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EVENT-RELATED BRAIN RESPONSES WHILE LISTENING TO ENTIRE PIECES OF MUSIC

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Abstract—Brain responses to discrete short sounds have been studied intensively using the event-related potential (ERP) method, in which the electroencephalogram (EEG) signal is divided into epochs time-locked to stimuli of interest. Here we introduce and apply a novel technique which enables one to isolate ERPs in human elicited by continuous music. The ERPs were recorded during listening to a Tango Nuevo piece, a deep techno track and an acoustic lullaby. Acoustic features related to timbre, harmony, and dynamics of the audio signal were computationally extracted from the musical pieces. Negative deflation occurring around 100 milliseconds after the stimulus onset (N100) and positive deflation occurring around 200 milliseconds after the stimulus onset (P200) ERP responses to peak changes in the acoustic features were distinguishable and were often largest for Tango Nuevo. In addition to large changes in these musical features, long phases of low values that precede a rapid increase – and that we will call Preceding Low-Feature Phases – followed by a rapid increase enhanced the amplitudes of N100 and P200 responses. These ERP responses resembled those to simpler sounds, making it possible to utilize the tradition of ERP research with naturalistic paradigms.

Key words: event-related potentials, music, electroencephalography, musical features, N100, P200.

INTRODUCTION

For centuries, music has been an important part of various cultures from tribal drumming rites or performances of a symphony orchestra to the urban underground electronic music scene. Making music together as well as listening to the music of a given culture assists in forming a sense of community. At an individual level, music has versatile effects, e.g. regulation of mood and emotions (Panksepp and Bernatzky, 2002 for a review). Along with the technical development of brain-imaging methods, the neural dynamics underlying music perception, cognition, and emotions started to fascinate researchers (Peretz and Zatorre, 2003; Koelsch, 2014). The field of neurosciences and music could offer explanations concerning the importance of music for humans as well as answer to questions like: Why is music perceived differently than other auditory stimuli like speech and environmental sounds? How are the musical characteristics related to harmony, dynamics and rhythm processed in the brain?

Traditionally, brain research of music with electromagnetic methods such as electroencephalography (EEG) and magnetoencephalography (MEG) has focused on understanding the neural processing of separated artificial sounds designed to suit to the specification of each particular experiment. This broad line of music-related research includes different sequential sounds used as stimuli – pure vs. complex tones (e.g., Pantev et al., 1995; Tervaniemi et al., 2000), consonant vs. dissonant chords (e.g. Brattico et al., 2010; Virtala et al., 2014), simple monophonic melodies with and without harmony (Fujioka et al., 2005; Brattico et al., 2006) and chordal cadences (Koelsch and Jentschke, 2008). In addition to oddball paradigms (Näätänen et al., 1978), multifeature paradigms have also been established both in adults (Marie et al., 2012; Kühnis et al., 2013; Tervaniemi et al., 2014) and in children (Chobert et al., 2011, 2014; Putkinen et al., 2014). These studies have offered precious information about the

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Abbreviations: EEG, electroencephalography; ERP, event-related potential; FIR, finite impulse response; HG, Heschl's gyrus; ICA, independent component analysis; ISI, inter-stimulus interval; MoRI, magnitude of the rapid increase; N100, negative deflation occurring around 100 milliseconds after the stimulus onset; P200, positive deflation occurring around 200 milliseconds after the stimulus onset; PLFP, Preceding Low-Feature Phase; RMS, root mean square; STG, superior temporal gyrus.

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processing of individual elements of music and paved the way toward the research of natural listening, in which the unique characters of music are perceived: spontaneity, impurity, interaction and continuous flow of overlapping notes.

