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Neural processing of musical meter in musicians and non-musicians

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ABSTRACT

Musical sounds, along with speech, are the most prominent sounds in our daily lives. They are highly dynamic, yet well structured in the temporal domain in a hierarchical manner. The temporal structures enhance the predictability of musical sounds. Western music provides an excellent example: while time intervals between musical notes are highly variable, underlying beats can be realized. The beat-level temporal structure provides a sense of regular pulses. Beats can be further organized into units, giving the percept of alternating strong and weak beats (i.e. metrical structure or meter). Examining neural processing at the meter level offers a unique opportunity to understand how the human brain extracts temporal patterns, predicts future stimuli and optimizes neural resources for processing. The present study addresses two important questions regarding meter processing, using the mismatch negativity (MMN) obtained with electroencephalography (EEG): 1) how tempo (fast vs. slow) and type of metrical structure (duple: two beats per unit vs. triple: three beats per unit) affect the neural processing of metrical structure in non-musically trained individuals, and 2) how early music training modulates the neural processing of metrical structure. Metrical structures were established by patterns of consecutive strong and weak tones (Standard) with occasional violations that disrupted and reset the structure (Deviant). Twenty non-musicians listened passively to these tones while their neural activities were recorded. MMN indexed the neural sensitivity to the meter violations. Results suggested that MMNs were larger for fast tempo and for triple meter conditions. Further, 20 musically trained individuals were tested using the same methods and the results were compared to the non-musicians. While tempo and meter type similarly influenced MMNs in both groups, musicians overall exhibited significantly reduced MMNs, compared to their non-musician counterparts. Further analyses indicated that the reduction was driven by responses to sounds that defined the structure (Standard), not by responses to Deviants. We argue that musicians maintain a more accurate and efficient mental model for metrical structures, which incorporates occasional disruptions using significantly fewer neural resources.

1. Introduction

Music, along with speech, constitute sounds that are universal and ubiquitous in the world's cultures. Both rely on similar acoustic characteristics, such as pitch and timbre variations, to convey information. One important shared characteristic exists in the time domain: both music and speech are highly dynamic, yet temporally structured in a hierarchical manner. The 'Dynamic Attending Theory' and the 'Predictive Coding Theory' posit that the various levels of temporal structure allow the brain to generate predictions and optimize neural resources when processing these temporally dynamic sounds (Jones and Boltz, 1989; Large and Jones, 1999; Snyder and Large, 2005; Vuust and Witek, 2014).

The last decade has seen an increased interest in understanding temporal structure processing. Growing evidence has suggested that the ability to process and track temporal structure may be related to other higher-level cognitive abilities, such as attentional skills (Khalil et al., 2013) and reading (Carr et al., 2014); and that temporal processing skills can change rapidly with early training experiences (Benasich et al., 2014; Tallal et al., 1996; Zhao and Kuhl, 2016).

Western music has a well-characterized hierarchy in the temporal domain, and thus serves as an excellent tool for investigating temporal structure processing at various levels (Fig. 1). While time intervals between notes in rhythmic passages are highly variable, the underlying beats can be realized even when physical notes are absent, providing a beat-level temporal structure (Honing, 2012). The beat-level temporal structure induces a sense of regular or isochronous pulses, which listeners usually feel the urge to synchronize their body movements to,

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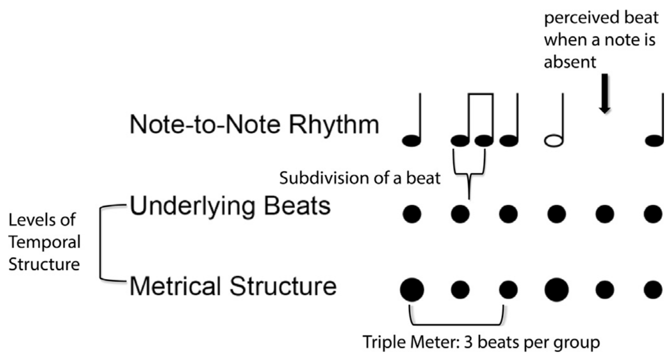

Fig. 1. Illustration of the hierarchy of temporal structure in music.

such as clapping hands and tapping toes (Drake et al., 2000). Further, these isochronous beats can be organized into units of alternating strong and weak beats, establishing a meter-level temporal structure. For example, there are two beats per unit in the duple meter (e.g. marching music: strong-weak-strong-weak), while there are three in the triple meter (e.g. waltz music: strong-weak-weak). This over-arching metrical structure in music provides a sense of grouping for beats, making the strong beats more salient and more predictable (Fitch, 2013). Investigating neural processing of meter-level temporal structure provides a unique window into understanding brain mechanisms associated with the extraction of temporal patterns or groups of beats and the predictions about future beats, in a way that minimizes prediction errors and optimizes neural resources.

The beat-level temporal structure provides the sense of regular pulses that are perceived to occur at equal time intervals. To understand the processing of regular beats, researchers have examined behaviors and neural activities when stimulus streams are presented at either isochronous or random intervals. Compared to randomly timed presentation, stimulus detection thresholds are lower when the stimuli are presented isochronously, and fewer neural resources are involved to process isochronous stimulus streams (Jones et al., 2002; Rohenkohl et al., 2012; Schwartze and Kotz, 2015; Schwartze et al., 2011; van Atteveldt et al., 2015). These results suggest that temporally regular and predictable beats are easier to process than randomly timed stimuli.

