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Subjective Beat Perception in Musical Rhythms in Adult Listeners

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SUBJECTIVE BEAT PERCEPTION IN MUSICAL RHYTHMS

IN ADULT LISTENERS

By

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ABSTRACT

Subjective Beat Perception in Musical Rhythms in Adult Listeners

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Synchronization to rhythmic stimuli is an everyday experience, whether it is exercising to the beat of music, dancing salsa, or rocking a baby to sleep. Commonly, humans synchronize their movements with the frequency of the beat (a quasi-isochronous pattern of prominent time points). Previous research has shown that the intended beat periodicity of a rhythmic stimulus can be observed in periodic neural activity; however, the extent to which this reflects robust perception of musical rhythm versus purely stimulus-driven activity is unknown. In Experiment 1 and 2, I investigated how long listeners can maintain a percept of the beat once the stimulus evidence becomes beat-ambiguous. In Experiment 3, I used electroencephalography (EEG to investigate whether steady state-evoked potentials (SS-EPs, the electrocortical activity from a population of neurons resonating at the frequency of a periodic stimulus) arising from auditory cortex reflect beat perception when the physical information in the stimulus is ambiguous and supports two possible beat patterns. In both experiments, participants listened to a musical excerpt that strongly supported a particular beat pattern (context), followed by an ambiguous rhythm consistent with either beat pattern (ambiguous phase). During the final probe phase,

listeners indicated whether a superimposed drum matched the beat. We found that participants perceived probes that matched the beat of the context as better fitting the ambiguous rhythm, compared to probes that did not match the beat of the context. We also found that SS-EPs during the ambiguous phase had higher amplitudes at frequencies corresponding to the beat of the preceding context. These findings support the idea that SS-EPs arising from auditory cortex reflect perception of musical rhythm and not just stimulus encoding of temporal features.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

People are exposed to rhythmic stimuli daily, whether from observing others moving, listening to music, or listening to speech. During auditory rhythmic events, it is common for listeners to synchronize with the stimulus, whether it is bobbing their head to the music at a rock concert, snapping their fingers at a jazz club, or synchronizing their pace with the music as they run. Adult listeners perform these types of synchronization behaviors with seemingly little effort. It is clear from this behavior that listeners are sensitive to the temporal regularities found in auditory events, specifically when those events are arranged in a rhythmic pattern. *Rhythm* can be defined as a pattern of temporal intervals in a sequence of events (Large & Palmer, 2002). When listeners find themselves synchronizing with a rhythm, they often clap or tap along with the *beat*, or periodic pulse (Parncutt, 1994; Large & Palmer, 2002). In music, these beats are grouped into measures that follow a specific temporal pattern. This temporal pattern, comprised of two or more levels of organization, is referred to as *meter* (Lerdahl & Jackendoff, 1983).

When listeners experience rhythmic events, they often perceive a hierarchical temporal pattern, comprised of both beat- and meter- level information. While the beat is periodic, each beat can be perceived as either strong or weak in salience. Meter dictates which beats are perceived as strong, and which beats are perceived as weak. For example, a group of six beats can be perceived with one of two beat patterns; one has two strong beats (SWW-SWW), with each strong beat followed by two weak beats. The other has three strong beats (SW-SW-SW), with each strong beat followed by one weak beat. Thus, while the sequences have the same number of events, the pattern of strong and weak events (meter) differs between the two sequences. Together, beat and meter are crucial to the temporal pattern that listeners perceive in rhythmic stimuli, particularly in music.

Music is comprised of sequences of events that vary on several factors, and this variability affects the way that listeners perceive the beat. One such physical change is differences in inter-onset interval (IOI), such that an event is perceived to be more salient after a longer IOI than a shorter IOI (Povel & Essens, 1985). The loudness of events can affect beat perception as well, such that an increase as small as 2 dB will cause one event to be perceived as more salient than another event (Thomassen, 1982). Beat perception is also affected by tempo, such that faster tempos result in more events occurring between strong beats, and slower tempos result in fewer events occurring between strong beats (Parncutt, 1994). In addition, beat perception is affected by the pitch accents, which can occur as either changes in the melodic contour of the sequence of events, or by pitch jumps, in which the pitch of a specific event is either significantly higher or lower than the events surrounding it (Ellis & Jones, 2009; Thomassen, 1982; Hannon et al., 2004). Music incorporates variance in all of these aspects, making it a uniquely complex and rich auditory scene for listeners. People are exposed to musical auditory information overwhelmingly more than monotone sequences of tones, yet most research conducted on beat perception uses monotone, simple stimuli with no musical variation. Thus, music offers the most salient and ecologically valid auditory experience for investigating subjective beat perception in human listeners.

While human listeners with and without musical training are capable of using information present in the stimulus to extract a beat, listeners surprisingly often infer a beat when there is no physical evidence supporting a particular beat. When listeners hear the ticking of a clock's second hand, they regularly perceive the sounds made to be occurring in a "tick-tock" pattern, even when every sound in the sequence is physically identical. This grouping of sounds into strong and weak beats is a form of *subjective beat perception*, or the subjective weighting of some temporal events as being more salient than others. When a listener is exposed to an isochronous monotone rhythm for a long period of time, he or she will begin to perceive some events as being stronger than others, thus experiencing a subjective beat pattern, despite no physical changes being made in the stimulus (Abecasis, Brochard, Granot, & Drake, 2005; Parncutt, 1994). Furthermore, when listeners experience subjective beat perception in an isochronous sequence of tones, deviants occurring in strong beat positions cause greater disruptions in temporal expectancies, as measured by event-related potentials (ERPs), compared to deviants occurring in weak beat positions (Brochard, Abecasis, Potter, Ragot, & Drake, 2003). In addition, this phenomenon of maintaining an internal percept of the beat is demonstrated with syncopated rhythms, or rhythmic patterns where events occur off the perceived beat (Fitch & Rosenfeld, 2007). Despite the fact that there is less physical support for the beat in syncopated rhythms, listeners are still able to maintain an internal percept of the beat. Research even suggests that syncopated rhythms are more enjoyable and rated happier than unsyncopated rhythms (Keller and Schubert, 2011). To date, no research has attempted to disentangle the inner subjective experience of the beat from the physical characteristics of the auditory stimulus that give rise to a particular percept of the beat.

To perceive beat and meter in musical stimuli, listeners may dynamically attend to specific features that support these levels of perception. The Dynamic Attending Theory suggests that perception of beat and meter in musical rhythms involves the synchronization of one's attention to frequencies that reflect these structures, which causes the brain to form temporal expectancies about incoming auditory information (Large & Jones, 1999; Jones & Boltz, 1989).

Allocating one's attention to specific points in time allows for natural organization of these events as they occur. Thus, perceiving musical rhythms in a hierarchical way is efficient because it allows us to predict when strong and weak beats are going to occur, and to direct our attention to the important time points in the stimulus.

Previous research suggests that adult listeners have better rhythm discrimination when the auditory stimulus contains physical support for a clear beat pattern. When asked to detect changes in a rhythm, adult listeners perform better when judging a simple rhythm with a clear beat (i.e. every beat position contains an event), compared to a complex rhythm, where the beat is less clear (i.e. not every beat position contains an event) (Grahn & Brett, 2007). The results suggest that participants attend to the beat-level information and rhythms with a clear beat pattern facilitate better change detection than rhythms without a clear beat pattern. It was concluded that adult listeners perceive the beat in musical rhythms and utilize it when performing rhythmic tasks. However, this study did not explicitly measure participants' perception of the beat in these rhythms, so it is not clear that they were consciously attending to the beat and using it to perform the task. To better measure perception of the beat in rhythmic stimuli and relate it to performance, future paradigms should ask participants to perform a task that directly measures their beat perception.

In one such study, participants were asked to judge how well a probe tone fit a series of context beats (Palmer & Krumhansl, 1990). Participants were told that the context beats were occurring in groups of 2, 4, 6, or 8, and this repeated 4 times. Results demonstrated that both musicians (5 or more years of formal music training) and non-musicians (less than 2 years of formal music training) gave more positive ratings to probes that followed beat-level expectancies in the music, compared to probes that did not. In addition, results showed that musicians gave more positive ratings to probes that followed a metrical structure. Specifically, musicians were more likely to positively rate a probe that not only matched the beat of the musical rhythm, but also a metrical organization of strong and weak beats. Non-musicians, however, were not sensitive to metrical level expectancies. Importantly, these musicians had not been trained in music theory. This suggests that rather than the musicians using theoretical concepts regarding meter, they likely were more sensitive to meter due to their rich experience with music (Palmer & Krumhansl, 1990). These results support the theory that as musicians are formally trained, their mental representations begin to incorporate the hierarchical levels of information that are supported by frequency distributions of the music they are being exposed to, thus allowing them to better attend to metrical structure in rhythms (Lerdahl & Jackendoff, 1983). Overall, these results show that most listeners are sensitive beat-level expectancies regardless of musical training, but musicians may have more refined metrical expectancies.

