Spectral signatures of the pupillary response as an implicit measure of musical absorption

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Background

The pupil of the eye becomes entrained to rhythmic auditory patterns [1].

Does this entrainment occur in the context of more complex instrumental music? And does pupillary entrainment have a relationship with listeners' subjective experience of music?

Because of the well-established link between pupillary activity and the attentional (norepinephrine) system, we hypothesized that:

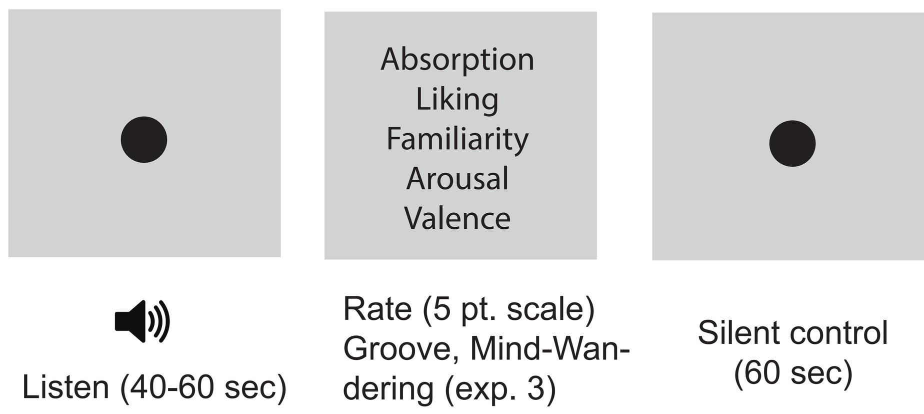
Feeling 'absorbed' in music – a state of focused, pleasurable attention – should be reflected in the pupillary signal.

Methods

In this study we re-analyze the pupil data of [2] (Exp. 1, N = 32; Exp. 2, N = 35) in combination with a replication experiment (N = 28). In all experiments, participants listened to 56 ~60 sec clips of instrumental music from a variety of genres (rock, hip hop, classical, metal, etc.) and subsequently rated their felt experience. The three experiments differed only in their instruction to fixate and/or reduce blinking activity.

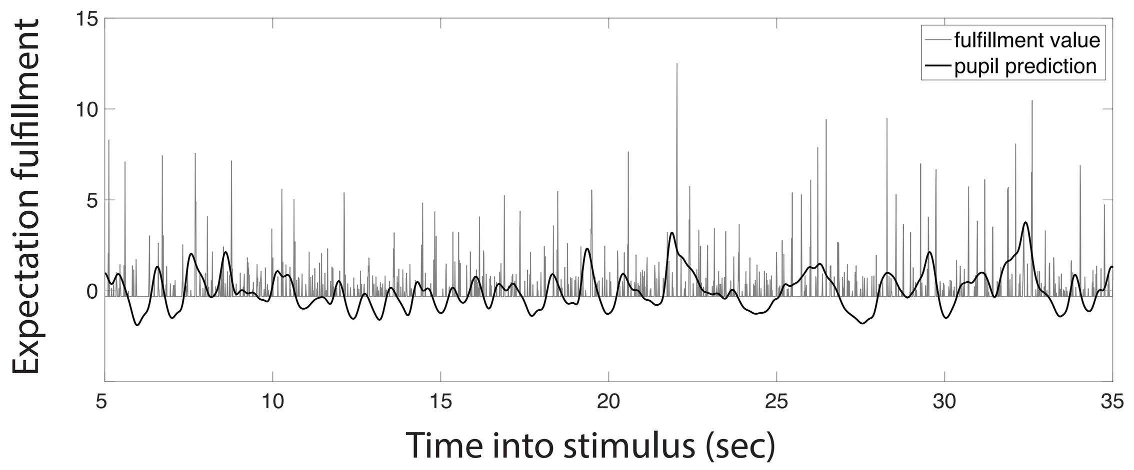
Participants instructed to immerse themselves into the music but told that it would not always be possible.
Exp. 1: fixate and minimize blinking.
Exp. 2: free gaze on gray screen.
Exp. 3: fixate, no instruction about blinking.

