Periodicity Pitch Detection in Complex Harmonies on EEG Timeline Data

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An acoustic stimulus, e.g., a musical harmony, is transformed in a highly nonlinear way during the hearing process in ear and brain. We study this by comparing the frequency spectrum of an input stimulus and its response spectrum in the auditory processing stream using the frequency following response (FFR).

Using electroencephalography (EEG), we investigate whether the periodicity pitches of complex harmonies (which are related to their missing fundamentals) are added in the auditory brainstem by analyzing the FFR. While other experiments focus on common musical harmonies like the major and the minor triad and dyads, we also consider the suspended chord. The suspended chord causes tension foreign to the common triads and therefore holds a special role among the triads.

While watching a muted nature documentary, the participants hear synthesized classic piano triads and single tones with a duration of 300 ms for the stimulus and 100 ms interstimulus interval. We acquired EEG data of 64 electrodes with a sampling rate of 5 kHz to get a detailed enough resolution of the perception process in the human brain.

Applying a fast Fourier transformation (FFT) on the EEG response, starting 50 ms after stimulus onset, the evaluation of the frequency spectra shows that the periodicity pitch frequencies calculated beforehand $\pm 3$ Hz occur with some accuracy. However, jitter turned out as a problem here. Note that the sought-for periodicity pitch frequencies do not physically exist in the frequency spectra of the stimuli.
1 Introduction

Hearing is one of the most important and enriching senses humans have. It not only allows us to communicate, but it also offers us to immerse ourselves in an abundance of emotions, concerning the musical aspect. Many people were looking for a scientific, rational, and mathematical explanation of how emotions caused by music work in our brains. Numerous approaches tackle this question, studying the consonance/dissonance of dyads or triads [1, 3, 7]. For instance, the major triad is often associated with emotional terms like pleasant or bright, and, in contrast to this, the minor triad with terms like sad or dark. Empirical studies as well as EEG experiments reveal a clear preference order on the perceived consonance/dissonance of common triads in Western music, e.g., major < minor [2, 7, 15].

The periodicity of complex chords can be detected by the human brain [9, 10]. We here concentrate on the detection of the periodicity pitch of a chord which corresponds to the reciprocal of the period length of the chord and can be derived from the physical waveform of the stimulus. The periodicity pitch can be computed for every musical harmony and is related to the missing fundamental frequency which usually is not present as tone component in the stimulus. Periodicity pitch and tone pitch represent distinct dimensions of harmony perception. The relative periodicity of a complex chord can be determined as the approximated ratio of the period length of the chord relative to the period length of its lowest tone component. The perceived consonance of a harmony decreases as the relative periodicity increases [17].

2 Aims

The goal of this research is to develop a model how the human brain perceives and processes musical sounds. For this, in our EEG experiments, six different harmonies (triads) and four single tones are presented (cf. Tab. 1). Concerning the triads we investigate whether the periodicity pitches of complex harmonies [17] (related to their missing fundamentals) are added in the auditory brainstem by analyzing the FFR [11, 12]. Those experiments have been done in a similar way before by Lee et al. [11, 12] with dyads and Bidelman and Krishnan [2] with triads and shall now be tested for reproducibility. Extending our experiment with the not so often examined suspended chord, we also expect some new insights regarding its dissolution by the major chord compared to other subsequent chords.

3 Related works

Lee et al. [11, 12] demonstrate that acoustic periodicity is an important factor for discriminating consonant and dissonant intervals. They measure human auditory brainstem responses to four diotically presented musical intervals with increasing degrees of dissonance and sought to explicate how the subcortical auditory system transforms the neural representation of acoustic periodicity for consonant versus dissonant intervals. They discover that the phase-locking activity to the temporal envelope is more accurate (i.e. sharper) in musicians than non-musicians.
The intervals show the highest response in the brainstem at about the periodicity pitch frequency (cf. [17, Sect. 2.6]).

Lerud et al. [13] build on this work. They aim at explaining the biophysical origin of central auditory nonlinearities. The nonlinear neural transformation in the brain is studied by comparing the frequency spectrum of the input stimulus and its response spectrum in the auditory brainstem. The latter shows additional frequencies which are not present in the input spectrum, in particular the periodicity pitch frequency. The authors introduce the concept of mode-locking and find good correlation between the response spectra and their model. Nevertheless, Stolzenburg [18] suggests that there might be easier explanations, namely the transformation of the input signal into pulse trains (spikes) whose maximal amplitude is limited by a fixed uniform value.