While some research supports the findings of Palmer and Krumhansl (1990) that listeners with formal music training are more aware of meter-level information in rhythms than those without formal music training, other studies have challenged these findings. In one supporting study, participants performed the same task as was used by Palmer and Krumhansl (1990), and the results were similar: while all participants gave more positive ratings to probe patterns that matched the beat, musicians alone gave more positive ratings to probe patterns that also matched the meter (Jongsma, Desain, & Honing, 2004). However, in another study, findings suggested that listeners without musical expertise demonstrate the ability to perceive metrical structure in musical rhythms (Ladinig, Honing, Háden, & Winkler, 2009). In this task, participants with less than one year of music training listened to rhythmic sequences and responded as quickly as possible when they detected a change in intensity. Participants had faster reaction times when the intensity deviation occurred on a strong beat compared to a weak beat. While this suggests that listeners without formal music training are sensitive to the metrical representation of rhythms, it may be that a rating task, such as those used in the studies discussed previously, are not sensitive enough measures to detect this in nonmusicians. Overall, the extent to which nonmusicians perceive and are explicitly aware of meter in musical rhythms is still unclear.

The human brain is capable of time-locking to, or tracking, auditory stimuli, and this phenomenon can be measured in the brain using EEG (Picton, Skinner, Champagne, Kellett, Maiste, 1987). When a stimulus is repeated with a regular rate, the brain response reflects a periodic change in amplitude in the electrical activity. This periodic change in amplitude reflects steady state-evoked potentials (SS-EPs). SS-EPs are stable in phase and amplitude over time (Regan, 1966), and they are frequency-locked to particularly relevant aspects of an auditory stimulus, thus offering the potential to show how neural activity at that time point differs from surrounding frequencies. By investigating the neural activity occurring at the beat frequency during musical stimuli, SS-EPs have the potential to shed light on subjective beat perception in the brain.

SS-EPs have been measured in previous research to investigate how the neural activity of adult listeners is related to beat perception when the listeners are asked to imagine one of two specific beat patterns. In one study, adult listeners imagined either a duple beat pattern (SW-SW-SW) or a triple beat pattern (SWW-SWW) while listening to an isochronous stimulus. EEG activity demonstrated SS-EPs with higher amplitudes occurring at frequencies that matched the beat frequencies predicted by the imposed beat pattern (Nozaradan, Peretz, Missal, & Mouraux, 2011), compared to non-beat-related frequencies. These results suggest that when a beat percept is actively imposed by the listener, periodic neural activity is enhanced at the frequencies corresponding to the imposed beat pattern. Importantly, the stimulus itself did not contain auditory information that would cause a specific beat pattern to be perceived. Therefore, these differences in brain activity are not due to differences in the stimulus itself, but rather top-down influences of the imposed beat pattern. It is important to note that this paradigm required participants to recognize the terminology used to describe the duple and triple meter patterns. For this reason, the experiment was only conducted with participants with some level of music training, as they were familiar with musical terminology and could adequately perform the task. This is a limitation to this paradigm, as it cannot be used with listeners who do not have musical training, including not only non-musicians but also infants and young children. To better understand how all listeners perceive these levels of the musical hierarchy, we must use a paradigm that can be administered to listeners without requiring them to have this explicit knowledge of musical terminology.

In a second study, the same paradigm was used with monotone stimuli designed to have an inherent regular beat structure (Nozaradan, Peretz, Mouraux, 2012). While the previous study relied on participants' ability to accurately imagine the correct imposed beat structure, this experiment provided structural cues in the rhythms that suggested a clear beat pattern (e.g. events occurring in strong beat positions). Thus, participants did not have to actively impose a beat pattern on the stimuli they heard to experience a subjective beat percept. The rhythms were designed based on the results of Essens and Povel (1985) to be heard with a duple beat pattern, and indeed tapping results demonstrated that in all five rhythms, a duple beat pattern was perceived. In this way, the paradigm could be used with participants with and without formal music training. The task was to listen for short accelerations in the stimulus. Results demonstrated SS-EPs with higher amplitudes occurring at frequencies that matched the duple beat frequency of the rhythm that participants heard (Nozaradan et al., 2012). Of the different rhythmic patterns that the experimenters used, enhancement of SS-EPs at the beat frequency was found with three of the five rhythms. The results suggest that beat perception may involve spontaneous neural activity that reflects the beat structure when processing rhythmic stimuli, and that this neural mechanism can be captured with SS-EPs. However, the beat frequency was strongly present in the sound envelope extracted from the physical stimulus, so it is unclear from this study whether the SS-EPs observed are related to an internal percept of the beat or simply faithful neural tracking of the stimulus itself. In addition, if the SS-EPs do indeed reflect beat perception, one might expect that enhancement would have been seen in all five rhythms, and not just three of them. While this paradigm provides a unique context to investigate neural correlates of subjective beat perception in listeners, no one has yet utilized it to investigate how an induced beat percept can be captured by SS-EPs that reflects activity beyond the stimulus in non-musicians.

To fully understand how rhythmic neural activity is related to subjective beat perception during musical rhythms, I designed a paradigm that A) creates a strong subjective perception of the beat that is long-lasting, and can be maintained over time, and B) provides behavioral and neural measures of beat perception on each trial. The current study had listeners complete a beat matching task. Listeners listened to a musical context with one of two different beat patterns, following by a beat-ambiguous rhythm that could be perceived as having either of two beat patterns. It was hypothesized that listeners would extract the beat from the musical context and maintain the same beat percept during the beat ambiguous rhythm. Finally, a probe drum came in and listeners had to judge whether the probe matched or mismatched the music. This paradigm is novel because it allowed me to not only investigate periodic neural activity when two different beat patterns are perceived in the same stimulus, but it also did not require participants to imagine the imposed meter. This is a crucial aspect to this paradigm, because it allowed me to ask non-musically trained participants to perform the task without attempting to explain and define musical terminology to them.

Experiment 1 and 2 investigated how long listeners were able to maintain the beat once the physical information in the stimulus was no longer disambiguating and two beat interpretations were possible. I hypothesized that if participants perceived the beat of the musical excerpt and maintained it when the musical rhythm became ambiguous, then they would have high performance on the rhythm task. High performance was achieved by correctly identifying when the drummer matches the beat of the music, and correctly rejecting the drummer when he does not match the music. In Experiment 3, participants completed the same task while I recorded EEG. I hypothesized that SS-EPs would have significantly higher amplitudes at predicted beat frequencies compared to other frequencies when participants performed accurately on the beat induction task. I expected that when I averaged neural activity on trials where the participant had accurate performance on the behavioral task, SS-EPs would have higher amplitudes occurring at the predicted beat frequencies.

CHAPTER 2

METHODOLOGY

General Paradigm

The paradigm used in Experiments 1, 2, and 3 consisted of three phases on each trial: 1) music context phase, 2) ambiguous phase, and 3) probe phase (See Figure 1A). I used rich musical stimuli in the music context phase to induce a subjective beat percept in the listener. Specifically, listeners heard rich musical excerpts with both pitch and rhythmic cues intended to induce perception of a specific beat pattern. I used a beat-ambiguous rhythm in the ambiguous phase, which had ambiguous physical cues that offered support for two different beat patterns. In the probe phase, I superimposed the beat-ambiguous rhythm with a click track comprised of snare drum hits and asked listeners to judge whether the probe matched or did not match the music. In Experiment 3, EEG was used to measure neural activity proposed to reflect how the listeners maintained the beat during the ambiguous rhythm.

Stimuli

The stimuli used in the music context phase consisted of short musical excerpts played on a piano with one of two different metrical structures. Both meters consisted of six regular temporal intervals per measure, but they included differing temporal cues (i.e., each with a different pattern of strong (S) and weak (W) events). *Duple* meter had a strong beat occurring on every other event (SW-SW-SW), and *triple* meter has a strong beat occurring on every third event (SWW- *SWW*) (see Figure 1B). There were eight duple- and eight triple-meter test musical excerpts created. In addition, there were two duple- and two triple- meter practice excerpts created. Beat and meter were induced in these stimuli by carefully controlling for when onsets occur in each measure, how pitch contour aligned with beat positions, and how certain phrases

