained deviations of the path taken by the EEG signal over time, although better analysis settings for

transient detection will be explored later in this paper. However, this first, hour-long examination provides a good overview of the data.

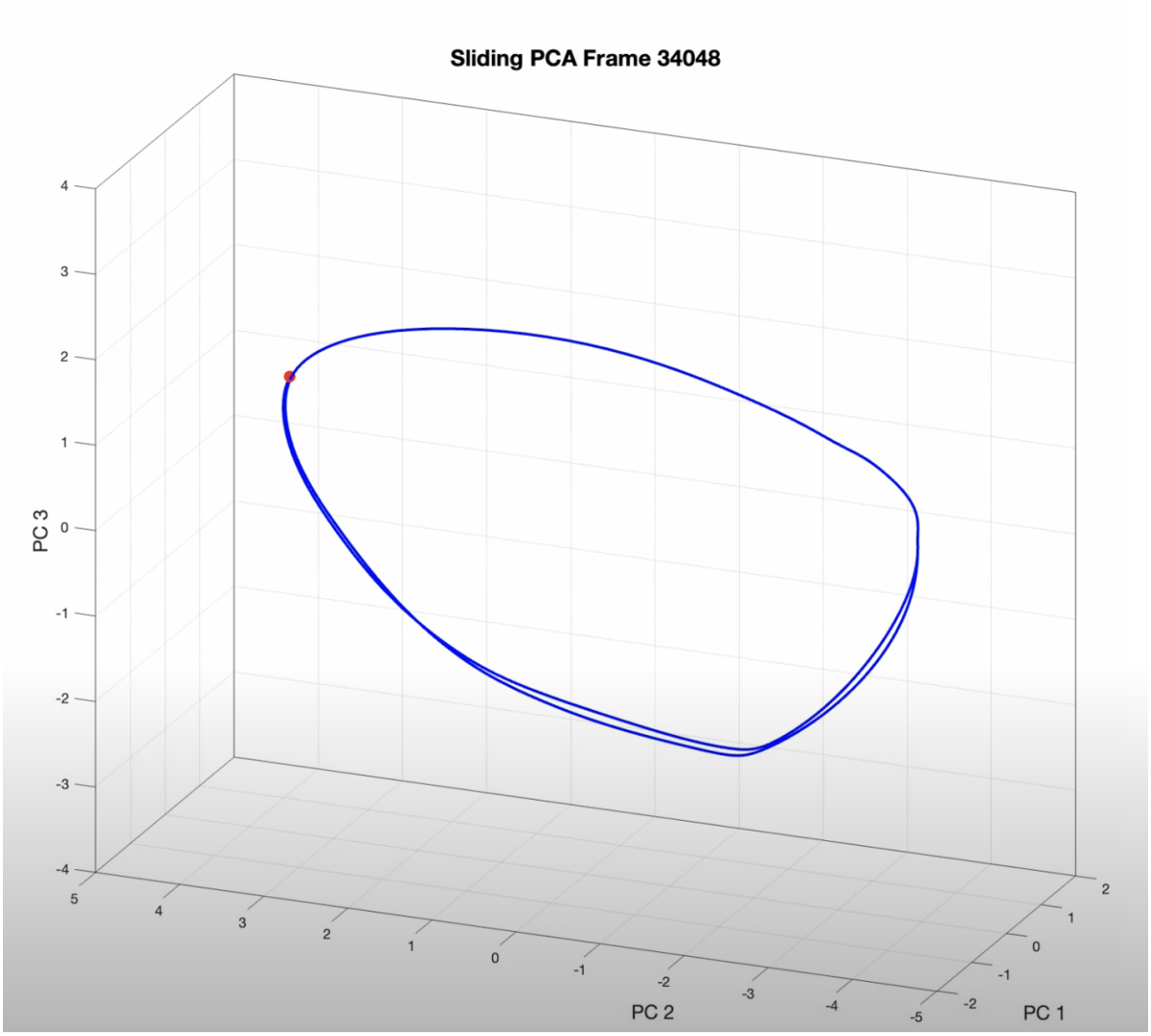

Figure 2: **Stimulus:** Multiple (11 songs plus 1 auditory illusion); 300 ms of *Threshold* by Sungazer is featured here. **Signal:** Z-scored log of the 60 Hz amplitude envelope, Gaussian-tapered (σ = 500 ms) over a 2000-ms window, recomputed at each millisecond. **PCs Plotted:** 1, 2, 3 (of 16). **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://www.youtube.com/watch?v=2MfvnuIZfIM`. **PCA Code:** `https://github.com/caldwbr/tempoLockPCA/blob/main/wholeSessionSlidingPCA.m`. **Video Code:** `https://github.com/caldwbr/tempoLockPCA/blob/main/wholeSessionSlidingPCAVideo.m`.

PCA emerged as a promising method after 60 Hz power crests and troughs across all electrodes showed periodic—but not phase-aligned—behavior in response to the song *Physical* by Dua Lipa (see Figure 3, where the song's beat is marked by blue lines and the phase-smearing across electrodes is visible). Operating under the hypothesis that TRN inhibitory pulses serve as a 'clock,' gamma power **troughs** were marked as dots. The thalamic reticular nucleus (TRN) was initially considered a candidate for synchronizing cortical timing, due to its role in delivering inhibitory pulses that might time-stamp salient events. These stamps were thought to undergo only fine smearing via core and matrix thalamic relays, with grosser phase-smearing arising from hierarchical propagation through cortical stages. But dynamic PCA offered a more compelling

explanation: despite the smearing, transients emerged as sharply unified perturbations along a shared low-dimensional trajectory: the cortex could still be a 'clock' (not exclusive to the thalamus).

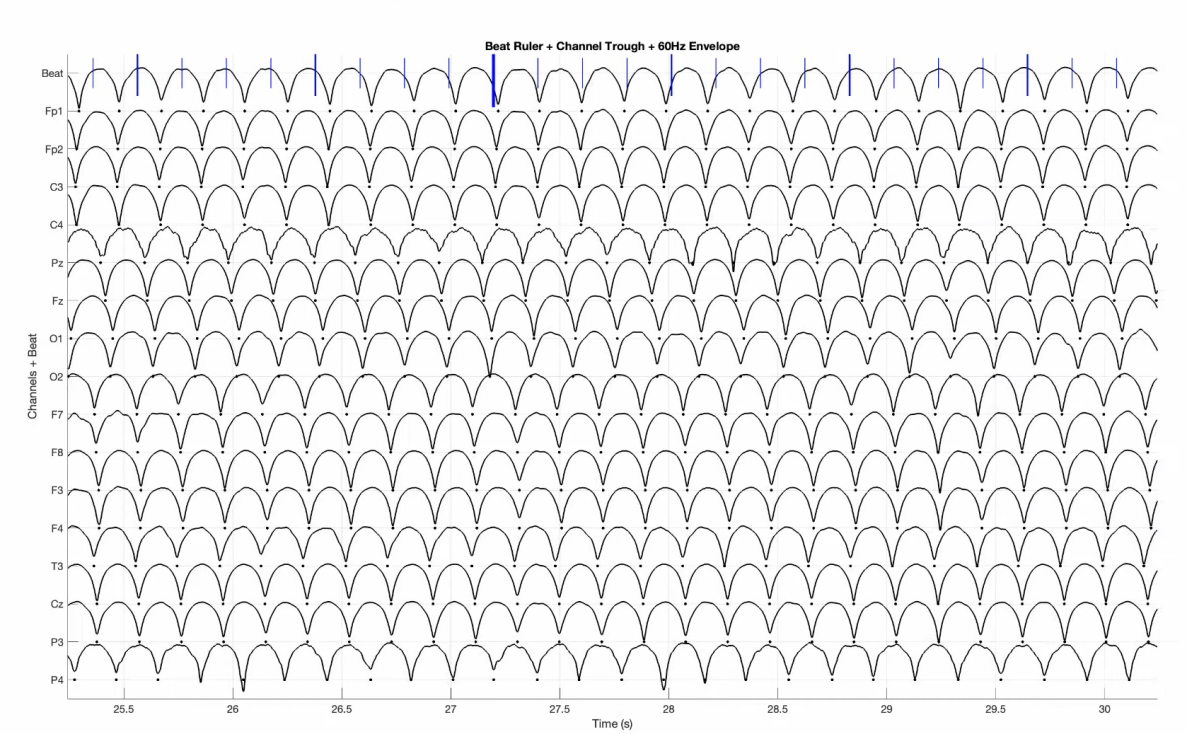

Figure 3: **Stimulus:** *Physical* by Dua Lipa (500 ms depicted here). **Signal:** Log of the 60 Hz power envelope. **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://www.youtube.com/watch?v=z1ByAxASAAk`. **Beat Ruler and Video Code:** `https://github.com/caldwbr/tempoLockPCA/blob/main/arches.m`.