Bidelman and Krishnan [1] measure brainstem FFRs from nonmusicians in response to the dichotic intervals. Neural pitch salience is computed for each response using temporal autocorrelation and harmonic pitch sieve analyses. Brainstem responses to consonant intervals are more robust and yield stronger pitch salience than those to dissonant intervals. In [2], the same authors measure the responses in the brain to four prototypical musical triads (major, minor, diminished, augmented). Pitch salience computed from FFRs correctly predict the ordering of triadic harmony stipulated by music theory. The correlation between the ranking of neural pitch salience [1, Fig. 3] and periodicity is also significant [17].

Ebeling [5, 6] presents a mathematical model to explain the sensation of consonance and dissonance on the basis of neuronal coding and the properties of a neuronal periodicity detection mechanism. This mathematical model makes use of physiological data from a neuronal model of periodicity analysis in the midbrain, whose operation can be described mathematically by autocorrelation functions with regard to time windows. The mathematical model makes it possible to define a measure for the degree of harmoniousness. This procedure works well for dyads, but for triads and more complex chords the correlation with empirical ratings is relatively low, which has already been noticed in [5, Sect. 2.5.3].

Langner [8, 9, 10] assumes, since all frequency components of a harmonic sound are multiples of its fundamental frequency, that the period of the fundamental is also encoded in the cochlea in amplitude modulations resulting from superposition of frequency components above the third harmonic. As a consequence, the period of the fundamental is coded temporally in spike intervals in the auditory nerve and analyzed by neurons in the auditory brainstem cochlear nucleus. As already mentioned, referring to Langner’s work, [17] demonstrates that the perceived consonance of a harmony decreases as the relative periodicity increases.

### 4 Methods

#### Subjects

Seventeen healthy adult listeners (10 females, 7 males; mean age 31.4 years) participated in this research. From all subjects an informed consent was obtained. The Ethical Review Committee Psychology and Neuroscience of Maastricht University approved this study.
| Stimulus Interval | Musical Pitches | Frequency Components (Hz) |
|-------------------|----------------|--------------------------|
| G major root position | G3 | 196.7 393.4 |
|                   | B3 | 246.7 493.3 |
|                   | D4 | 293.4 586.8 |
| C major 2nd inversion | G4 | 390.2 783.7 |
|                   | C5 | 523.6 1047.2 |
|                   | E5 | 657.0 1317.4 |
| G minor root position | G3 | 196.6 393.2 |
|                   | B♭3 | 233.3 466.6 |
|                   | D4 | 293.3 586.5 |
| G augmented root position | G3 | 196.9 393.9 |
|                   | B♭3 | 247.0 494.0 |
|                   | D♯4 | 310.4 624.2 |
| G diminished root position | G3 | 196.7 393.4 |
|                   | B♭3 | 233.4 466.8 |
|                   | D♭4 | 276.7 556.8 |
| G suspended root position | G3 | 196.3 392.6 |
|                   | C4 | 262.9 525.7 |
|                   | D4 | 292.8 588.9 |
| C                  | C3 | 130.8 |
| C                  | C5 | 523.3 |
| G                  | G2 | 98.0 |
| G                  | G4 | 392.0 |

Table 1: Stimuli and the corresponding frequencies. The suspended chord used in this experiment is a suspended fourth.
Stimuli

A set of ten musical harmonies (6 triads and 4 single tones) were presented: five of six triads were G chords in root position (major, minor, augmented, diminished, and suspended), and one triad was a C major chord in its second inversion (cf. Tab. [1]). In addition, C3, C5, G2, and G4 were presented as single tones. The timbre of the stimuli was a synthesized classic piano sound with clear peaks in the corresponding fundamental frequencies (cf. Fig. [1]). The duration of each stimulus was 300 ms. In all triads the sought-for periodicity pitch frequencies did not physically exist in the frequency spectra of the stimuli.