56 music clips, 14 silent trials

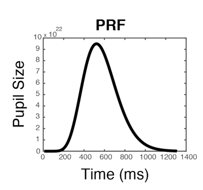


Predicting the pupil signal via oscillator model and convolution

Each stimulus was fed through a linear oscillator model [3] to attain the prominent metric periodicities in the signal. In this study we also wished to test the ability of a fulfillment metric from our model to predict the continuous pupil signal. Unlike the salience metric previously used to predict pupil data [1], the fulfillment index takes into account the phase of the oscillators and projects an expectation into the future. This projection is compared with the actual incoming signal, to generate a measure of expectation fulfillment (high when incoming > predicted, and vice versa).

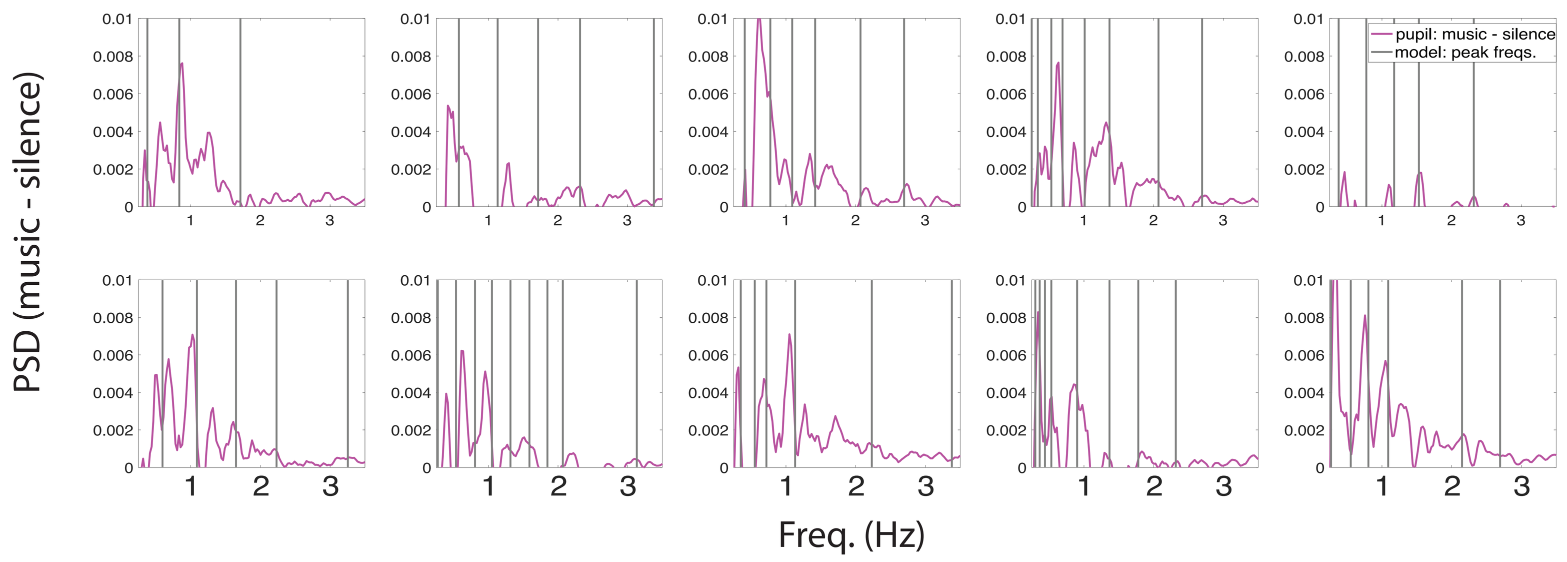


The black trace (left) is generated by convolving the fulfillment values with a pupillary response function (PRF, below).