Further, **dynamic** PCA was conceptualized after examining how phase-alignment to the beat exhibited **drift** of participating electrodes over time (stimulus: *Physical* by Dua Lipa, see Figure 4). Here, green marked phase-alignment to the beat, and the full spectrum of color showed the range of lead-to-lag of electrodes' 60 Hz amplitude troughs relative to actual beat. X and y are reserved for placing the electrodes on the headplot (note that not all are correctly placed), and z is used to denote the log of the amplitude of 60 Hz at each electrode. However, a more likely explanation arose during this study, when it was realized that the PCA ring rate was holding steady at about 5.14 Hz invariant of song stimuli, and small brain regions came in and out of phase alignment as a mere matter of the discrepancy between PCA ring rate and song tempo, just as two metronomes at slightly different tempos will come in and out of synchrony over time.

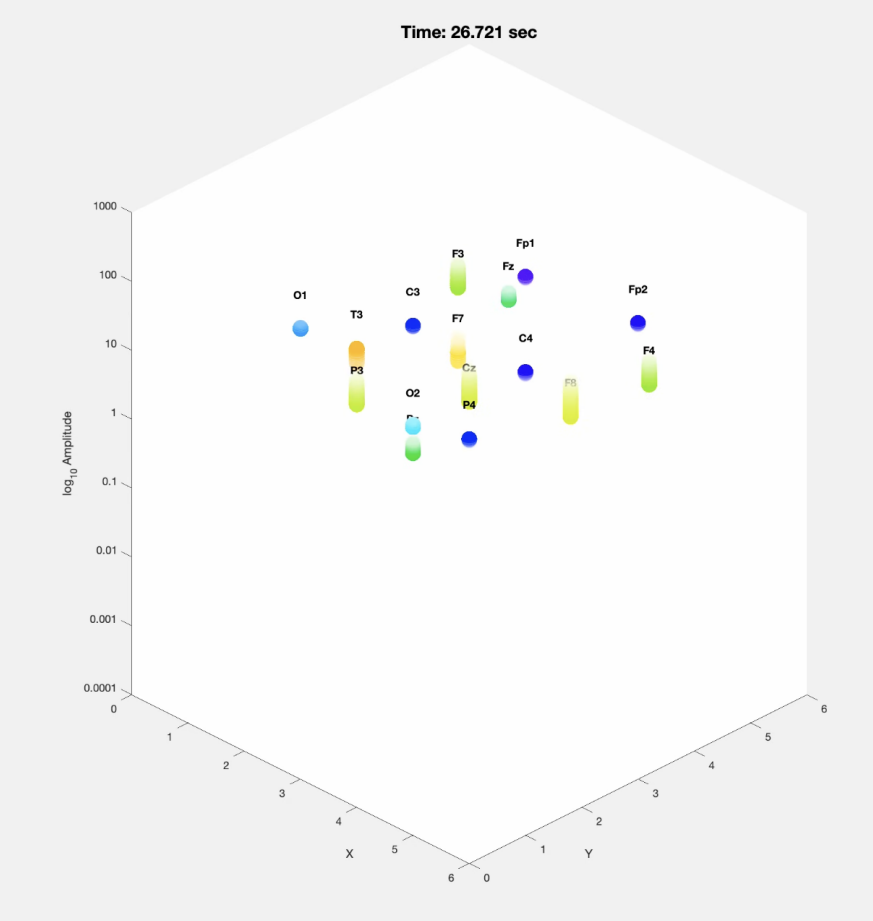

Figure 4: **Stimulus:** *Physical* by Dua Lipa (21 ms depicted here over the fading tails of dots). **Signal:** Log of the 60 Hz power envelope. **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://www.youtube.com/watch?v=00FaOVnM3nk`. **Video Code:** `https://github.com/caldwbr/tempoLockPCA/blob/main/headplotGammaAmplitudePhases.m`.

Following the initial promising results (Figure 2), dynamic PCA was run repeatedly across different songs, with parameter tweaks to probe for additional insights. In Figure 5, for the stimulus *Ordinary World* by Duran Duran, 11 frequency bands from 50 to 60 Hz (in 1 Hz steps) are plotted with slight temporal and spatial offsets. Color indicates frequency, ranging from blue (50 Hz) to red (60 Hz). A compromise between static and dynamic PCA was used here by running PCA at 300 evenly spaced timepoints in the song, and interpolating the weights to get scores at each millisecond. Weights were also examined over time, although the coarse PCA runs likely contributes to the slow 'breathing' of many of the weights (Figure 6). Returning closer to fully dynamic PCA (doing PCA once every 100 ms) at 0.5 Hz resolution (from 50 to 60 Hz) yielded an interesting result as seen in Figure 7. In Figure 8, two window sizes, Gaussians, and PCA run intervals are compared (still only quasi-dynamic PCA). In Figure 9, five window sizes, Gaussians, and PCA run intervals are plotted for three frequencies (52, 55, and 58 Hz). Still in the quasi-dynamic PCA realm, Figure 10 uses amplitude of 49 to 61 Hz (in 0.5 Hz steps) and gets similar results.

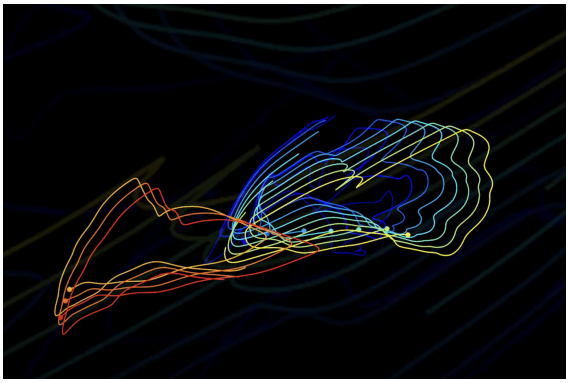

Figure 5: **Stimulus:** *Ordinary World* by Duran Duran (200 ms depicted here as tracer trajectories). **Signal:** Z-scored log of the 50-60 Hz amplitude envelopes, Gaussian-tapered (σ = 200 ms) over an 800-ms window. PCA was performed at 300 coarse timepoints across the song, and the resulting weights were interpolated to all timepoints using piecewise cubic Hermite interpolation. **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://www.youtube.com/watch?v=qCJ6LiBi25I`. **PCA Code (likely):** `https://github.com/caldwbr/tempoLockPCA/blob/main/spectralOrdinaryWorld50to60Hz.m` **Video Code (likely):** `https://github.com/caldwbr/tempoLockPCA/blob/main/spectralOrdinaryWorld50to60HzVideo.m`.

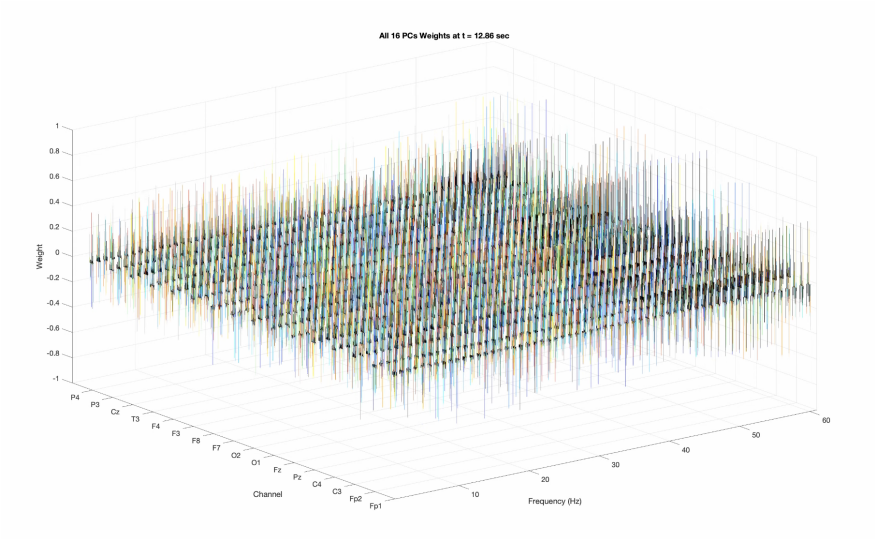

Figure 6: **Stimulus:** *Ordinary World* by Duran Duran (one time point depicted here as instantaneous weight values). **Signal:** Z-scored log of the 1-60 Hz amplitude envelopes, Gaussian-tapered (σ = 200 ms) over an 800-ms window. PCA was performed at 300 coarse timepoints across the song, and the resulting weights were interpolated to all timepoints using piecewise cubic Hermite interpolation. **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://www.youtube.com/watch?v=4RFVjYWOT6Y`. **Video Code:** `https://github.com/caldwbr/tempoLockPCA/blob/main/spectralOrdinaryWorldWeightsVideo.m`.