Several research groups have taken the next step and studied the brain processes evoked by long musical excerpts with different EEG analysis approaches. For example, Bhattacharya et al. (2001) showed that the gamma-band synchrony increases over distributed cortical areas with musical practice. This increase found in professional musicians in comparison with laymen refers to more advanced musical memory when dynamically binding together several features of the intrinsic complexity of music. In addition, professional training in music refines emotional arousal, which was studied in a whole musical piece by Mikutta et al. (2014). During high arousal, professional musicians exhibited an increase of posterior alpha, central delta, and beta rhythm. Also among laymen, music is shown to be a powerful stimulus modulating emotional arousal (Mikutta et al., 2012). To create these modulations in emotional states and to transmit esthetic experiences, confirmation and violation of expectations are crucial in music perception. Pearce et al. (2010) showed that low-probability notes, when compared to high-probability notes, elicited larger late negative event-related potential (ERP) component (at a time period of 400–450 ms), and increased beta-band oscillation over the parietal lobe and stronger long-range brain synchronization between multiple brain regions. Meyer et al. (2006a,b) investigated the perception of musical timbre by choosing as stimuli instrument sounds and comparing them to the sine wave sounds. In addition to the enhanced N1/P2 responses, they revealed how instruments with varying timbre activated also brain regions associated with emotional and auditory imagery functions. Grewe et al. (2005) studied the strong emotional experience of chills evoked by music noting that the peak emotion of chills is a result of attentive, experienced and conscious musical enjoyment. Furthermore, results by Schaefer et al. (2011) suggest that recollecting an event with emotional content involves multiple neural retrieval subprocesses. These studies indicate that the immersive sound space created by music, and its creation of strong subjective experiences with vivid memories, emotions and imagination, can indeed be investigated with multifaceted EEG analyses.

Several functional MRI (fMRI) studies have focused on using natural continuous music. Typically, excerpts from real musical pieces are used as stimuli (Morrison et al., 2003; Koelsch et al., 2006; Pereira et al., 2011; Brattico et al., 2011) and more recently even full musical pieces (Alluri et al., 2012, 2013; Abrams et al., 2013; Toiviainen et al., 2014). Due to the slower temporal dynamics of hemodynamic reactions recorded with fMRI compared to the electromagnetic brain research methods, in the former fMRI studies brain activity is averaged across several seconds, thus collapsing the fast dynamic feature changes that occur in key moments in the musical pieces. In addition, the fMRI device produces loud background noise which interacts with the auditory stimuli and may distort the results (see Novitski et al., 2001, 2006). Alluri et al. (2012) took the research of natural music further and studied the neural processing of individual musical features with fMRI during listening to a record of real orchestral music. In their novel approach, the fMRI data were correlated with computationally extracted musical features to study the brain activation relevant to each particular musical feature. However, the sampling rate of the data was 2 s, producing overlapping of the fast cranial processing within each sample. Similarly, Alluri et al. (2013) used two medleys, one comprising full songs by Beatles and the other comprising instrumental pieces belonging to the classical, jazz or pop/rock genres as stimuli. In both studies by Alluri and colleagues, the musical features were chosen so that they depict the musically and acoustically most relevant events and characteristics of the musical pieces at two analysis window durations. Both short-term features characterizing timbral properties and long-term features related to context-dependent aspects of music were shown to correlate with activation in various brain regions, with the largest consistency among features and musical genres for an anterior area of the superior temporal gyrus (Alluri et al., 2013). When investigating the neural activity for the low- or high-level acoustic features, it was found that the timbral features activated mainly the auditory cortex and the somatomotor regions of the cerebral cortex, as well as the cerebellum, whereas the tonal and rhythmic features activated limbic and motor regions of the brain (Alluri et al., 2012).

To combine the development toward real musical stimuli of EEG and the studies of individual musical features of fMRI, we created a novel experimental paradigm to reveal music-induced brain responses by extracting several relevant individual musical features from continuous musical pieces and studying the electrophysiological brain responses evoked by changes in these features. We decided to investigate the electric brain activity elicited by the same acoustic features extracted from musical pieces belonging to three very different musical genres: a Tango Nuevo piece, a deep techno track and an acoustic lullaby. The Tango Nuevo piece, Adios Noniño by Astor Piazzolla was the same piece used by Alluri et al. (2012, 2013) in their fMRI studies. In these studies, they observed that low-level musical features, as used in our study, are mainly processed in the auditory brain regions located in temporal cortices.

Previous knowledge from the processing of artificial sounds was utilized in our study of continuous music, in which the sounds are connected to each other in an overlapping and dynamic manner. The single-trial ERP method was considered the best option for studying the immediate neural responses on auditory areas of temporal cortices corresponding to rapid changes in low-level musical features. We hypothesized that the rapid changes in the musical features of real music would elicit similar sensory components as revealed in the conventional ERP studies using tone stimuli, and that the amplitudes of the ERP components would be dependent on the magnitude of the rapid increase in the individual feature value (Picton et al., 1977; Polich et al., 1996) as well as the duration of the preceding time period