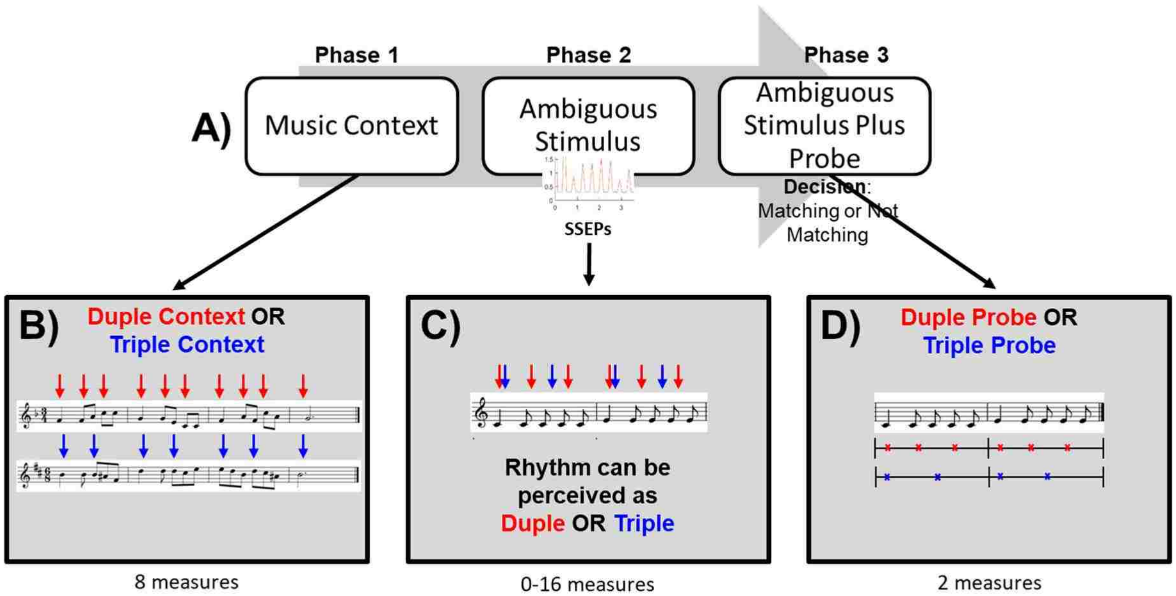

Figure 1. Trial structure used in all three experiments. A) Schematic of the progression of each trial. B) Musical examples of the SW-SW-SW patterned context (i.e. duple meter) and the SWW-SWW patterned context (i.e. triple meter) presented during Phase 1. Strong events for this pattern are shown in red (duple) and blue (triple). C) Musical notation for the beat-ambiguous rhythm presented in Phase 2. This rhythm was repeated for 0-8 measures (Experiment 1), 12-16 measures (Experiment 2), or 16 measures only (Experiment 3). Blue arrows indicate where strong beats would be perceived in duple meter, and red arrows indicate where the strong beats would be perceived in triple meter. D) Beat-ambiguous rhythm plus the superimposed drum probe, as indicated by the colored x's, which were presented during Phase 3 for 2 measures. Blue x's indicate the pattern of drum beats for the duple probe, and red x's indicate the pattern of drum beats for the triple probe.

were repeated to give a sense of pulse, according to well-known theories of beat and meter perception (Lerdahl & Jackendoff, 1983). These stimuli were analyzed for number of onsets per measure, total number of onsets, average pitch, average pitch range, and average pitch jumps to ensure no significant differences between the two meter types. We know that listeners are sensitive to these features when listening to music (Hannon, Snyder, Eerola, & Krumhansl, 2004), so it was important to ensure that there were no significant differences on these factors between the two meters. This ensures that any differences in performance are due to differences in perception of the beat and not due to an overall difference in the physical attributes of the stimulus.

The stimulus used in the ambiguous phase was a rhythm played on a piano that was beat-ambiguous, such that it could be perceived as being in duple meter (*SW-SW-SW)* or triple meter (*SWW-SWW).* The rhythm has 6 temporal intervals, with the second one being a silent interval (i.e. x-o-x-x-x-x). This rhythm is often found in actual composed pieces of music (i.e. marches, waltzes), and it was purposefully included in all the musical excerpts created for the music context phase described above. Importantly, while the musical excerpts exhibited changes in rhythm, pitch contour, and repetition that support a particular metrical pattern, the beat-ambiguous rhythm did not exhibit these clear physical attributes that support a particular meter. Thus, the beat-ambiguous rhythm capitalizes on the structure of the duple and triple meters presented in this paradigm, such that it can be perceived as following either metrical structure (See Figure 1C). It was expected that beat induction caused by the clear meter of the musical excerpt would cause this beat-ambiguous rhythm to be perceived as having the same meter as the music.

The stimuli used in the probe phase consisted of a probe click track overlaying the beat-ambiguous rhythm. If the probe matched duple meter, then a snare hit occurred on every other interval of the rhythm (i.e. x-o-x-o-x-o), and if the probe matched triple meter, then a snare hit occurred on every third interval of the rhythm (i.e. x-o-o-x-o-o) (See Figure 1D).

Stimuli were created and sequenced using MIDI as a part of the Logic Pro-X program for Macintosh computers (Apple Inc., 2015). Ecologically valid sounds were chosen to represent musical instruments, including patches for the Steinway Grand Piano and the Snare Drum. The stimuli were created in two channels for the musical excerpts (left hand and right hand of the piano), one channel for the beat-ambiguous rhythm (right hand of the piano only), and two channels for the beat-ambiguous rhythm plus click track (right hand of the piano and snare drum hits). These stimuli were exported as stereo wav files, which were analyzed using the program Adobe Audition audio editing software to ensure equality between left and right channels. The snare drum stimulus was comprised of hits equaling half the duration of one beat-interval in the ambiguous stimulus. Because the beat-ambiguous stimulus and musical excerpts were presented as two different tempos, this resulted in a snare drum stimulus duration of 100 ms or 150 ms, depending on whether it was a slow or fast trial (to be described below).

It is important to note that because the two metrical patterns differ in the number of strong beats per measure, the length of time between strong beats, or *inter-beat-interval* (IBI), differs between the two meters. In duple meter, there is one interval occurring between strong beats (SW-SW-SW) and in triple meter, there are two intervals occurring between strong beats (SWW-SWW). This results in an inherent confound in the perceived tempo between these two meters. To account for differences in tempo between the two meters, all stimuli were presented at 2 different tempos. The *fast* tempo had an inter-onset-interval (IOI) of 200 ms, and the *slower* tempo had an IOI of 300 ms. Thus, one measure of the fast tempo consisted of six 200 ms temporal events, making it 9.6 seconds long, and one measure of the slow tempo consisted of six 300 ms temporal events, making it 14.4 seconds long. In the duple meter condition, this resulted in an IBI of 400 ms for the fast tempo (comprised of two 200 ms intervals), and an IBI of 600 ms for the slow tempo (comprised of two 300 ms intervals). In the triple meter condition, this resulted in an IBI of 600 ms for the slow tempo (comprised of three 200 ms intervals), and an IBI of 900 ms for the fast tempo (comprised of three 300 ms intervals). Thus, there were three possible IBIs (400 ms, 600 ms, and 900 ms), with the 600 ms IBI occurring in both meters (See Figure 2). Previous research has suggested that adult listeners have a preferred tempo (e.g. rate) around 600 ms (McAuley, Jones, Holub, Johnston, & Miller 2006). Based on this evidence, it

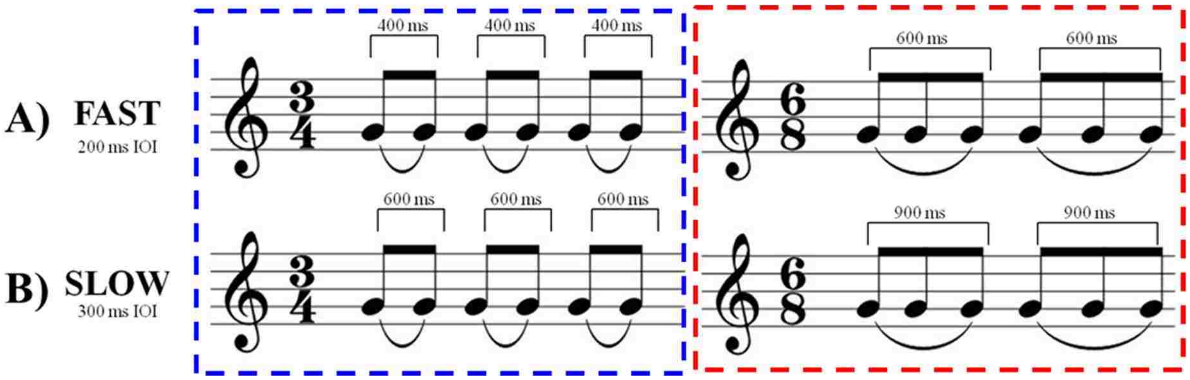

Figure 2. Tempo conditions used. Duple meter is in blue and triple meter is in red. (A) In the fast condition, an inter-onset interval (IOI) of 200 ms is used, which creates an inter-beat interval of 400 ms for duple meter, and 600 ms for triple meter. (B) In the slow condition, an inter-onset interval (IOI) of 300 ms is used, which creates an inter-beat interval of 600 ms for duple meter, and 900 ms for triple meter.

was expected that listeners might be more likely to perceive a particular beat pattern if it had an IBI of 600 ms. If listeners were more likely to prefer music with an IBI of 600 ms, then they would perform better on duple meter trials that are presented at the slow tempo and triple meter trials that are presented at the fast tempo. This matched IBI condition allowed me to still examine the effects of induced beat perception at both duple and triple meter.

General Procedure

Participants were told that their task was to help Drummer Dan improve his drumming skills. To do so, they listened in on a music lesson between Drummer Dan and his music teacher, Piano Polly. Participants were told that Piano Polly would play something on her piano, and then after a while, Drummer Dan would try to play along with her. The participants' job was to respond as quickly as possible and indicate whether or not Drummer Dan's playing was "matching" Piano Polly's song or was "not matching" by pressing either M or N on the keyboard, respectively (Experiment 1 & 2) or one of two labeled response buttons on a Cedrus Response Box. (Experiment 3). The trial ended as soon as the participant made a response. On each trial, a musical excerpt was presented during the music context phase, consisting of 8 measures.

Immediately following the musical excerpt, the beat-ambiguous stimulus was presented, repeating for up to 18 measures. During the final two repetitions of the beat-ambiguous stimulus, the probe click track accompanied the beat-ambiguous stimulus. This probe either matched the musical stimulus beat pattern, or it matched the opposite musical stimulus beat pattern (see Figure 1D). The paradigm is designed to be suited for all ages of participants, and this will prove especially useful for future studies with younger populations.