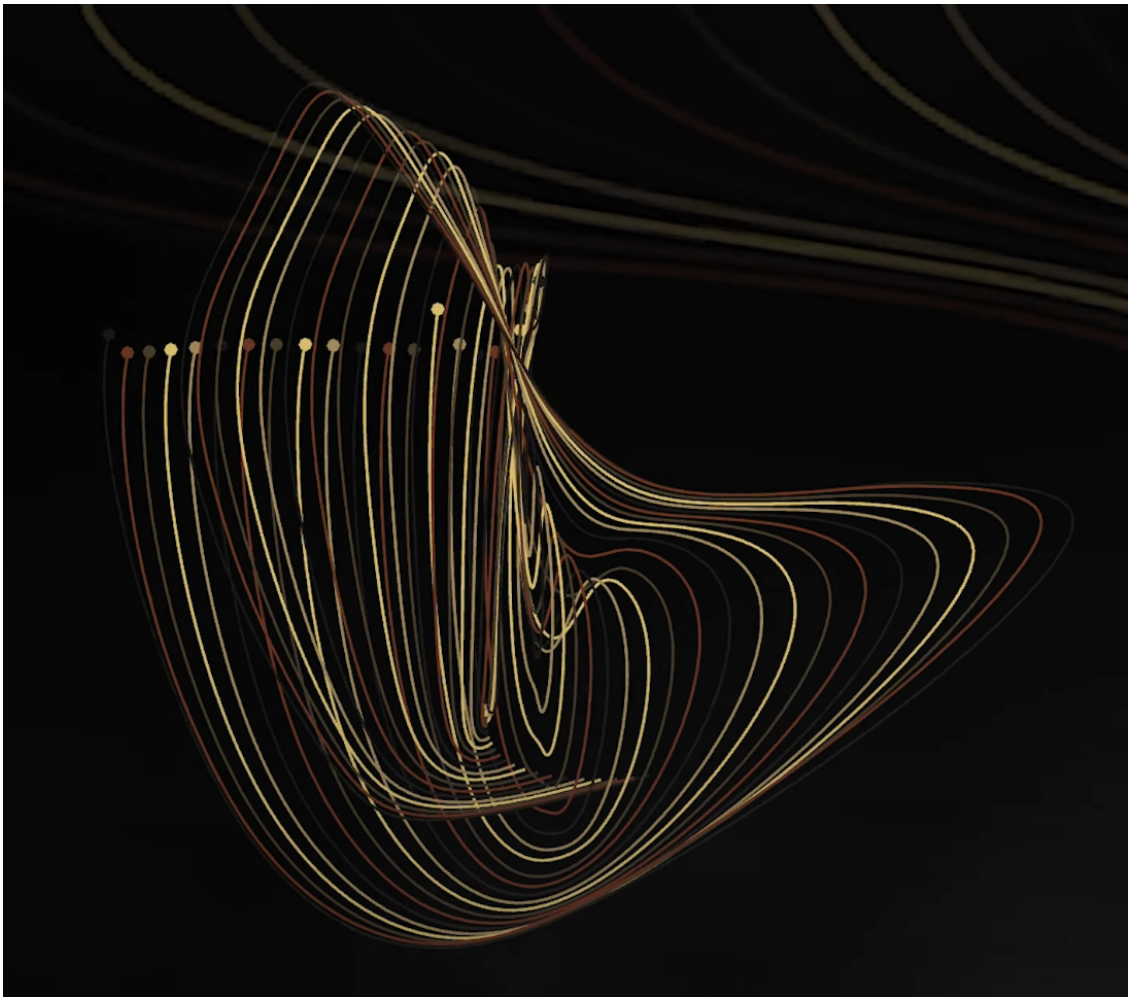

Figure 7: **Stimulus:** *Smells Like Teen Spirit* by Nirvana (∼200 ms of trajectories depicted here). **Signal:** Z-scored log of the 50-60 Hz amplitude envelopes (0.5 Hz intervals), Gaussian-tapered (σ = 200 ms) over an 800-ms window. PCA was performed roughly every 100 ms across the song, and the resulting weights were interpolated to all timepoints using piecewise cubic Hermite interpolation. **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://www.youtube.com/watch?v=LmoGnT2lQW4`. **Video Code (likely similar to this):** `https://github.com/caldwbr/tempoLockPCA/blob/main/teenSpiritVideo.m`.

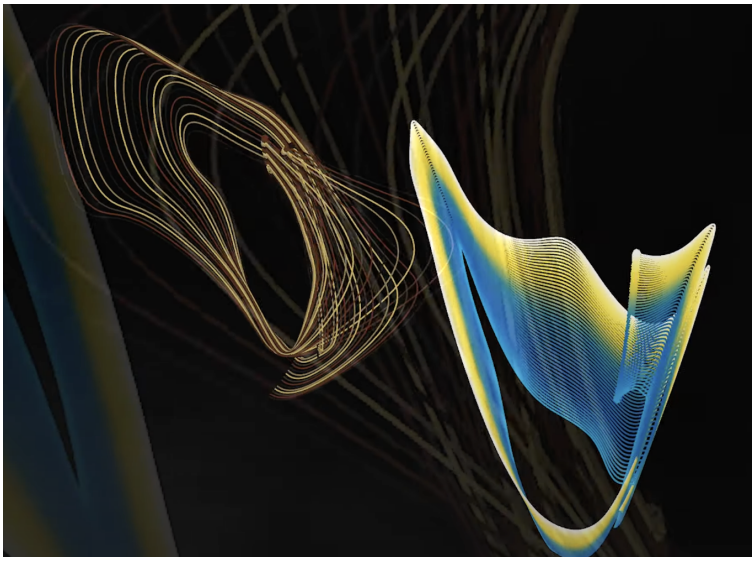

Figure 8: **Stimulus:** *Smells Like Teen Spirit* by Nirvana (∼200 ms of trajectories depicted here). **Signal:** Z-scored log of the 50-60 Hz amplitude envelopes (0.5 Hz intervals). **Brown Rings:** Dynamic PCA with a *narrow window* was run on the amplitude envelope of each frequency across electrodes (200 ms window, Gaussian taper with $\sigma = 50$ ms, 100 ms repetition interval, 1000 Hz interpolation resolution). **Blue/Green/Yellow Rings:** Dynamic PCA with a *wide window* was run on the same amplitude envelopes (10,000 ms window, Gaussian taper with $\sigma = 1000$ ms, 333 ms repetition interval, 1000 Hz interpolation). **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://www.youtube.com/watch?v=oeXUFsWJjKY`.

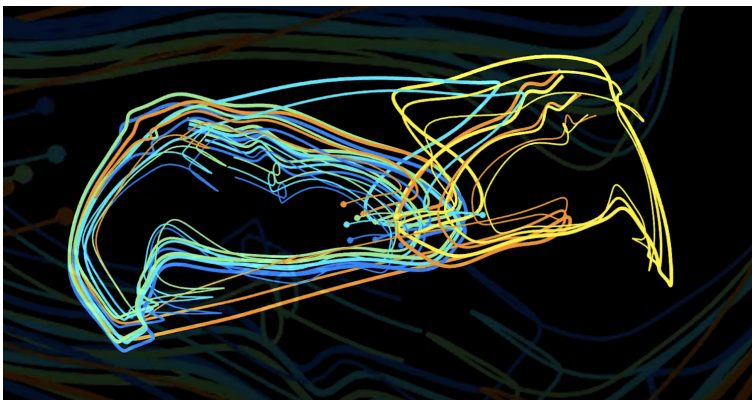

Figure 9: **Stimulus:** *Ordinary World* by Duran Duran (∼200 ms of trajectories depicted here). **Signal:** Dynamic PCA was applied to the z-scored log of the amplitude envelopes of 52 Hz, 55 Hz, and 58 Hz (thin to thick lines, respectively) using a range of window sizes (indicated by color): 2 s, 1 s, 800 ms, 600 ms, and 300 ms. The corresponding number of PCA repetitions was 340, 680, 850, 1140, and 2280, respectively. This figure explores how both window duration and frequency influence the resulting PC trajectories. **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://www.youtube.com/watch?v=2gkz-QBflH8`.

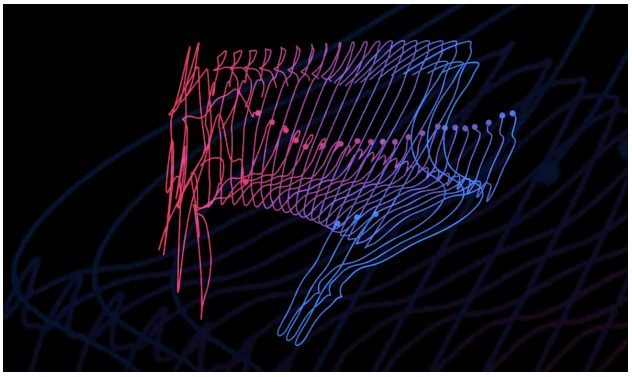

Figure 10: **Stimulus:** *Ordinary World* by Duran Duran (∼200 ms of trajectories depicted here). **Signal:** Quasi-dynamic PCA was performed on the amplitude envelope of each frequency using a 300 ms window with a Gaussian taper ($\sigma = 75$ ms), repeated 2,280 times across the session. The first three principal components of each frequency are plotted as colored tracers. Each tracer has a 40 ms lag relative to the actual music, and both temporal and spatial artificial offsets were added per frequency (10 ms/Hz and 0.2 a.u./Hz, respectively, counting from highest frequency as baseline). **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://www.youtube.com/watch?v=ZVfgCM7YcVU`.