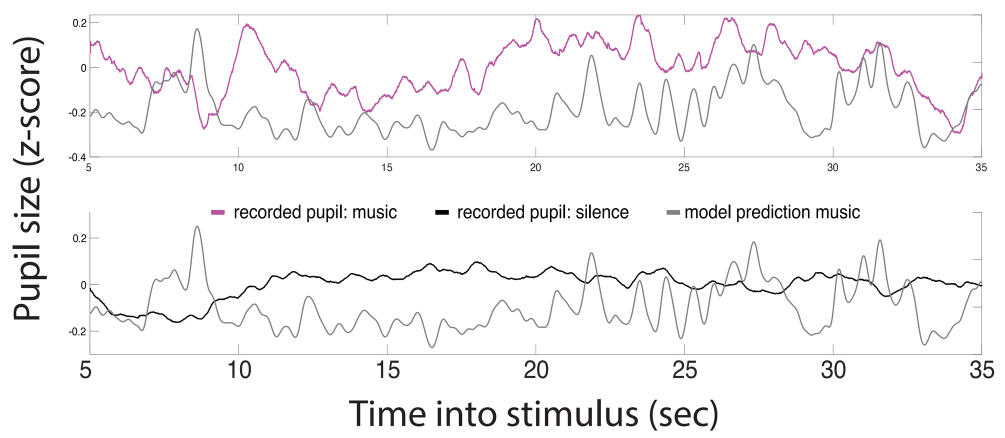
Results

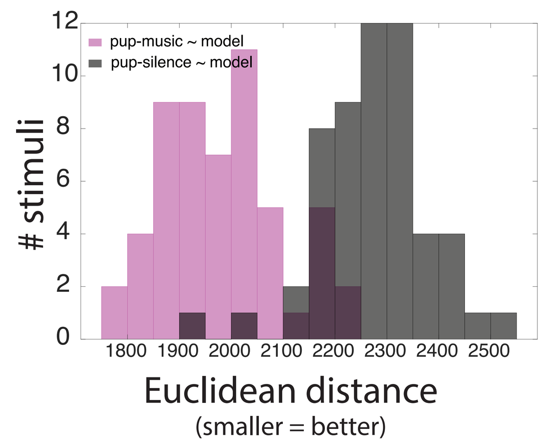
Spectral peaks during music listening at modelled periodicities



Above: Difference in average power spectral density while listening to music vs. silence for ten different stimuli. Vertical lines represent salient periodicities predicted by the oscillator model.

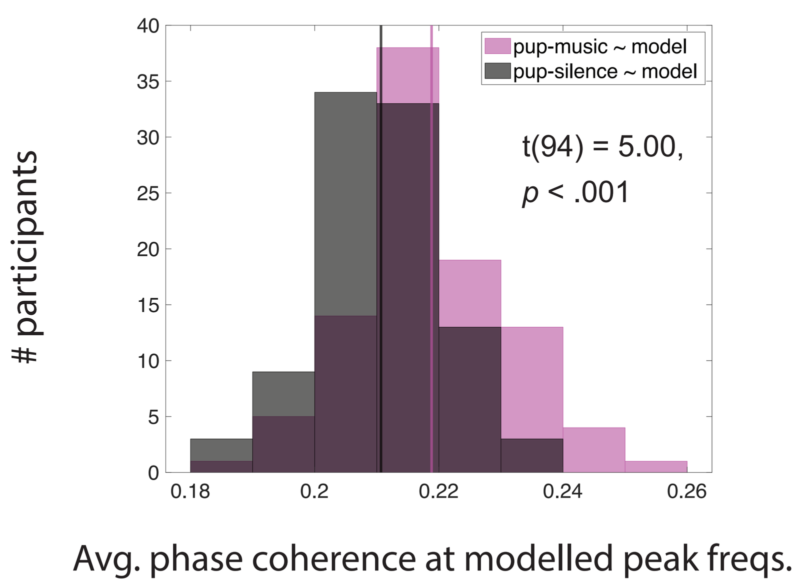
Similarity between pupil and model time series is above chance





Above, left: Example time courses of predicted pupil data (gray) for one stimulus vs. the avg. recorded pupil data for that same stimulus (top, magenta) vs. silence (bottom black).
Right: significantly lower (t(54) = -25.85, *p* < .001) warping cost between pupil and model for music vs. silence, for each stimulus.