Before completing the test trials, participants were presented with two demonstration trials and eight practice trials. During the demonstration trials, the listener heard examples of a matching probe and a non-matching probe. Half of the participants heard a duple meter example trial first, and half the participants heard a triple meter example trial first (counterbalanced for matching and not-matching click track). Then, each participant completed 8 practice trials and received feedback on their performance. In Experiment 1, if the listener responded correctly on 6 of the 8 practice trials, they moved on to the test trials. If the listener responded incorrectly on 3 or more practice trials, they repeated the practice block. Participants could only repeat the practice once, for a maximum of 16 practice trials. After Experiment 1, analyses revealed that repeating the Practice Block resulted in no change in performance between Practice Block 1 and Practice Block 2. Thus, in Experiments 2 and 3 participants only completed one block of practice trials, regardless of performance.

Each unique musical excerpt was presented once for each cell of the design, resulting in eight repetitions of each musical excerpt across meter (duple and triple), tempo (fast and slow), and probe (matching and non-matching). Participants completed 4 blocks of trials in Experiment 1 and 2, each containing 16 trials, and 8 blocks of trials in Experiment 3, each containing 8 trials. The same musical excerpt was only heard on a maximum of two trials in a row. Presentation software (Neurobehavioral Systems, Inc., 2015) was used to present all auditory and visual stimuli to the participants, to control the experimental program, and to record button presses and reaction time data.

In addition, participants were asked to fill out a survey, which asked questions regarding background information and demographic information. This included information such as their age, sex, race, and year in school. They also answered questions about their music and dance experience. This included questions about their years of formal music training, instruments played, years of formal dance training, and types of dance practiced.

CHAPTER 3

EXPERIMENT 1

Participants

A total of 20 participants (12 female) were recruited from the UNLV Psychology Participant Pool (M_{age} = 21.65 years, *SD* = 3.67 years, Range: 18-32 years). They all received course credit for participation in the study. Participants all reported having normal hearing. In addition, participants had minimal music training (*M* = 2.40 years, *SD* = 2.46 years, Range: 0-7 years) and minimal dance training (*M* = 2.40 years, *SD* = 5.30 years, Range: 0-18 years).

Procedure

Experiment 1 used the methods described above, with the exception that the ambiguous phase consisted of a variable number of repetitions of the beat-ambiguous rhythm. Because I am interested in how listeners sustain perception of the beat, it was important to consider how long adult listeners can maintain their subjective perception of the beat once the beat-salient information (i.e. the musical excerpt) is complete. The beat-ambiguous rhythm was presented for 0, 2, 4, or 8 measures (henceforth referred to as the delay condition). In the 0-measure condition, the trial proceeded directly from stage 1 to stage 3, such that the drumming click track begins at the same time as the beat-ambiguous rhythm (See Figure 3). In the fast condition (IOI=200 ms), this resulted in trials that are 12.0, 14.4, 16.8, or 21.6, seconds long, respectively. In the slow condition (IOI=300 ms), this resulted in trials that are 18, 21.6, 25.2, or 32.4 seconds long, respectively.

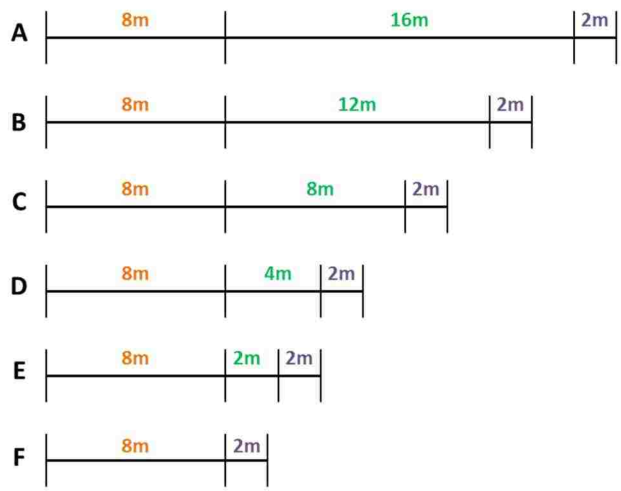

Figure 3. Trial lengths used in Experiment 1, Experiment 2, and Experiment 3. The number of measures (m) is indicated for the music context phase (orange), the ambiguous phase (green), and the probe phase (purple). In each trial length condition, the music context phase (i.e. musical excerpt) is 8 measures, and the probe phase is 2 measures. The ambiguous phase has a variable length (i.e. delay manipulation). Experiment 1 used C-F, Experiment 2 used A-C, and Experiment 3 used A only. The lengths are as follows: A) 16 measure delay, B) 12 measure delay, C) 8 measure delay, D) 4 measure delay, E) 2 measure delay, and F) 0 measure delay (i.e. no delay).

Results and Discussion

Overall, I expected that listeners would experience a strong percept of the beat during the musical context and they would maintain that percept during the ambiguous rhythm. If this occurred, I expected participants to accurately reject the drum probe when it did not match their maintained beat percept and to accurately identify probes that did match their beat percept. Beat induction was examined using a 2 × 2 × 2 x 4 (Trial Type [matching, not matching] x Tempo [fast, slow] x Context [duple, triple] x Delay [0 measures, 2 measures, 4 measures, 8 measures]) repeated measures ANOVA, where the dependent measure was *proportion matching responses* (i.e., proportion of button presses that indicated the drummer was matching the piano player). This revealed an overall main effect of trial type, such that participants responded *matching* significantly more in matching trials than non-matching trials, $F(1,19) = 53.66$, $p<.001$, $\eta p^2 = 0.74$ (See Figure 4). This demonstrates that listeners experienced a salient and robust subjective

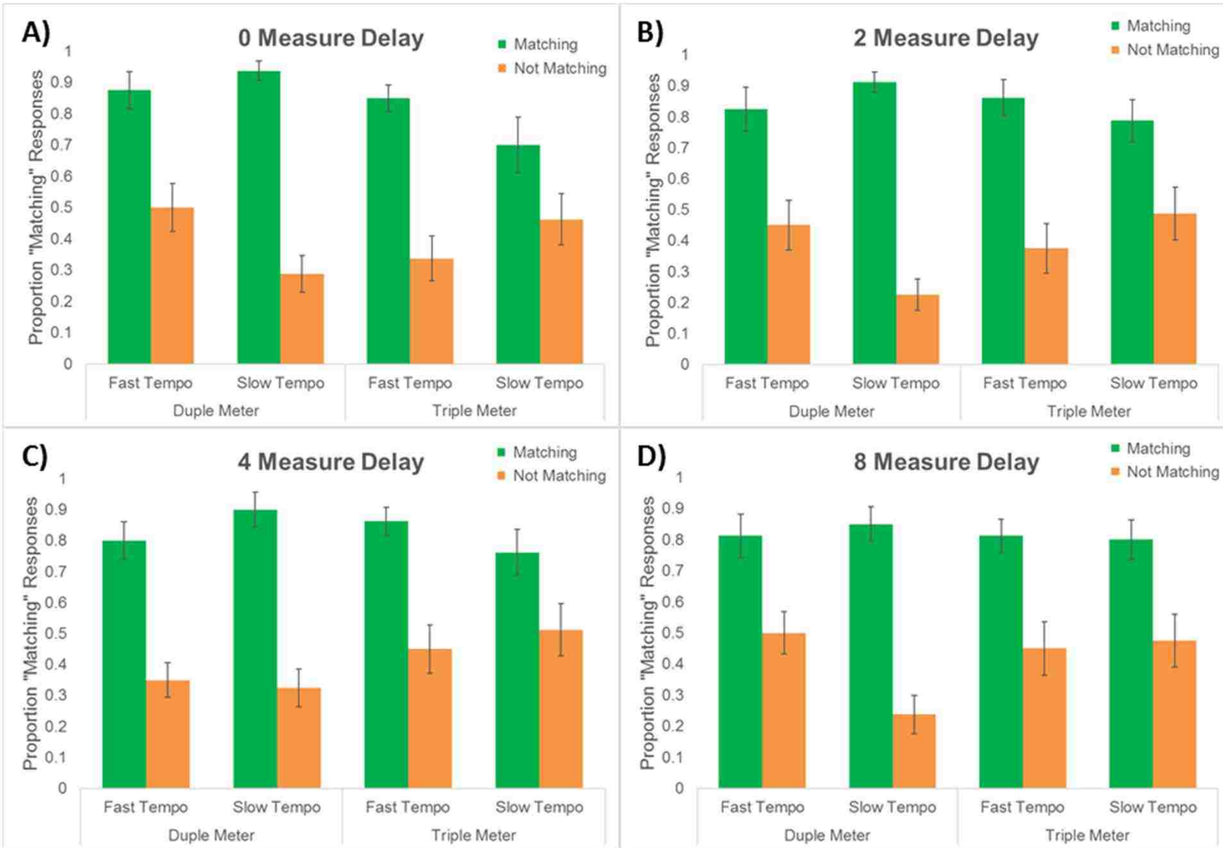

Figure 4. Experiment 1 results. Proportion of "matching" responses by meter, tempo, and trial type for A) 0 measure delay, B) 2 measure delay, C) 4 measure delay, and D) 8 measure delay. Perfect performance in any condition would be 100% in the Matching trials (green bar) and 0% in the Not Matching trials (orange bar).

beat percept during the musical excerpt and *maintained* this beat perception throughout the beat-ambiguous rhythm, thus leading to high accuracy on the behavioral task. There were no main effects of meter ($F(1,19) = 0.35$, $p = 0.562$, $\eta p^2 = 0.02$), delay ($F(1,17) = 0.01$, $p = 0.998$, $\eta p^2=0.00$), or tempo ($F(1,19) = 1.52$, $p = 0.233$, $\eta p^2 = 0.07$). This suggests that listeners were not more likely to respond *matching* for duple or triple meter, fast or slow tempos, or based on delay condition.