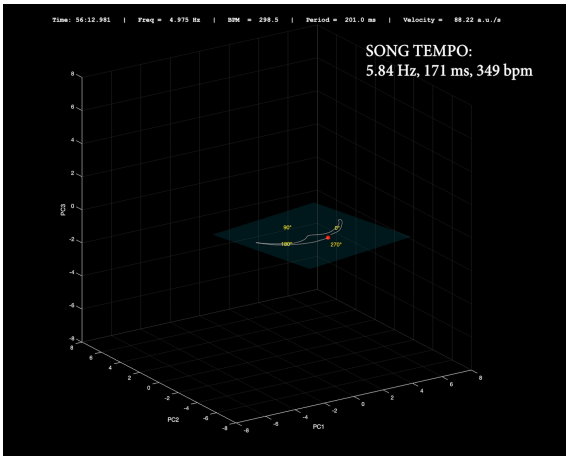

Figure 11: **Stimulus:** *Alone* by Heart. **Description:** A plane was dynamically fitted to periodic PCA behavior to allow tracking of phase, ring frequency, and ring period. While ring rate did not match song tempo, transients still appeared to cause perturbations to tracer trajectory. **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://youtu.be/LMT_RsWPGYQ`. **Code:** `https://github.com/caldwbr/tempoLockPCA/blob/main/ringTrackingVideo.m`.

For the song *Alone* by Heart, PCA was run on the z-scored log of the amplitude envelope of 61.5 Hz of all electrodes. The tracer's periodic behavior was then analyzed by dynamic fitting of a plane and phase-tracking to allow the dynamic computation of period and frequency of rings (see Figure 11). It was found that the brain PCA rings were actually consistently **slower** (5.09 Hz +/- 0.208 Hz) than the tempo (5.84 Hz). The transients still appeared to unitarily impact tracer trajectory (see Figure 12).

Ring tracking was tried again on the song *Threshold* by Sungazer (which was a first listen during the EEG recording). A steady ring rate of 5.181 Hz (period of 193 ms) was found in the ring portion of the song (27-140 seconds), with +/- 0 Hz and +/- 0 ms for one standard deviation. Yet, this was **faster** than the tempo of the song by nearly 1 Hz (song tempo estimated at 4.29 Hz, 257.5 bpm, 233 ms between beats). See Figure 13 for details.

Ring tracking was attempted on the song *Smells Like Teen Spirit* by Nirvana, only to find that the

trajectory was too unstable for reliable period detection (overshooting period calculation by multiple numbers of cycles). An attempt was made at using the shape of the trajectory for period calculation which was too computationally expensive. Finally, using simple PC1 local minima, local maxima, and local minima sequences to detect ring periods (above a threshold of 160 ms) proved robust to capturing the messy periodic dynamics of PCA for *Teen Spirit*. It was found to have a ring rate of 5.142 Hz (+/- 0.254 Hz). The actual tempo of 4.910 Hz (corresponding to a period of 203.6 ms or 294.7 BPM) fell **within one standard deviation** of the observed ring rate. However, this alignment is likely coincidental.

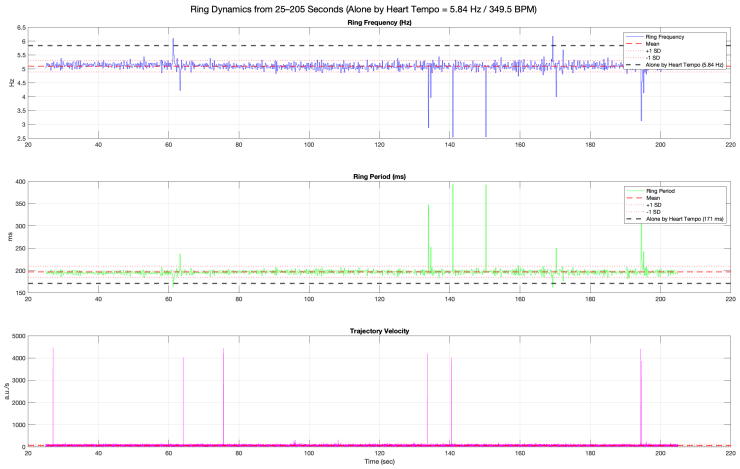

Figure 12: **Stimulus:** *Alone* by Heart. **Description:** The PCA rings for 61.5 Hz amplitude (across 16 electrodes) did not match the tempo of the song (too slow by nearly 1 Hz). PCA ring rate of 5.09 +/- 0.208 Hz; song tempo was 5.84 Hz. **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Code:** `https://github.com/caldwbr/tempoLockPCA/blob/main/ringRate.m`.

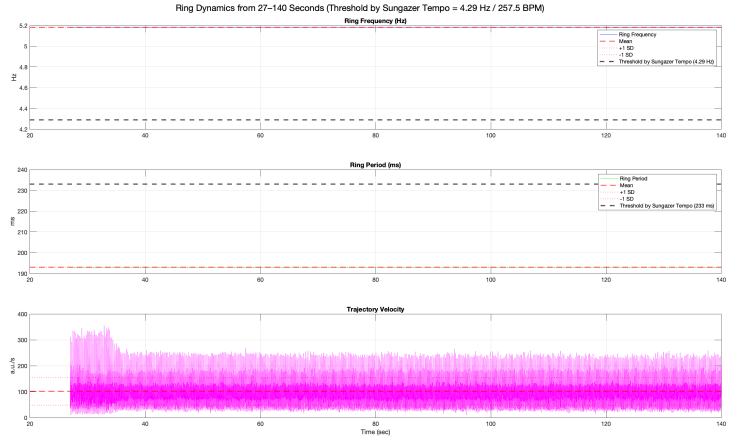

Figure 13: **Stimulus:** *Threshold* by Sungazer. **Description:** The PCA rings for 61.5 Hz amplitude (across 16 electrodes) did not match the tempo of the song (PCA rings were too rapid by nearly 1 Hz). PCA ring rate of 5.181 +/- 0 Hz and estimated song tempo of 4.29 Hz. **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://www.youtube.com/watch?v=w4jiZjV2Knw`.

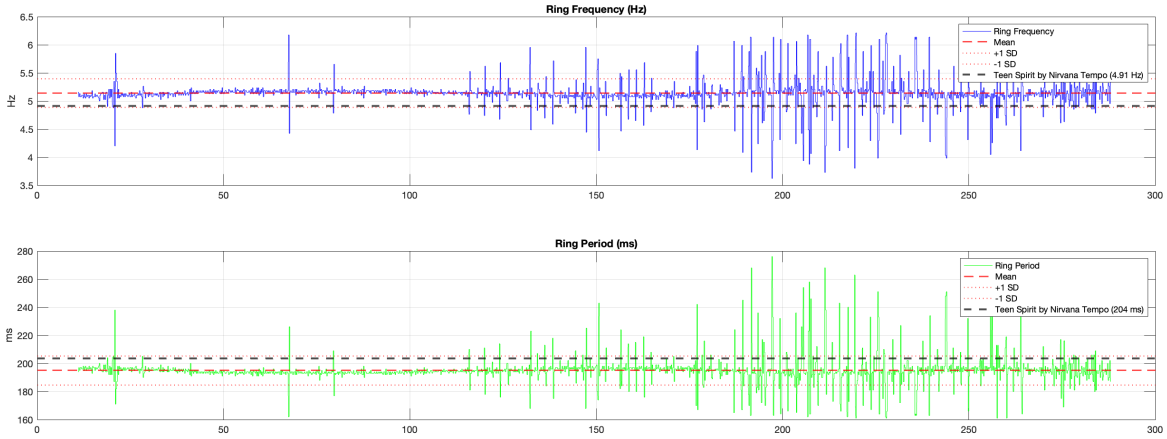

Figure 14: **Stimulus:** *Smells Like Teen Spirit* by Nirvana. **Description:** The tempo of the song (4.91 Hz) was within one standard deviation of the PCA ring rate (5.142 +/- 0.254 Hz) for 61.5 Hz amplitude (across 16 electrodes), yet it is likely that this song's tempo simply happened to be close to a naturally resonant PCA cortical ring rate. **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://youtu.be/7yY9AdPn834`. **Messy Ring Detection and Video Code:** `https://github.com/caldwbr/tempoLockPCA/blob/main/teenSpiritRingTrackingAndVideo.m`.

For America's *A Horse with No Name* stimulus, ring rate was found to be 5.149 +/- 0.055 Hz (period of 194.2 +/- 2.1 ms), more than 1 Hz faster than the song's tempo (4.064 Hz, beat interval of 247 ms): Figure 15. For *Espresso* by Sabrina Carpenter, ring rate held a roughly 3:2 relation to the beat of the song (triplet to eighth), probably by happenstance, as ring rate is coming in at about 5.1 Hz invariant of song tempo for song stimuli studied to this point for this subject and session of EEG: Figure 16.