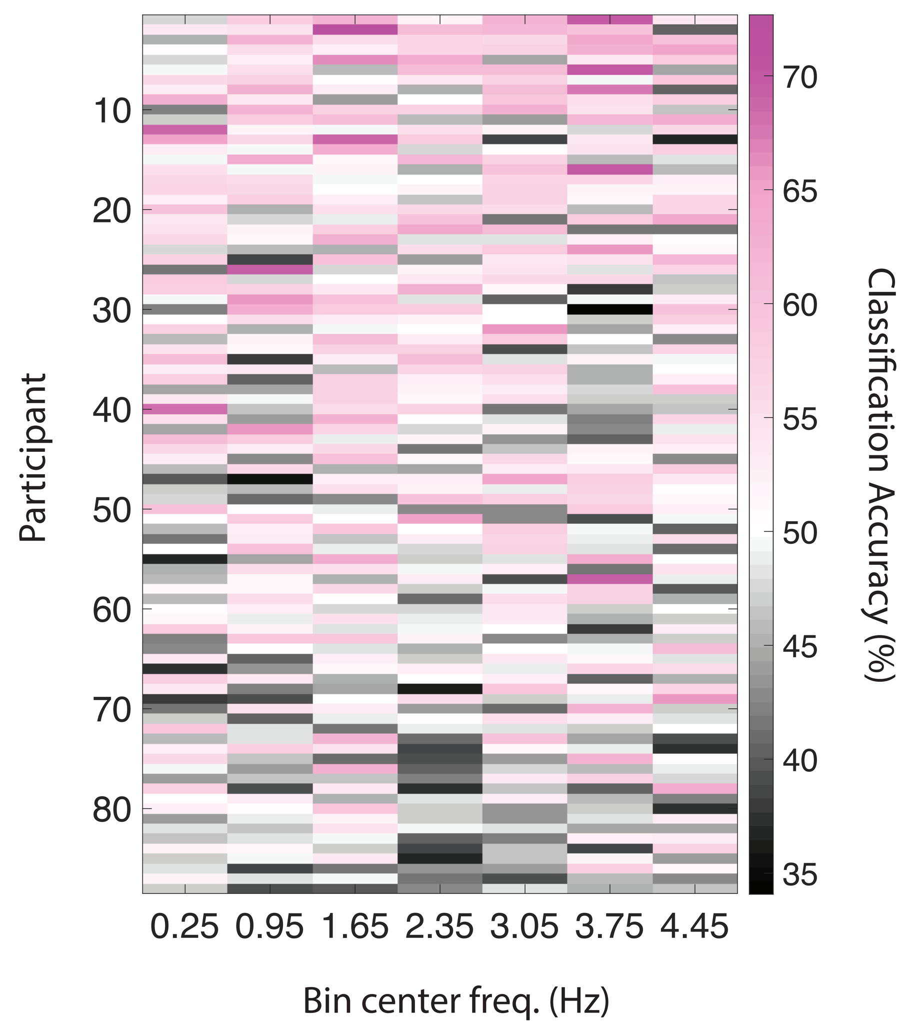
Phase coherence between pupil and model above chance



Left: For each participant / stimulus, we computed 1) cross-power spectral density (CPSD) between the pupil and model prediction and 2) the CPSD between a randomly selected pupil trace from that participant's silent trials and the model prediction for that stimulus. The phase coherence between pupil and model for any stimulus was defined as the squared absolute value of the pupil-model CPSD, divided by the power spectral density of the CPSD of the individual signals with themselves. We calculated a single true and null coherence estimate for each participant, each stimulus by averaging the true vs. null coherence estimate at each peak frequency under 4 Hz.

Predicting absorption from pupil data

Absorption ratings (5 pt. scale) were z-scored and recoded as 0 (<= 0) or 1 (> 0). Overall, there were 2809 absorbed trials and 2261 not absorbed trials. Individual participants averaged 29 (+/- 7) absorbed and 24 (+/- 7) not absorbed trials. We trained Gaussian classifiers (70-30 train-test split, 500 fold cross-validation) to predict their absorption ratings from the pupil-model coherence in the .05 – 4 Hz range (in ~ .5 Hz bins).



Left: Each row represents a participant and each column the frequency band from which we trained the classifier (i.e., each cell represents the accuracy of a classifier trained as described above for one participant and band). The rows are sorted by participant with the highest to lowest accuracy. Overall, there do not seem to be particular participants or sub-bands driving the effect, though the sub-band centered on 1.65 Hz is on average 2% higher in accuracy than the others (53% vs. 51%). The classifiers had a mean and max accuracy of 51% and 72%, respectively. Averaging across all bands, the accuracy was significantly above chance defined as 50% (t(87) = 4.41, *p* < .001).

Discussion

Pupillary entrainment occurs while listening to complex instrumental music

Our model can predict the frequency, amplitude, and phase of pupillary oscillations above chance.These results extend our previous study of pupillary entrainment which used only reduced rhythmic percussion patterns [1] to naturalistic music.

Phase coherence between the pupil signal and a model of musical expectations predicts listeners felt absorption

While previous studies have shown neural entrainment to the beat, few have related such entrainment to subjective experience. Here we connect peripheral nervous system entrainment to felt absorption into music. With the assumption that the pupil indexes norepinephrine activity and, more broadly, the attentional system, these results speak to the utility of using pupillometry to 1) read out attented musical features, 2) predict listeners' subjective states, 3) test models of musical expectations.

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References [1] Fink et al., 2018, *JEMR* [2] Lange et al., 2017, *Consc. Cog.* [3] Tomic & Janata, 2008, *JASA*

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