I expected to find an interaction between tempo and meter, such that listeners have better beat perception when the IBI is 600 ms, the tempo at which most adult listeners prefer to hear the beat (McAuley et al., 2006). As expected, results demonstrated a significant Trial Type x Meter x Tempo interaction, $F(1,19) = 9.84$, $p = .005$, $\eta p^2 = 0.34$. Specifically, this interaction was driven by higher proportions of *matching* responses on matching trials (i.e. high accuracy) when the IBI of the probe was 600ms (e.g. duple slow and triple fast), as well as lower proportions of *matching* responses on not-matching trials (i.e. high accuracy) when the IBI of the probe was 600ms (e.g. duple slow and triple fast).

There was a significant Meter x Delay interaction, $F(3,17) = 8.46$, $p = 0.001$, $\eta p^2 = 0.60$). While this interaction seemed to be driven by higher proportions of *matching* responses at the level of the 0-measure delay condition for duple trials ($M = 0.65$, $SD = 0.16$) compared to triple trials ($M = 0.59$, $SD = 0.11$), $t(1,19) = 2.76$, $p = .013$ (uncorrected), a post-hoc Tukey test reveals that no pairwise comparisons were statistically significant ($p>0.05$). No other interactions were significant.

Overall, Experiment 1 revealed that listeners are able to maintain the induced percept of the beat, and they can do this equally well no matter the delay condition. If beat perception requires continuous stimulus evidence to be sustained, we would expect that listeners would have higher accuracy on the behavioral task when the delay was shorter (i.e. 0 measures) versus when the delay was longer (i.e. 8 measures). Since there was no main effect of delay, this suggests that listeners could accurately maintain the beat regardless of the length of the ambiguous rhythm before the probe. However, it is possible that Experiment 1 did not contain long enough delay conditions to see this effect. To further test whether there is a perceptual limit to how long non-musician listeners can maintain the beat, I designed Experiment 2 to explore longer delay conditions.

CHAPTER 4

EXPERIMENT 2

Participants

A total of 20 participants (13 female) were recruited from the UNLV Psychology Participant Pool (M_{age} = 19.70 years, *SD* = 3.42 years, Range: 18-32 years). They all received course credit for participation in the study. Participants all reported having normal hearing. In addition, participants had minimal music training (*M* = 2.60 years, *SD* = 3.95 years, Range: 0-14 years) and minimal dance training (*M* = 1.80 years, *SD* = 2.63 years, Range: 0-8 years).

Procedure

Experiment 2 used the same methods as Experiment 2, with the exception that the beat-ambiguous rhythm was presented for 8, 12, or 16 measures. In the fast condition (IOI=200 ms), this resulted in trials that are 21.6, 26.4, or 31.2 seconds long, respectively. In the slow condition (IOI=300 ms), this resulted in trials that are 32.4, 39.6, or 46.8 seconds long, respectively.

Results and Discussion

As in Experiment 1, I expected that listeners would experience a strong percept of the beat during the musical context and they would maintain that percept during the ambiguous rhythm. The repeated measures ANOVA revealed an overall main effect of trial type, such that participants responded *matching* significantly more in matching trials than non-matching trials, $F(1,19) = 15.58$, $p = .001$, $\eta p^2 = 0.45$ (See Figure 5). There was no main effect of meter ($F(1,19)$

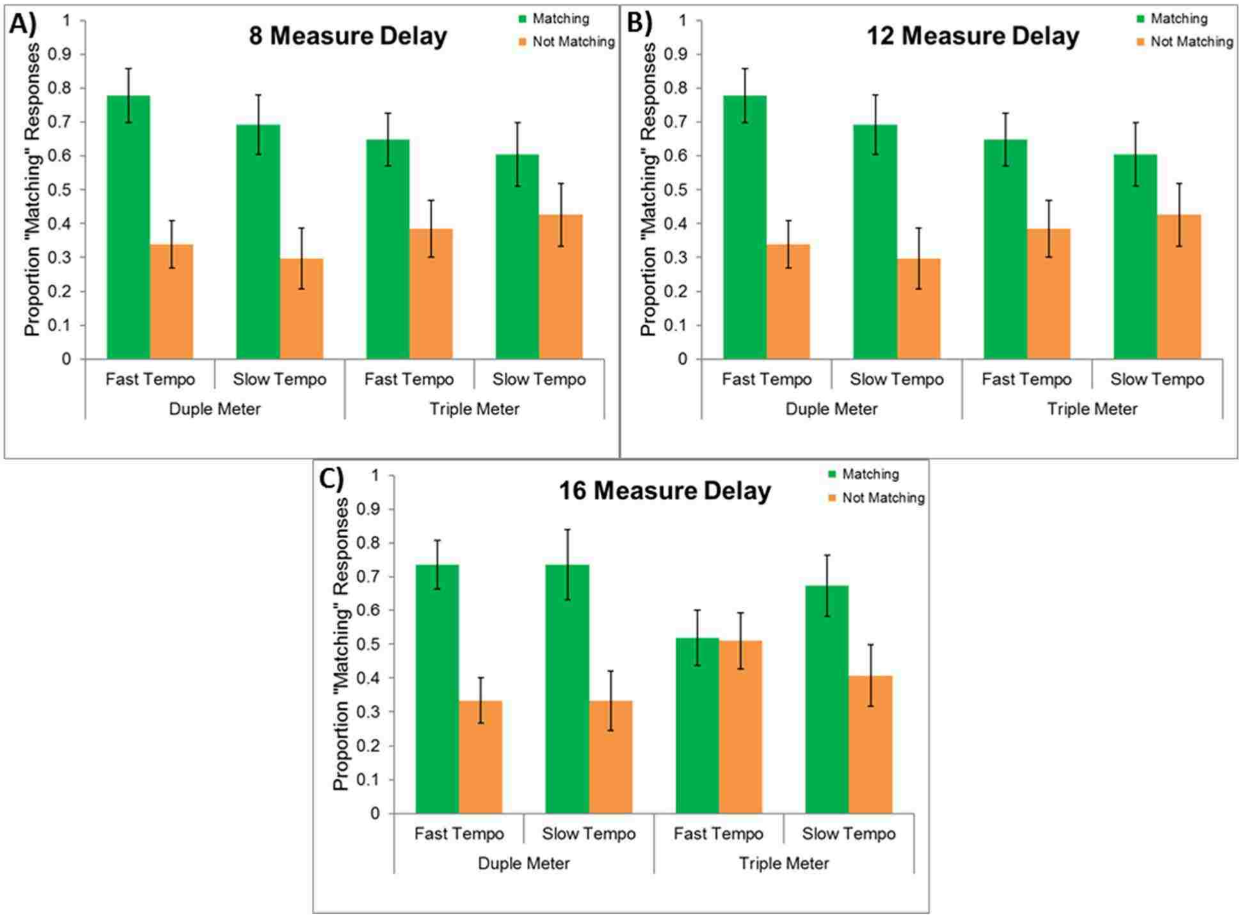

Figure 5. Experiment 2 results. Proportion of "matching" responses by meter, tempo, and trial type for A) 8 measure delay, B) 12 measure delay, and C) 16 measure delay. Perfect performance in any condition would be 100% in the Matching trials (green bar) and 0% in the Not Matching trials (orange bar).

= 1.14, p = .300, ηp^2 = 0.06), tempo (F(1,19) = 0.04, p = .843, ηp^2 = 0.00), or delay (F(1,18) = 0.478, p = .628, ηp^2 = 0.05) suggesting that participants did not perform better in any given condition. There were no significant interactions. This is surprising, considering Experiment 1 revealed a Trial Type x Meter x Tempo interaction. I would have predicted that this interaction would have been present in Experiment 2 as well, demonstrating that listeners perform better when the IBI is 600ms. However, this was not the case. It is possible that this interaction with tempo is fragile and does not replicate across studies. It could also be that having an IBI close to the average preferred tempo for adult listeners is helpful in this task for shorter delays, but not longer delays. Since these effects were observed across different groups of subjects, future studies should explore this effect further by having participants complete all delay conditions between 0 measures and 16 measures.

CHAPTER 5

EXPERIMENT 3

Participants

Twenty-two participants (9 female) were recruited from the UNLV Psychology Participant Pool (M_{age} = 19.77 years, *SD* = 2.45 years, Range: 18 – 26 years). Participants had minimal music training (*M* = 2.27 years, *SD* = 2.39 years, Range: 0 - 7 years) and minimal dance training (*M* = 0.64 years, *SD* = 1.68 years, Range: 0 - 7 years). Six additional participants were excluded: 3 because of excessively messy EEG data, 1 because he reported tapping his finger to keep track of the beat during the ambiguous rhythm, and 2 because of a recording error with the EEG equipment. All participants had normal hearing, demonstrating hearing thresholds below 25 dB for Frequencies between 250 Hz and 8000 Hz in both the left and right ear. All participants received course credit for participating in the study.