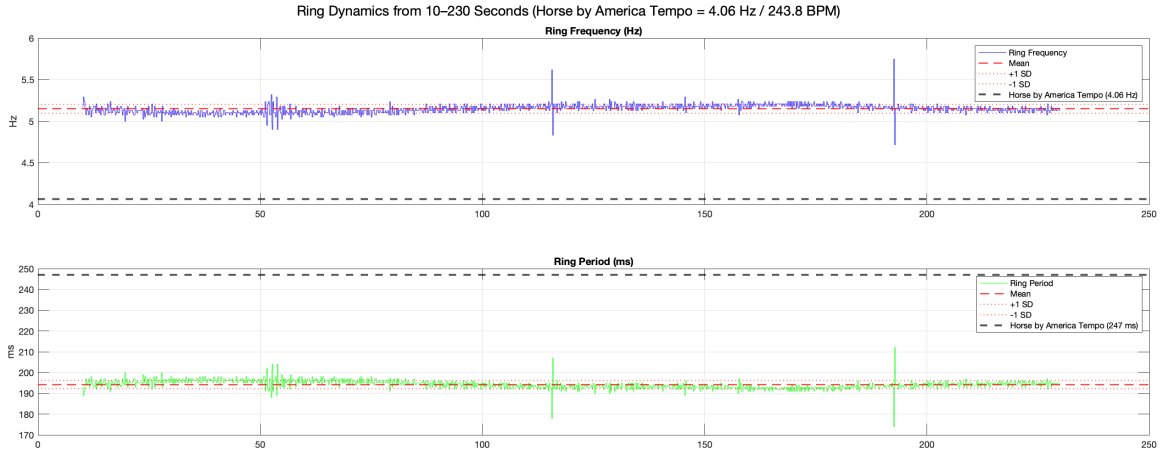

Figure 15: **Stimulus:** *A Horse with No Name* by America. **Description:** The ring rate (5.149 +/- 0.055 Hz) was more than 1 Hz faster than the song tempo (4.064 Hz). **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://youtu.be/F-BQPJS7u58`.

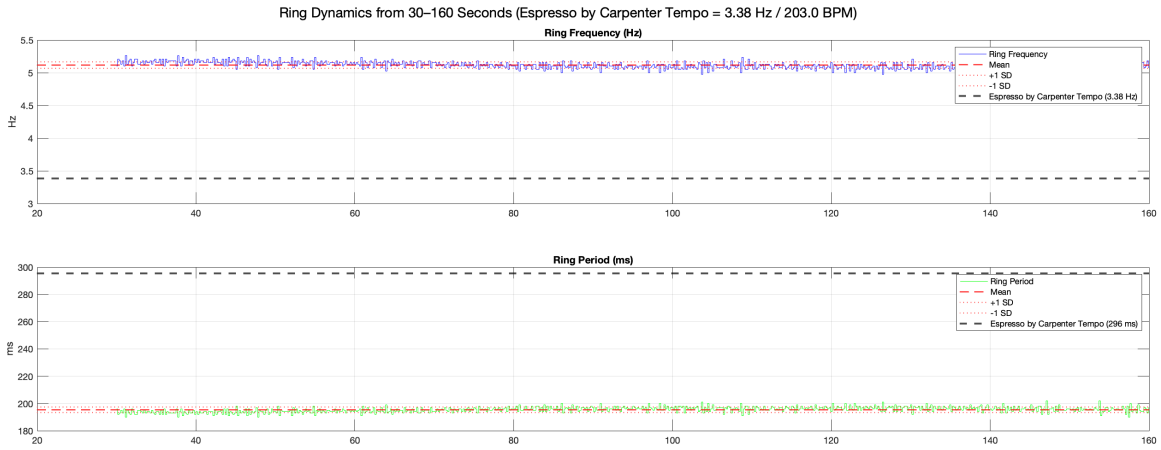

Figure 16: **Stimulus:** *Espresso* by Sabrina Carpenter. **Description:** PCA ring data was 5.116 +/- 0.052 Hz (period of 195.5 +/- 2.0 ms); song tempo was 3.383 Hz (beat interval of 295.6 ms). 3x PCA ring period (586.5 ms) was <5 ms shorter than 2x song tempo beat interval (591.2 ms), likely incidental. **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://youtu.be/C16TtrJQUI0`.

More results:

- *Ocean Eyes* by Billie Eilish — Figure 17
- *Physical* by Dua Lipa — Figure 18
- *I Could Fall in Love* by Selena Quintanilla — Figure 19
- *Dreaming of You* by Selena Quintanilla — Figure 20
- *Old Fashioned Love Song* by Three Dog Night — Figure 21
- *Ordinary World* by Duran Duran — Figure 22

Figure 17: **Stimulus:** *Ocean Eyes* by Billie Eilish. **Description:** PCA ring data was 5.159 +/- 0.040 Hz (period of 193.8 +/- 1.5 ms); song tempo was 4.64 Hz (beat interval of 215.5 ms). **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://youtu.be/ezi5fu7uzq0`.

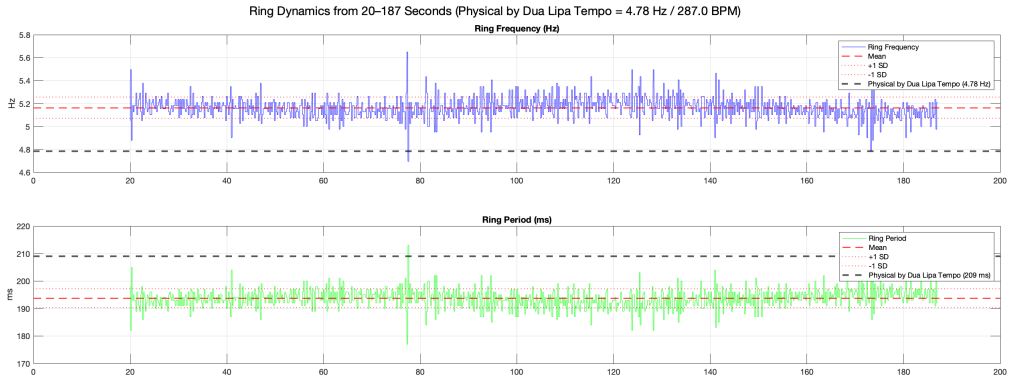

Figure 18: **Stimulus:** *Physical* by Dua Lipa. **Description:** PCA ring data was 5.163 +/- 0.092 Hz (period of 193.8 +/- 3.5 ms); song tempo was 4.783 Hz (beat interval of 209.0 ms). **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://youtu.be/KevvTzQZc5U`.

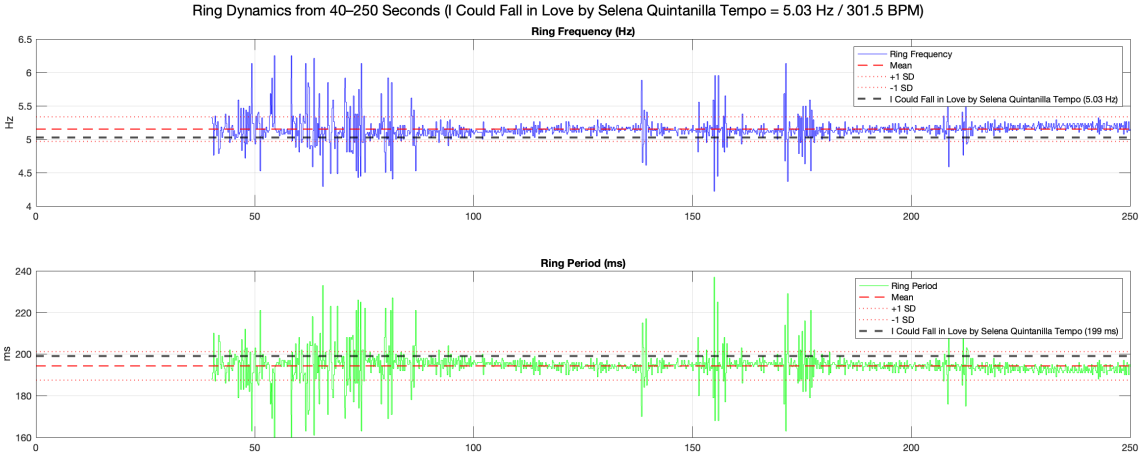

Figure 19: **Stimulus:** *I Could Fall in Love* by Selena Quintanilla. **Description:** PCA ring data was 5.149 +/- 0.184 Hz (period of 194.4 +/- 6.8 ms); song tempo was 5.025 Hz (beat interval of 199.0 ms). **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://youtu.be/ilHbzWGC7h8`.