Procedure

The EEG experiment procedure followed those in [11, 12] and [16]. The ten musical intervals were presented with single polarity binaurally by loudspeakers in a soundproof Faraday cage with an incoming intensity at around 67 dB. The interstimulus interval lasted 100 ms. Responses were collected using Brain Products EEG system with 64 electrodes. The contact impedance was < 5 kΩ for all considered electrodes. The musical intervals were each repeated 1,000 times in a different order and their response recorded with a sampling rate of 5 kHz. While hearing, the participants watched a muted nature documentary.
Analysis

First all electrodes were re-referenced with the left mastoid electrode. The EEG responses were bandpass filtered in the range of 15–700 Hz. If participants showed a greater activity than ±35 µV, the corresponding trial was rejected. For the analysis two approaches from [4] were examined:

1. the evoked method: All remaining trials and their baselines, the 50 ms response before each trial, were averaged. An FFT was performed on the averaged baselines as well as on the averaged trials (starting 50 ms after stimulus onset). We examined the outcomes of four types of baseline correction [14], including the absolute, the relative, and the log-arithmic baseline correction, as well as the results without any correction. To be counted, the FFT spectrum must pass a signal-to-noise-ratio (SNR) of > 1.0 at the desired periodicity pitch frequencies in the range of ±3 Hz. The SNR in this case is a measure how salient the frequency peak of interest is in relation to the corresponding frequency value in the baseline.

2. the induced method: An FFT was applied on each trial, starting 50 ms after stimulus onset, and on its baseline individually. All FFTs were averaged. We again proved the outcomes of four types of baseline correction mentioned above, as well as the results without any correction. To be counted, the FFT spectrum had to pass a SNR > 1.0 at the desired periodicity pitch frequencies in the range of ±3 Hz.

5 Results and Conclusions

Unfortunately, in the auditory brainstem responses we rarely found the sought-for periodicity pitch frequencies and the stimulus frequencies did not appear in the frequency spectra at all. There was no difference in the method or baseline corrections we used. For meaningful and correct results the hardware of the used system is quite important. EEG systems are not jitter-free and it is impossible to find the correct delay for each trial, because jitter-effects are not of equal durations and vary from trial to trial. Those problems can be overcome with a parallel but separate recording of the sound with which the starting point of the auditory stimulus can be set offline afterwards.

[16, p. 11] recommends that the deviation τ caused by jitter should not exceed 0.1 ms for a properly functioning system. We can derive this order of magnitude for the jitter as follows: According to the Nyquist-Shannon sampling theorem, a sampling rate of \( f = 5 \text{ kHz} \) allows to detect frequencies up to \( f/2 = 2.5 \text{ kHz} \) in principle. Because of the bad SNR ratio in the EEG experiments, however, the average of many trials has to be considered in order to reduce noise (cf. Sect. [4]). If we want to detect the peaks of cosine components in the averaged signal and assume that the jitter is uniformly distributed around zero by ±τ, then we obtain

\[
x = \int_{-\tau}^{\tau} \cos(\omega t)/(2\tau) \, dt = \sin(\omega \tau)/(\omega \tau)
\]

with \( \omega = \frac{2\pi}{T} \) and \( 1/T = f/2 \) as expected value for the peaks – instead of \( \cos(0) = 1 \). We find the first zero of \( x \) for \( \omega \tau = \pi \). It should be \( x > 0 \) and thus \( \tau < 1/f = 0.2 \text{ ms} \).
Another main issue is the presentation of the sound. One reason might be that providing the sound through loudspeakers cause a significant attenuation of the sound intensity. Although loudspeakers should serve its purpose, it would be good to use magnetic shielded in-ear headphones to also avoid delays or even possible hearing difficulties of the participants with increasing age. Since the auditory brainstem shows low-pass characteristics [16], it is necessary to choose stimuli with low frequencies 80–300 Hz and instruments with frequencies in this target range, otherwise the relatively low amplitudes of those frequencies will be superimposed by noise and will not occur in the spectrum of the EEG response. The synthesized classic piano sound was possibly not be the best choice because of its high harmonics. Because the highest frequency of all stimuli is well below 2.5 kHz, the sampling rate of 5 kHz should not be a problem. Future work will address these issues.

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