Procedure

We used the same methods in Experiment 3 as in Experiment 1, with the exception that the ambiguous phase was always 16 measures. Because this experiment aimed to investigate neural activity by transforming it into the frequency domain, several repetitions of the beat-ambiguous rhythm are needed to perform fast-Fourier transforms (FFTs) that accurately capture the periodic neural activity with sufficient control for noise. Therefore, it is most efficient to present the beat-ambiguous rhythm for as long as possible before presenting the behavioral probe (i.e. the drumming click track). In Experiment 2, participants demonstrated the ability to maintain a beat percept for up to 16 measures of the ambiguous rhythm, so this delay length was used in Experiment 3.

Electrophysiological Recording. EEG recordings were collected using a Biosemi ActiveTwo systems. A 64-electrode cap was placed on the scalp according to the International 10/20 system. Eye and movement artifacts were monitored using eight additional electrodes places on the outer canthus of each eye, the inferior and superior areas of the left orbit, the left and right mastoids, and approximately 1/2 centimeter in front of the preauricular point of the left and right ear. The signals were recorded using an average reference amplified and low-pass filtered at 500 Hz and digitized using a sampling rate of 1024 Hz.

Electrophysiology Analysis. The continuous EEG recordings were filtered using a 0.1 Hz high-pass Butterworth zero-phase filter to remove very slow drifts in the recorded signals. Epochs lasting the length of Phase 2 of each trial (the ambiguous rhythm, not including the probe) were obtained. The length of the epoch depended on the tempo condition, with fast trial epochs being 19.2 seconds (i.e. 16 measures, where 1 measure = 1.2 seconds) and slow trial epochs being 28.8 seconds (i.e. 16 measures, where 1 measure = 1.8 seconds). All EEG processing steps were performed using Letswave (Mouraux and Iannetti, 2008), which runs in Matlab (The MathWorks).

For each subject and condition, EEG epochs were averaged across trials. This was done to enhance the signal-to-noise ratio by reducing the contribution of activities not strictly phase locked to the stimulus across trials. To investigate periodic neural activity occurring during subjective beat perception, the average waveforms were then transformed in the frequency domain using a discrete Fourier transform (Frigo and Johnson, 1998). This created a frequency spectrum of signal amplitude (µV) ranging from 0 to 500 Hz with a frequency resolution of 0.052 Hz in the fast condition and a frequency resolution of 0.035 in the slow condition (Bach and Meigen, 1999). This analysis procedure was used in similar studies, allowing for comparison of the EEG epochs to the beat frequencies in the auditory stimuli presented (Nozaradan et al., 2011, 2012).

To obtain valid estimates of the SS-EPs, I removed unwanted noise by subtracting the average amplitude measured at neighboring frequency bins. The support for this procedure is that in the absence of an SS-EP, the signal amplitude at a given frequency bin should be similar to the signal amplitude of the mean of the surrounding frequency bins (Mouraux et al., 2011; Nozaradan et al., 2011; Nozaradan et al., 2012). Thus, performing this subtraction removes baseline activity at the frequency bin of interest, leaving only the activity directly related to the SS-EP. At each frequency bin, I subtracted the average of activity 3-5 bins away in either direction (i.e. -5 to -3 bins and +3 to +5 bins). In addition, because we were interested in effects pertaining to the frequency domain and artifacts produced by eye blinks or muscle movements do not occur at a regular frequency, these artifacts would be subtracted out as noise during this transformation of the data. In addition, traditional methods for rejecting artifacts requires rejection of trials with large eyeblinks, which are nearly unavoidable in the current paradigm, where trials were 31.2s or 46.8s in length. Thus, trial rejection based on eyeblinks was not performed for the steady state response analyses.

Next, I extracted SS-EPs in the obtained frequency spectrum for frequencies of interest: 1.11 Hz, 1.67 Hz, 2.50 Hz, 3.33 Hz, and 5.00 Hz. This allowed me to compare the frequencies of the measured SS-EPs to the stimulus properties of the beat-ambiguous rhythm (stage 2), during which I would expect SS-EPs to be occurring at the same frequencies as the subjective beat imposed by the preceding musical stimulus (stage 1). I expected that the SS-EPs observed would be related to the subjective beat frequencies suggested by the musical stimulus presented in each trial. The fast tempo condition has a stimulus frequency of 5.00 Hz (duple beat pattern: 2.50 Hz;

triple beat pattern: 1.67 Hz), and the slow tempo condition has a stimulus frequency of 3.33 Hz (duple beat pattern: 1.67 Hz; triple beat pattern: 1.11 Hz). It was thus expected that SS-EPs with higher amplitudes would be found at the duple frequencies when a duple context preceded the ambiguous rhythm, and at the triple frequencies when a triple context preceded the ambiguous rhythm. The magnitude of the SS-EPs was estimated by taking the maximum amplitude measured occurring at the beat-related frequency. Similar to previous studies, SS-EP magnitudes were averaged across all scalp electrodes for each trial type and participant (Nozaradan et al., 2011, 2012).

Overall, it was expected that if listeners sustained their beat perception throughout the ambiguous phase and responded accurately on the task, then they would also show neural activity that reflects the beat pattern they sustained. Accuracy is defined as the proportion of correct responses, where a correct response on trials where the probe matches the context (i.e. Matching Trials) is “Matching”, and a correct response on trials where the probe does not match the context (i.e. Nonmatching Trials) is “Not Matching”. If listeners failed to sustain this perception of the beat, it is expected that these listeners would not show neural activity that relates to any specific beat pattern. Thus, only correct trials were included in the ANOVA investigating whether SS-EPs during the beat-ambiguous rhythm differ between the duple beat percept (i.e. duple context) and the triple beat percept (i.e. triple context).

Correlation analyses were used to test for a relation between beat perception, as measured by accuracy on the behavioral task, and the periodic neural activity, as measured by the SS-EP amplitudes. The frequency related to the beat depends on both tempo and meter, so correlations were done separately for the four meter/tempo conditions: duple fast, duple slow, triple fast, and triple slow. In addition, I was interested in whether SS-EP amplitudes would predict accuracy on a trial-to-trial basis. To investigate this, I used generalized estimating equations to determine whether correct perception of the beat on individual trials was predicted by the amplitude of the beat-related SS-EPs on those trials. All trials were included for all correlational analyses and the generalized estimating equations.

Results and Discussion

Behavioral Results. Similar to the results of Experiments 1 and 2, the repeated measures ANOVA revealed an overall main effect of trial type, such that participants responded *matching* significantly more in matching trials than non-matching trials, $F(1,21) = 23.29$, $p<.001$, $\eta p^2 = .53$ (See Figure 6). There were no main effects of meter ($F(1,21) = 1.90$, $p = .183$, $\eta p^2 = 0.08$) or tempo ($F(1,21) = 2.11$, $p = .161$, $\eta p^2 = 0.09$), suggesting that participants did not perform better in any given condition. There were also no significant interactions.

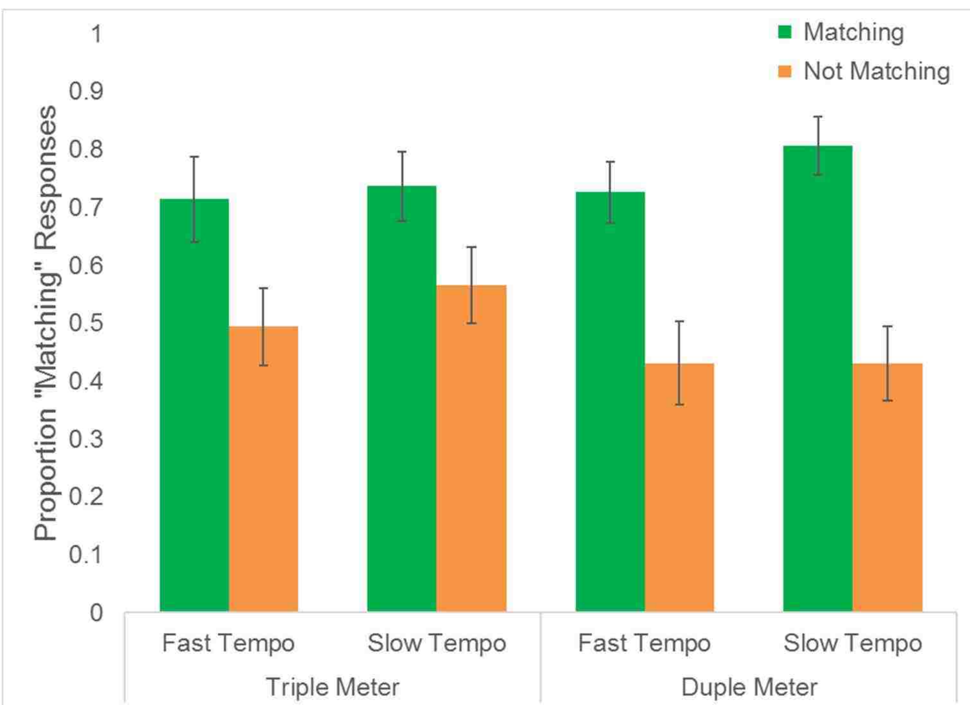

Figure 6. Experiment 3 behavioral results. Proportion of "matching" responses by meter, tempo, and trial type. Delay was 16 measures for all trials. Perfect performance in any condition would be 100% in the Matching trials (green bar) and 0% in the Not Matching trials (orange bar).