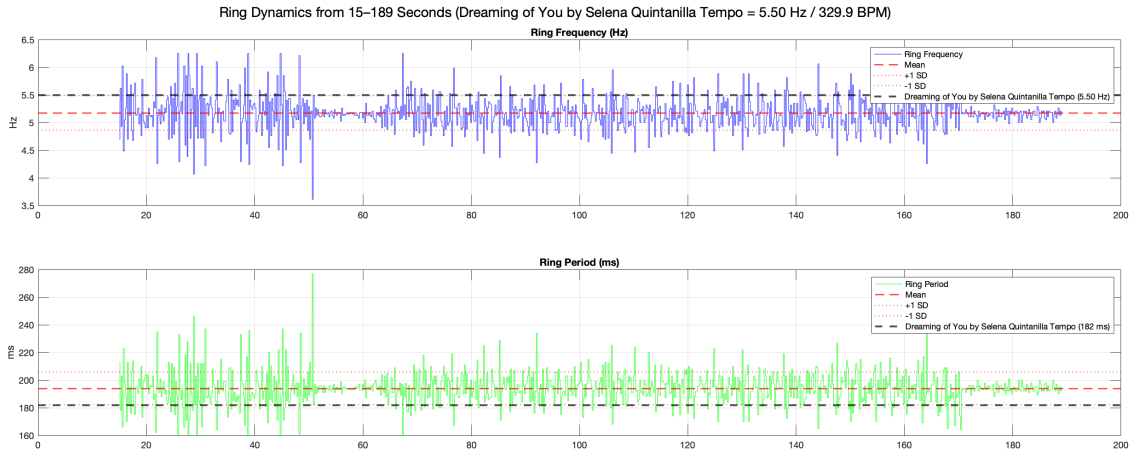

Figure 20: **Stimulus:** *Dreaming of You* by Selena Quintanilla. **Description:** PCA ring data was 5.174 +/- 0.312 Hz (period of 194.0 +/- 11.8 ms); song tempo was 5.498 Hz (beat interval of 181.9 ms). **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://youtu.be/NYmrOVvOkjc`.

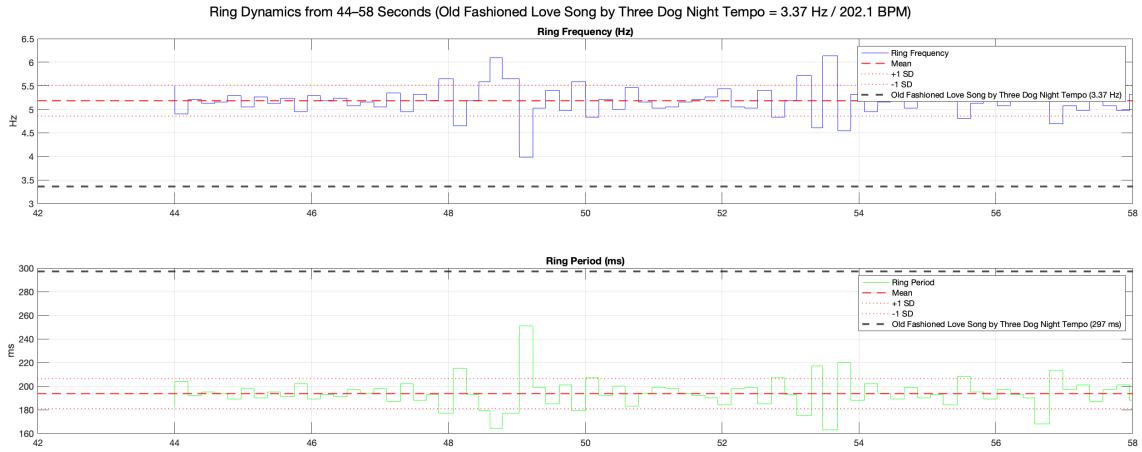

Figure 21: **Stimulus:** *Old Fashioned Love Song* by Three Dog Night. **Description:** PCA ring data was 5.184 +/- 0.328 Hz (period of 193.7 +/- 12.6 ms); song tempo was 3.365 Hz (beat interval of 297.2 ms). Again, 3x PCA ring rate coincidentally aligns roughly with 2x song tempo (interval difference of only 13 ms). **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://youtu.be/EMzl5Q25Pro`.

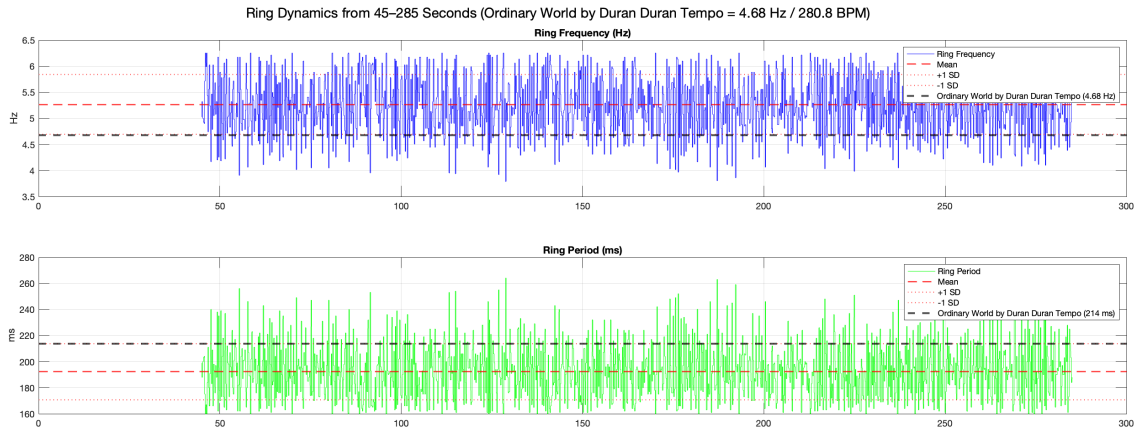

Figure 22: **Stimulus:** *Ordinary World* by Duran Duran. **Description:** PCA ring data was 5.174 +/- 0.312 Hz (period of 194.0 +/- 11.8 ms); song tempo was 4.68 Hz (beat interval of 213.7 ms). **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Results:** `https://youtu.be/N8wiQBTX42Q`.

Figure 23 concludes this subsection by showing that PCA ring rate remains fairly inflexible at ∼5.15 Hz, invariant to song stimulus tempo.

3.2 Exploring Transient Locking

A few examples of potential transient locking are provided in Figures 24, 25, 26, 27, and 28.

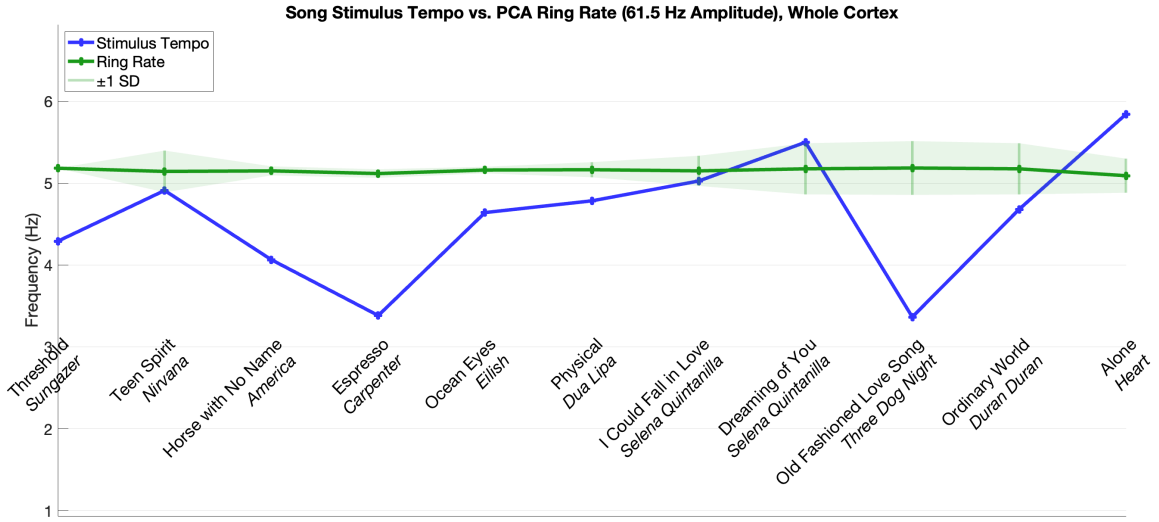

Figure 23: **Description:** PCA ring rate remained at ∼5.15 Hz, invariant to the changing tempo of the eleven stimulus songs. Average ring rate of 5.153 Hz; average standard deviation of +/- 0.167 Hz. **Electrodes:** 16 total (whole cortex): Fp1, Fp2, C3, C4, Pz, Fz, O1, O2, F7, F8, F3, F4, T3, Cz, P3, P4. **Matlab code for this figure:** `https://github.com/caldwbr/tempoLockPCA/blob/main/tempoVsRingRate.m`.