Studies have also suggested that the motor system plays a role in tracking the beat-level temporal structure, and that the ability to synchronize body movements to beats requires intricate communication between sensory and motor systems (Arnal, 2012; Patel and Iversen, 2014). Using isochronous stimulus stream vs. randomly timed stimuli, one recent fMRI study observed higher level of activities in the basal ganglia (putamen) for isochronous streams (Geiser et al., 2012). Using stimulus streams varying in their difficulty for beat extraction and perception, other fMRI studies reported that higher levels of activity in the basal ganglia and supplemental motor areas were associated with listening to streams where regular beats were more easily extracted (Grahn and Brett, 2007), and that a stronger perception of beats was related to stronger activity in supplementary motor areas and the premotor cortex across individuals (Grahn and McAuley, 2009). Using EEG, a recent study also demonstrated that participants' beta-band oscillatory activities (highly associated with sensorimotor systems) rebounded after a decrease following a stimulus. The slope of the rebound was associated with stimulus rate only when the stimulus stream was isochronous (not when the stimulus stream was randomly timed), suggesting the endogenous and predictive nature of the rebound (Fujioka et al., 2009, 2012). A recently proposed model suggests that a larger subcortical-cortical network, incorporating the frontal cortex, basal ganglia and cerebellum in addition to the auditory system, is at play for processing beat-level temporal structure (Schwartze and Kotz, 2013).

The meter-level temporal structure involves further organizing beats into groups or units through accenting some beats. While the accents for such perceptual organization are commonly conveyed through acoustic cues in the stimulus, such as intensity (strong-weak), pitch (high-low) or duration (long-short), it has been demonstrated that subjective accents can happen at the perceptual level even when the stimuli are acoustically identical (Brochard et al., 2003; Nozaradan et al., 2011; Potter et al., 2009). For example, using isochronous stimulus streams, individuals responded to deviants more when the deviants occurred at odd positions compared to at even positions in the stream, suggesting that individuals perceptually organized beats into group of two and it was easier to detect deviant at the perceptually stronger locations. The effects were observed to be earlier in the neural responses in musicians than non-musicians (Brochard et al., 2003). Further, when musically trained individuals were instructed to subjectively impose metrical structures (duple or tripe) onto isochronous beats; peaks in their EEG power spectrum were observed at the frequencies corresponding to the imagined meter (Nozaradan et al., 2011).

Other studies examined meter-level temporal structure representation and processes by providing accents in the stimuli. Using short and controlled musical excerpts in different meters, listeners' cortical responses (event-related potentials, or ERPs) to identical sounds were measured and compared when the sounds were at metrically stronger locations in musical passages, or weaker locations (Fitzroy and Sanders, 2015). More specifically, the ERPs to sounds at metrically stronger locations had a more negative N1 peak (a negative peak in event-related potentials at around 100 ms after sound onset) and a more positive P2 peak (a positive peak occurring around 200 ms), compared to ERPs to sounds at metrically weaker locations. This result is interpreted to be in line with the 'Dynamic Attending Theory', hypothesizing that attention is directed to time windows that carry more information (Jones and Boltz, 1989) (i.e. metrically stronger locations). In another study, accents were induced through an increase in intensity in the first part of the isochronous streams. Participants' beta-band modulations to the isochronous tones were measured during the second part of the stream when the acoustic accents disappeared. Beta-band activities were observed to have decreased more after perceptually stronger (or accented) beats than weaker beats even though the sounds were identical (Fujioka et al., 2015). Another commonly used method to study meter-level temporal structure processing is through measuring neural responses to occasional violations to an established meter. Such violation-detection response (e.g. Mismatch Negativity or MMN) can reflect how well the metrical structures were represented. By violating a meter structure at metrically strong and weak positions, non-musicians' MMNs were observed to be earlier when violations occurred at strong metrical positions compared to weak positions, even without attention (Ladinig et al., 2009, 2011). Taken together, research so far has demonstrated that metrically strong beats are processed differently in the brain, in comparison to metrically weak beats.

The current study is designed to examine neural processing of metrical structure from a slightly different perspective: 1) does neural processing of metrically strong beats change with the characteristics of the metrical structures (i.e. Temp: fast vs. slow, Meter Type: duple vs. triple) and 2) whether such neural processing is influenced by early music training experience.

In the current study, we considered the basic unit of metrical structure to be the time interval between strong beats (inter-strong-tone interval). We varied two important parameters of the basic unit to change the metrical structure: tempo and structure type. Tempo was determined by the duration of the inter-strong-tone interval (i.e. shorter time intervals result in a faster tempo). Structure type was determined by the number of beats in each unit (e.g., two beats per unit in duple meter, three beats per unit in triple meter). So far, few studies have specifically examined the effects of these two parameters on meter processing. In one study, participants exhibited shorter latencies in their EEG responses to deviants that violated a duple meter than those that violated a triple meter structure (Abecasis et al., 2005). Using MEG, another study observed differences between processing