Electrophysiological Results. A 2 × 2 × 2 (Tempo [fast, slow] x Context [duple, triple] x Beat Frequency [duple, triple]) repeated measures ANOVA was used to determine whether SS-EPs elicited were selectively enhanced at the expected frequencies. This revealed a significant Beat Context x Beat Frequency interaction, $F(1,19) = 4.54$, $p = .046$, $\eta p^2 = 0.19$ (See Figure 7).

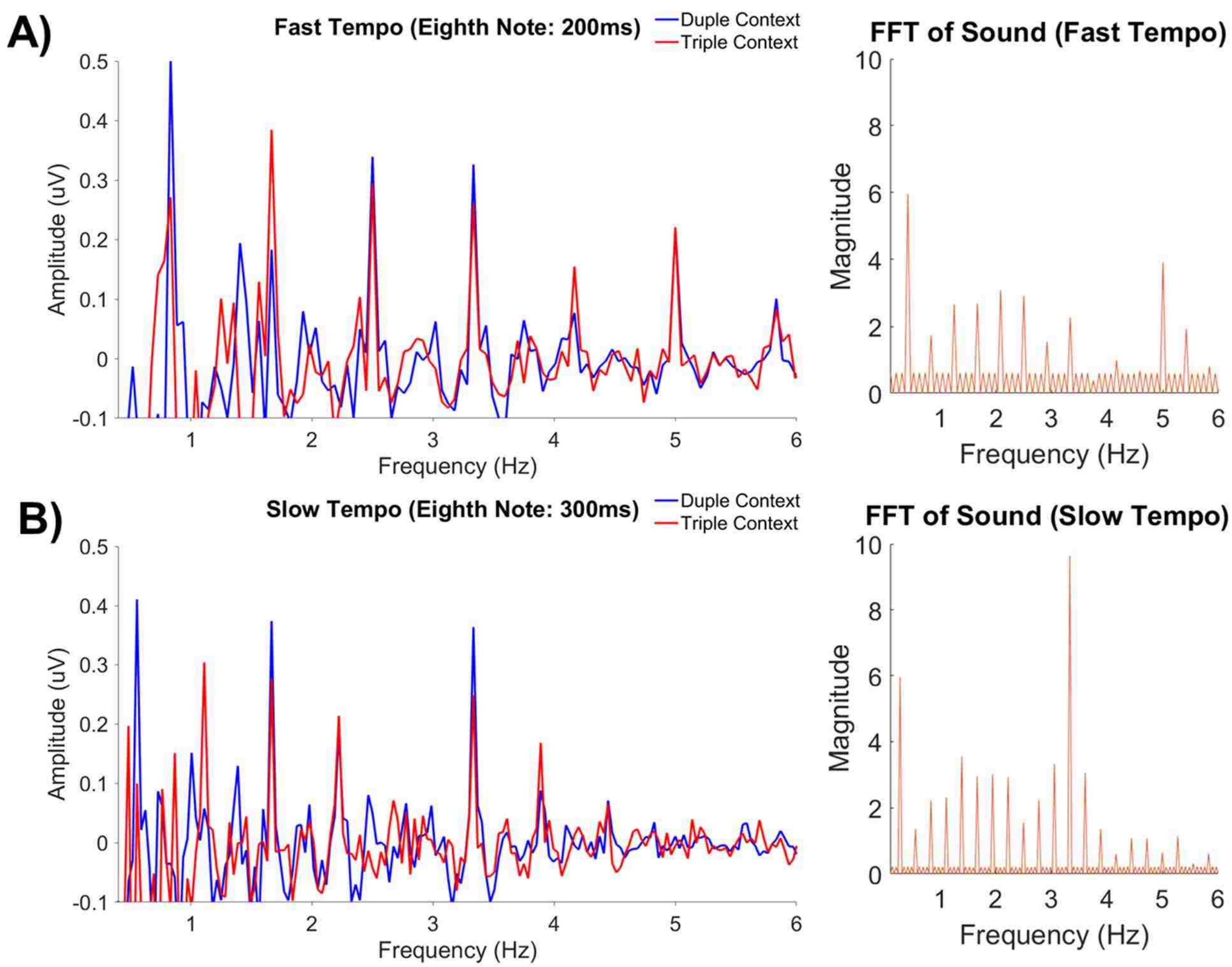

Figure 7. Experiment 3 SS-EP results. Amplitude (in microvolts) is plotted as a function of Frequency (in Hertz). Waveforms are averaged across all 64 scalp electrodes. Only trials where the participant responded correctly (i.e. accurately accepted a matching probe or accurately rejected a mismatching probe) are included in the averages. Trials where participants heard a duple meter musical excerpt in the context are plotted in blue, and trials where participants heard a triple meter musical excerpt in the context are plotted in red. Hilbert functions were performed on the stimuli to see what frequencies are represented in the physical stimulus. A) SS-EPs for the Fast tempo (left) and the corresponding Hilbert function from the stimulus (right). At the fast tempo, a duple beat pattern would be heard at 2.5 Hz (blue arrow), and a triple beat pattern would be heard at 1.67 Hz (red arrow). The stimulus frequency is 5 Hz (black arrow). B) SS-EPs for the Slow tempo (left) and the corresponding Hilbert function from the stimulus (right). At the slow tempo, a duple beat pattern would be heard at 1.67 Hz (blue arrow), and a triple beat pattern would be heard at 1.11 Hz (red arrow). The stimulus frequency is 3.33 Hz (black arrow).

Specifically, this interaction revealed that SS-EPs at the duple frequency were higher when the context was duple (M = 0.41 μV, SD = 0.07 μV) compared to when the context was triple (M = 0.21 μV, SD = 0.06 μV), and SS-EPs were higher at the triple frequency when the context was triple (M = 0.47 μV, SD = 0.11 μV) compared to when the context was duple (M = 0.31 μV, SD = 0.06 μV). There were no significant main effects of tempo ($F(1,19) = 0.577$, $p = .457$, $\eta p^2 = 0.03$) or context ($F(1,19) = 3.37$, $p = .082$, $\eta p^2 = 0.15$), and there were no other significant interactions. This result demonstrates that periodic neural activity is related to the subjective beat percept experienced while listening to the beat-ambiguous rhythm. No significant main effects of meter or tempo suggests that SS-EP amplitudes do not significantly differ overall between duple and triple meter or between the fast and slow tempo.

Relation Between Neural Activity and Perception. I expected to find that the behavioral performance of listeners may be related to their neural activity, such that individuals with higher amplitudes of SS-EPs occurring at the beat frequency would also show better performance on the behavioral task. Results demonstrated no significant correlations between duple fast accuracy and the duple fast SS-EP amplitude ($r = 0.33$, $p = .130$), duple slow accuracy and the duple slow SS-EP amplitude ($r = -0.12$, $p = 0.590$), triple fast accuracy and the triple fast SS-EP amplitude ($r = 0.24$, $p = 0.284$), or triple slow accuracy and the triple slow SS-EP amplitude ($r = 0.33.$, $p = 0.137$)). This suggests that across participants, averaged SS-EP amplitudes were not significantly related to accuracy on this beat induction task.

However, it is still possible that brain activity can be used to predict performance on a trial-to-trial basis. It could be that within-subject variation in brain activity is predictive of performance on individual trials, but this is masked when correlations are run at the group level. Thus, I ran a Generalized Estimating Equations analysis to investigate whether accuracy (i.e.

whether the participant responded correctly or incorrectly) on trials could be significantly predicted by brain activity, and whether this varied based on the trial manipulations of meter and tempo. Individual trials were coded as 0 (incorrect) or 1 (correct) based on participant responses. Then, I extracted SS-EP amplitudes for each trial at the beat-related frequency. The following parameters were set for the analysis: subject variable: subject ID, within-subject variables: trial number, type of model: binary logistic, dependent variable: accuracy, factors (i.e. categorical variables): tempo, meter, covariates (i.e. continuous variables): beat frequency. Results demonstrated that the 3-way Beat Frequency x Meter x Tempo interaction was a significant predictor of accuracy (Wald $\chi^2 = 11.55$, $p = .009$), while beat frequency alone was not a significant predictor (Wald $\chi^2 = 0.70$, $p = .403$). As shown in Figure 8, the interaction shows that higher SS-EP amplitudes at the beat frequency predicts much higher performance on triple fast and duple fast trials, somewhat higher performance on triple slow trials, but lower performance on duple slow trials. This is surprising, considering that duple slow trials have an IBI of 600ms, which should be a preferred tempo for hearing the beat. Further studies are needed to understand the mechanisms behind this pattern of results. Regardless, this is some of the first evidence that SS-EPs can be used to predict beat perception.