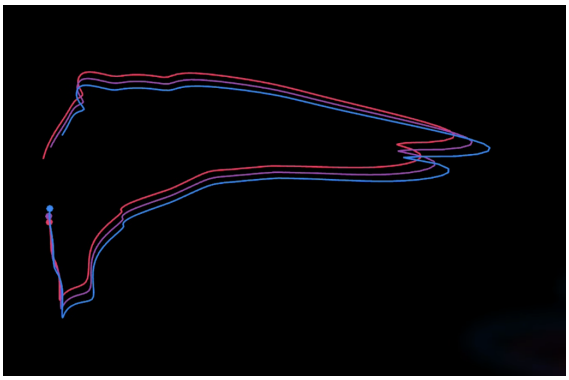

Figure 24: **Stimulus:** *Ordinary World* by Duran Duran (about 200 ms featured here). **Signal:** Three frequencies were processed (61.5 Hz, 62.0 Hz, 62.5 Hz); dynamic PCA was run on the amplitude of each frequency (300 ms window, $\sigma = 75$ ms Gaussian taper, 2280 repetitions) and the first three principle components of each are plotted as tracers of varying color, with a 40 ms lag relative to reality (music). Also, a temporal and spatial offset was added per frequency ($\sim$20 ms/Hz, $\sim$0.2 a.u./Hz). **Description:** At 0:19 seconds into this video, a pluck of a guitar note appears to coincide with a ripple and trajectory change in PCA space (right side of ring). If one watches the video at reduced speed (0.25x or 0.5x), it becomes easier to see these apparent perturbations of the tracer trajectory by transient events (lagging roughly 40-60 ms behind reality [music]). It is yet uncertain how to quantify the possible statistical significance of these apparent correlations. Future study could examine this in greater detail. **Full video:** `https://www.youtube.com/watch?v=7H2b3Li32P4`.

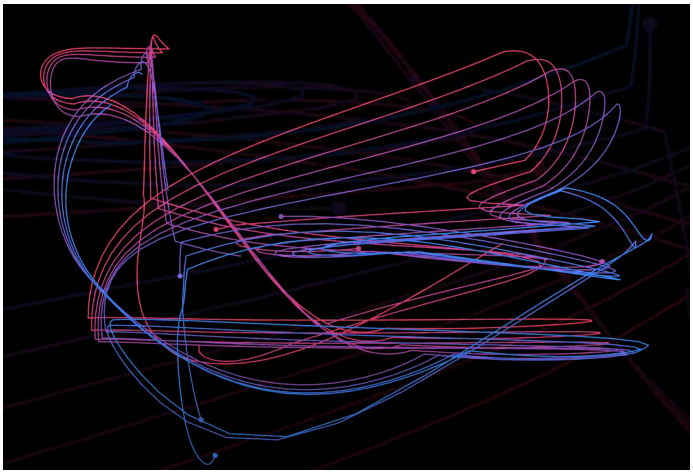

Figure 25: **Stimulus:** *Espresso* by Sabrina Carpenter (about 200 ms featured here). **Signal:** Eight frequencies were processed (55-62 Hz); dynamic PCA was run on the amplitude of each frequency (tiny 50 ms windows, sigma = 10 ms Gaussian taper, 7520 repetition times) and the first three principle components for each frequency were plotted by color coded ring 'tracers.' This window may have been a little too tight (there might be some flipping of trajectories due to sign indeterminacy of PCA weights). The tracers lag reality (the music listened to) by 40 ms to align the transients better (this might be the lag amount of consciousness behind reality). Additionally, the tracers were given artificial temporal and spatial offsets of 10 ms/Hz and 0.1 a.u./Hz for better visibility. **Description:** At 1:16 seconds into this video, a drum hit appears to coincide with a ripple of tiny triangles (upper left) in PCA space. This video appears to display a sort of shape-snapping, perhaps based on ring rate, which was not exactly aligned with the song tempo (a close match at 3x ring rate and 2x tempo was found). It is uncertain whether the shape-snapping is at the same rate as the PCA rings. **Full video:** `https://www.youtube.com/watch?v=PTpY6mkHJEE`.

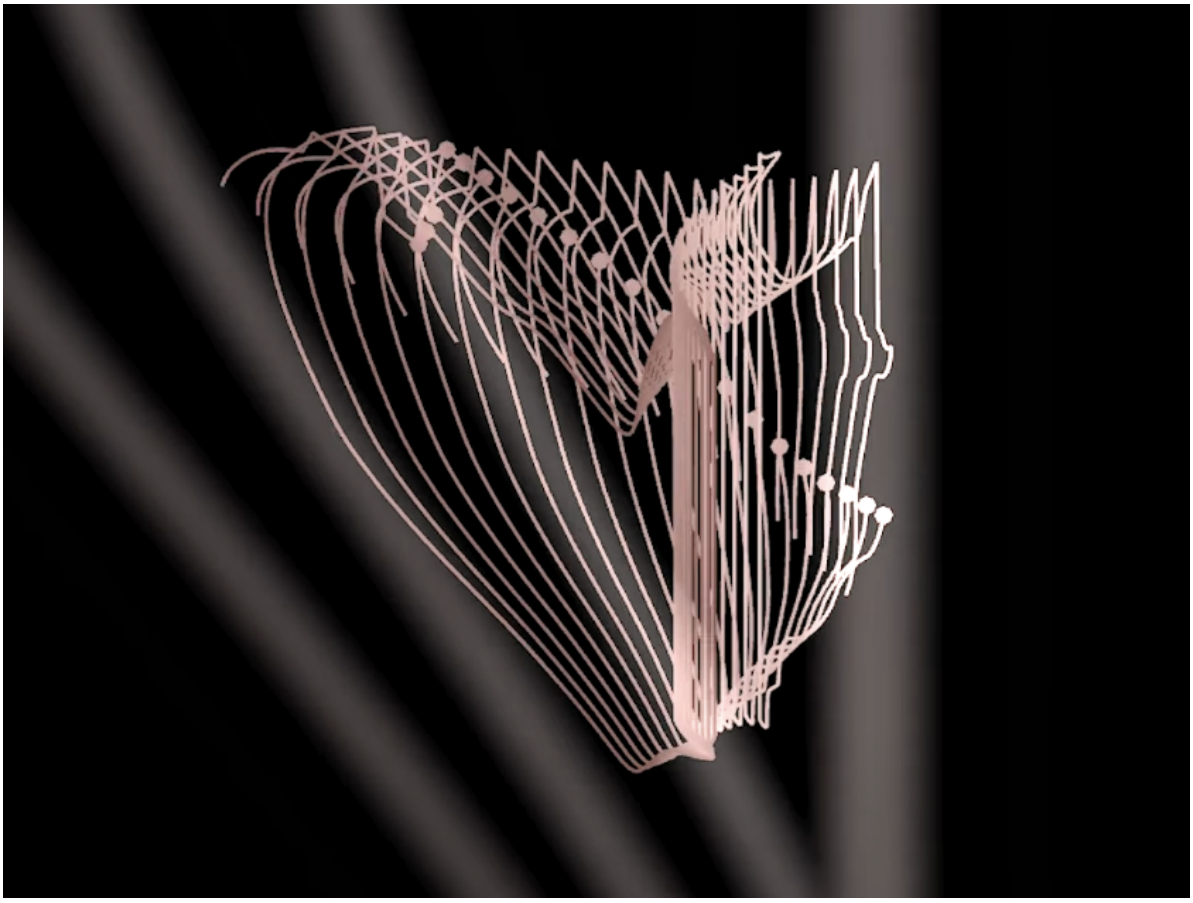

Figure 26: **Stimulus:** *Alone* by Heart (about 200 ms featured here). **Signal:** Several gamma frequencies (likely 52.5 to 62.5 Hz in 0.5 Hz steps) were processed with dynamic PCA (exact settings uncertain on this video). **Description:** At 1:55 seconds into this video, a drum hit appears to coincide with a sudden upward ripple of spectral ring fabric (side of ring facing viewer) in PCA space. The tracers exhibit interesting behavior during the intro of the song; it is currently uncertain what purpose if any it might serve. **Full video:** `https://www.youtube.com/watch?v=7w3nYI-WkPU`.

4 Conclusion

This paper has presented results using dynamic PCA, quasi-dynamic PCA, and TFP fabric to examine potential tempo and transient locking of the cortex to musical stimuli. It was found that PCA rings begin right at the end of the intro of each song (or at the end of the first verse for *Espresso*). It is currently unknown whether the song tempo is triggering the periodicity in cortex PCA space, whether the subject happened to close their eyes right at these moments, or whether it is due to something else. Nevertheless, the ring rate held steady at about 5.15 Hz, invariant to song tempo variations. Fairly robust transient locking was found, although a way to prove potential statistical significance has not yet been envisioned, and is encouraged for future study.

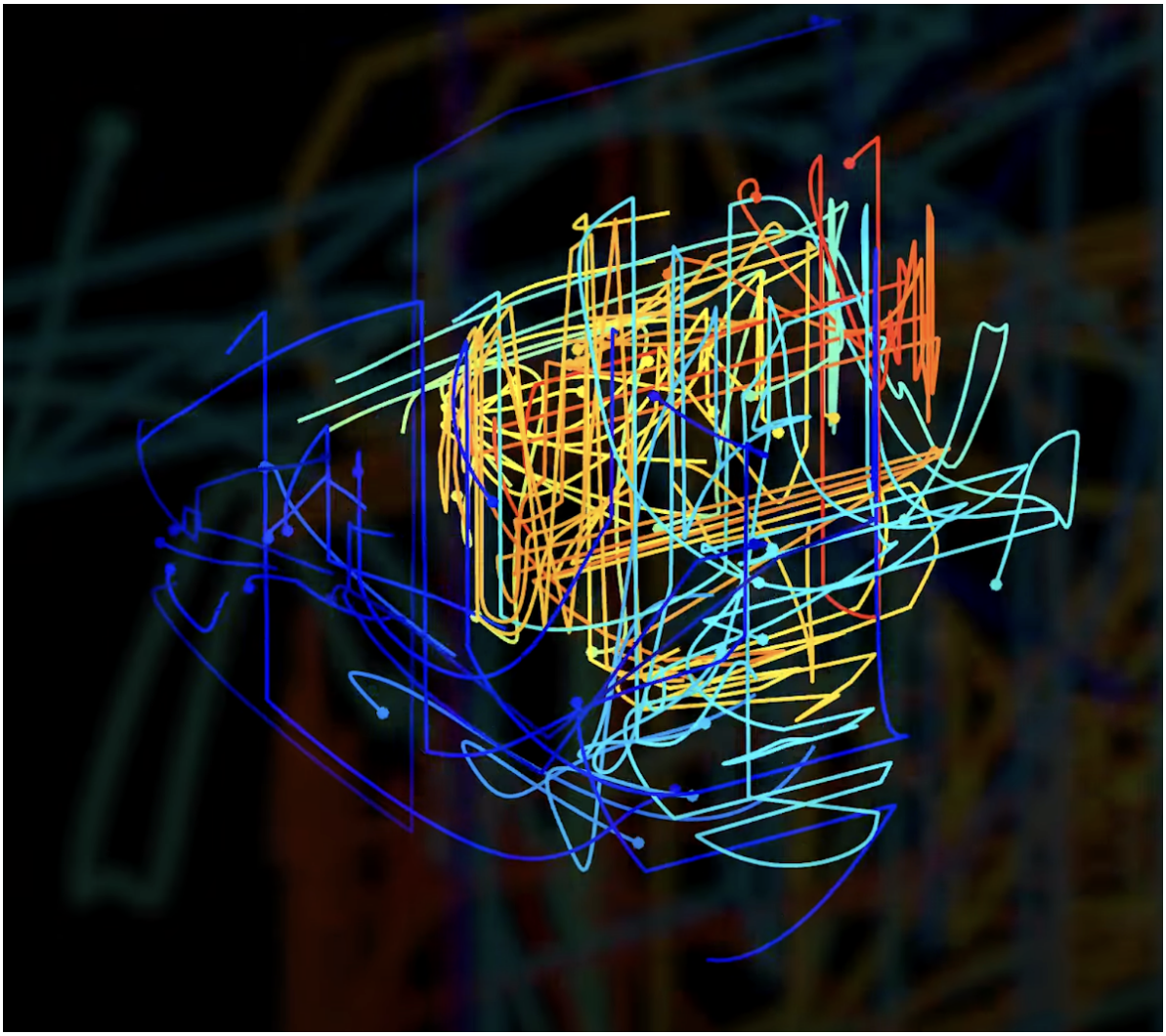

Figure 27: **Stimulus:** *Alone* by Heart (about 200 ms featured here). **Signal:** EEG data were cleaned, upsampled, and transformed using 46 complex Morlet wavelets (1–10 Hz in 0.2 Hz steps) to obtain the analytic signal. A 3600 ms sliding window of power at each frequency was tapered with a compound Gaussian kernel (σ = 301 ms, 31 ms, and 3 ms), log-transformed, and Z-scored. These cleaned time-frequency-power matrices were then input into dynamic PCA, performed independently at each millisecond and frequency (over 10 million PCA iterations total) to obtain the first three principle components for each frequency for each millisecond. Each frequency is a tracer of a different color. The tracers are lagged relative to reality (music) about 40 ms (may represent brain processing lag). **Description:** At 0:58 seconds into this video, a snare hit appears to coincide with a sudden impact of the orange tracer against an invisible plane in PCA space. These low-frequency (1-10 Hz) tracers exhibit qualitatively different behavior than the gamma tracers. Alpha and beta tracers were studied also, which rapidly change shape and exhibit less attractor behavior, but it is currently uncertain what can be said about them. **Full video:** `https://www.youtube.com/watch?v=YPkVqfVwo-g`.

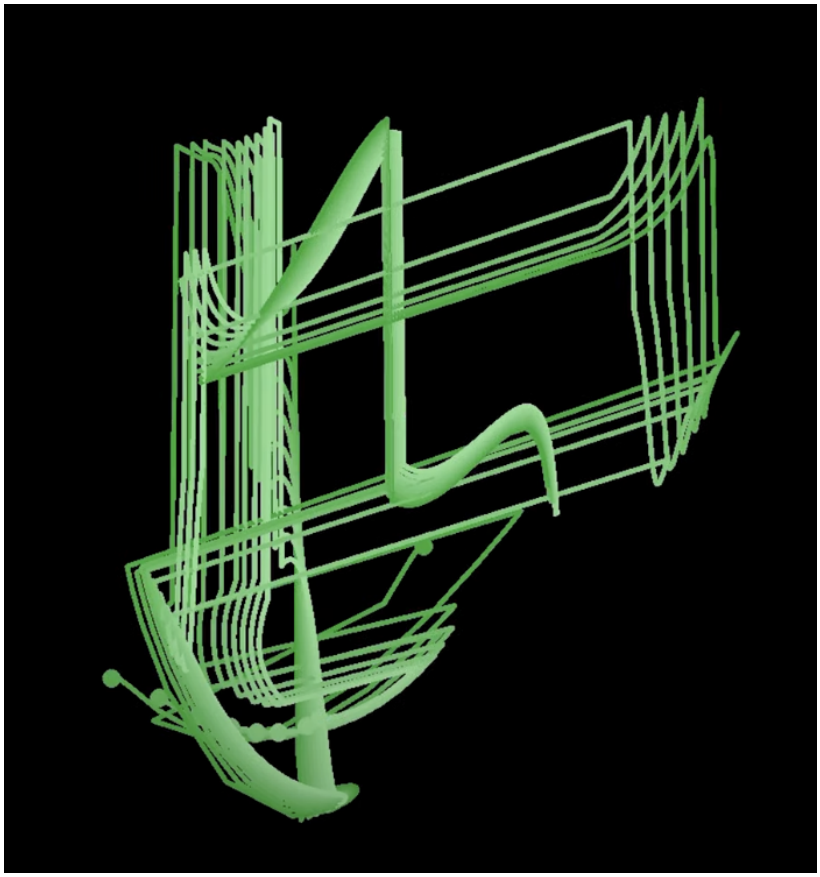

Figure 28: **Stimulus:** *Alone* by Heart (about 200 ms featured here). **Signal:** Data were cleaned, upsampled to 1 kHz, and convolved with nine complex Morlet wavelets spanning 9.8–10.2 Hz in 0.05 Hz steps to obtain the analytic signal. The power of each frequency was smoothed with a compound Gaussian window consisting of two standard deviations ($\sigma = 31$ ms and $\sigma = 3$ ms), combined across time to preserve both coarse trends and sharp transients. Dynamic PCA was performed on the Z-scored log-power of each frequency using this tapered window, generating three principal components per time point (for each frequency) without temporal interpolation. Each frequency tracer was plotted through time with a slightly different shade of green. 224,633 runs of PCA were done for each frequency (one for each millisecond of the song). A window of 602 ms was used. The tight window and tight Gaussian result in what could be termed a 'bank-style' print of brain activity. The broken drinking glass, cylinders, planar surfaces, and spherical surfaces are features of a purported 'bank' (shape) schema. **Description:** At 2:10 into this video, the rightmost portion of tracers here seem to print at the exact timing of a keyboard chord being played. Alpha amplitude tracers sometimes appear to do more transient-locking than gamma amplitude tracers (this might have to do with PCA settings though, too). **Full video:** `https://www.youtube.com/watch?v=WTcfmvzmN4U`.

References

[1] Caldwell, B. (2025). *Spectral Amplitude Modulation in EEG: Potential Correlations with Musical Stimuli.* May 11, 2025.

[2] Saxena, S., Russo, A. A., et al. (2022). Motor cortex activity across movement speeds is predicted by network-level strategies for generating movement. *eLife*, 11, e67620. https://doi.org/10.7554/eLife.67620