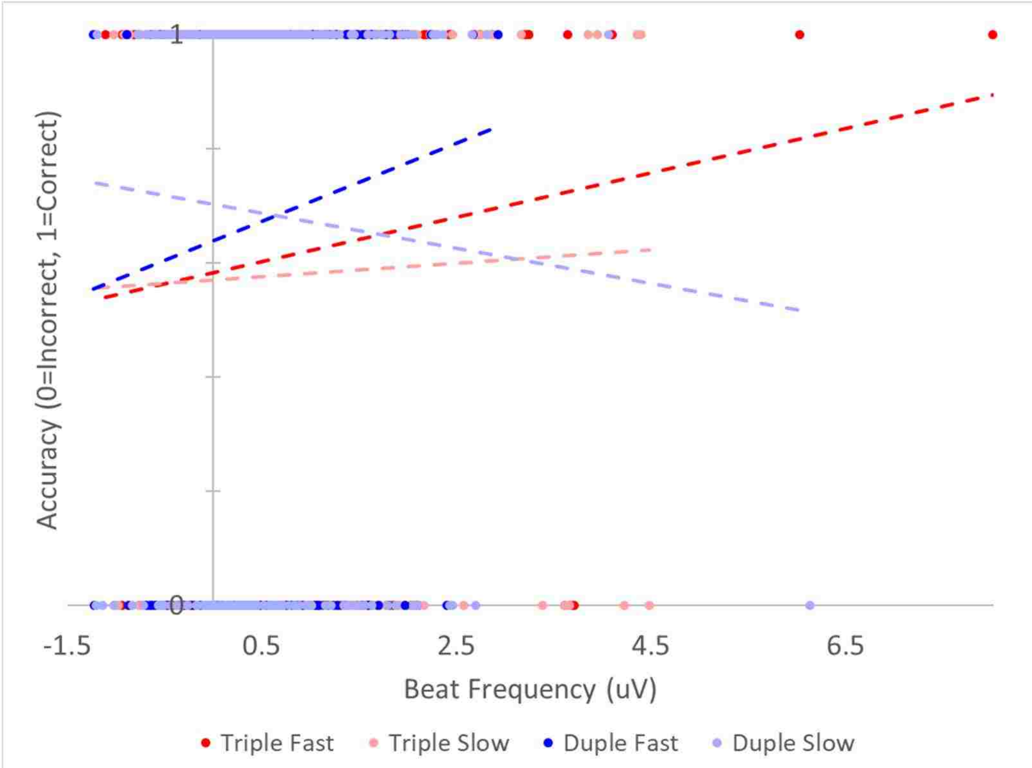

Figure 8. Experiment 3 results of generalized estimation equation analysis. Accuracy (0=Incorrect, 1=Correct) is plotted as a function of beat frequency (in microvolts). Data points represent individual trials from all participants. Trial type is plotted based on the two factors: meter and tempo. Triple meter is plotted in red and duple meter is plotted in blue. The fast tempo is plotted in darker shades, and the slow tempo is plotted in the lighter shades.

CHAPTER 6

GENERAL DISCUSSION

The novel paradigm used in this project successfully demonstrated that a rich, ecologically valid stimulus can induce a strong beat percept and be used for measuring neural correlates of beat perception. Most previous research that has investigated sustained beat perception has been limited to listeners with music experience, due to the need to ask participants to imagine a particular beat pattern (Iverson, Repp, & Patel, 2009; Nozaradan et al., 2011). The paradigm in the current study did not rely on listeners having knowledge of musical terminology, thus allowing me to extend our knowledge on subjective beat perception to listeners without musical training. In addition, no study to date has investigated the relation between subjective beat perception and related neural activity directly. This paradigm collected behavioral responses on every trial, which were then directly compared to the neural responses collected on that same trial, allowing for the first relation of neural activity to listener perception.

In Experiments 1 and 2, I investigated the persistence and strength of subjective beat perception by investigating how long adult listeners could maintain the beat percept. Results demonstrated that listeners can maintain the beat for up to 16 measures of the beat-ambiguous rhythm (19.2 seconds in the fast condition and 28.8 seconds in the slow condition). This ability is impressive, as the beat-ambiguous rhythm can be perceived as having two different beat patterns, and thus one could predict that the ability to hold on to a specific pattern would diminish over time. It is possible that listeners will continue to perceive the same beat pattern that was supported by the context, regardless of how long one presents the ambiguous rhythm. Future studies will need to extend the trials to even longer delay conditions to see if this is true. In addition, one other way to extend these findings would be to introduce counter-evidence during the ambiguous rhythm that contradicts the beat percept that is being maintained. It would be hypothesized that if the counter-evidence supported a different beat pattern that fits with the ambiguous rhythm, the listener would re-organize their beat percept and switch to the beat-pattern supported by the counter-evidence. However, if the counter-evidence does not support either of the possible beat patterns, it is possible that subjective beat perception will survive and will not be altered.

In Experiment 3, I investigated whether rhythmic neural activity reflects listeners' subjective beat perception by A) measuring beat perception with the same behavioral task as Experiment 1 and 2 and B) measuring periodic neural activity as it occurs while the listeners sustains their percept of the beat. Overall, results showed higher SS-EPs at beat-related frequencies, compared to non-beat-related frequencies. This finding is interesting because the differences in these SS-EPs were demonstrated during the same auditory stimulus. Thus, any differences present in the neural activity are thought to originate from top-down processing of the auditory stimulus, such that listeners' perception of the beat affected the magnitude of the beat-related frequencies supported by that beat percept. This suggests that periodic neural activity generated in the brain may reflect an underlying temporal mechanism that gives way to subjective beat perception. This process is what allows us to predict when the beat is going to occur and coordinate our movements, such as is necessary for performing an instrument, dancing to music, or even tapping to music on your steering wheel. In addition, the participants in this study had a very minimal amount of music training. This is the first study to demonstrate modulations of steady-state responses in the brain that reflect beat perception in non-musicians.

Results demonstrated that the correlational relationship between the composite SS-EP amplitude and trial accuracy was not significant across participants for either duple or triple meter. To further investigate whether performance on the beat induction task could be predicted by the corresponding brain activity, I used a binary logistic generalized estimating equation to model trial-by-trial variation in performance, with beat frequency amplitude, meter, and tempo entered as potential predictors. The strongest model found indicated that the three-way Meter x Tempo x Beat Frequency interaction was a strong predictor of performance on this task. This is a significant contribution to the field of auditory neuroscience because this is the first evidence of a relationship between steady state responses in the brain and perception in a beat perception task. This result suggests that enhanced amplitudes for SS-EPs related to the beat allows individuals to maintain the beat better during the induction phase (Phase 2), which then allows them to more accurately judge whether the probe is correct or incorrect. It is important to note that while the model was significant, the prediction made by the model was not what we expected to find for all trial types. Overall, it seems that beat-related SS-EPs has a positive relationship with performance when the tempo was fast. However, the triple slow beat-related SS-EP amplitudes were only slightly predictive of better performance. Furthermore, the duple slow beat-related SS-EP amplitudes had a negative relationship with performance, such that higher SS-EP amplitudes were related to worse performance on the task. These results suggest that the mechanisms underlying the relationship between beat-related frequency enhancement of brain activity and perception may differ depending on stimulus qualities, such as tempo. It also suggests that researchers should be cautious in claiming that beat-related SS-EP responses that are enhanced lead to enhanced perception. Importantly, this study demonstrates that it is possible to model rhythm perception using neural activity, regardless of the direction of the relationship, and this is a crucial next step to being able to better characterize neural mechanisms underlying beat processing.

The results from the current study support previous work demonstrating enhanced SS-EPs at frequencies related to metrical levels in the stimulus. Studies have demonstrated not only larger amplitudes for strong beats in auditory rhythms (Nozaradan et al., 2011, Nozaradan et al., 2012), but also stressed syllables in language (Ding, Melloni, Zhang, Tinn, & Poeppel, 2016), and even in an imagery task using visual stimuli, in which participants imagined flashes as being more salient on strong beats of a "visual rhythm" (Celma-Miralles, de Menezes, & Toro, 2016). While these studies evidenced neural responses that are possibly related to perception, no one to date has collected behavioral data simultaneously with EEG data. In contrast, my study provides support for the notion that SS-EP responses do indeed reflect participant perception to some extent, at least in the auditory modality with music. Future research should aim to replicate these previous findings with other types of stimuli by using a behavioral measure on each trial to investigate whether SS-EP enhancement can predict trial-by-trial perception more generally with stimuli besides those we used here.

Recent research has demonstrated that it is possible to measure rhythm-related SS-EPs using EEG with 6- and 15- month old infants while they listen to an auditory rhythm (Cirelli, Spinelli, Nozaradan, & Trainor 2016). While this study found a relationship between parent music training and beat-related SS-EPs, there is still no evidence that the infants were actually perceiving the beat. In addition, this study found enhancements at frequencies supporting multiple beat patterns, which makes it unclear whether the infants were perceiving a particular beat pattern. Previous behavioral infant studies have suggested that infants are sensitive to differing beat patterns in music (Hannon & Johnson, 2005), and even newborns may be sensitive to the downbeat of a musical measure (Winkler, Háden, Ladinig, Sziller, & Honing, 2009). Future work should design a paradigm that measures both perception and neural activity in infants while listening to a rhythm with a clear beat. One possibility would be to use a conditioned head turn task, such that babies are trained to look one way when they hear one beat pattern (i.e., duple) and another way when they hear another beat pattern (i.e., triple), while simultaneously recording EEG. This would allow for one to investigate whether infants are A) sensitive to the beat and B) whether this sensitivity is reflected in beat-related frequencies in their neural activity.

While the evidence we have presented here suggests that better maintenance of a beat percept leads to enhancement at beat-related frequencies, it is also possible that overall better encoding of the auditory stimulus leads to better performance on beat-related tasks. Previous research has demonstrated a relationship between not only slow frequencies that correspond directly to the beat, as was evidenced here, but also frequencies in beta and gamma bands (Fujioka, Trainor, Large, & Ross, 2009; 2012). These previous studies have demonstrated that neural activity at beta frequencies is modulated when humans hear an isochronous stimulus, such that upcoming events are predictable. Power at these beta frequency bands is enhanced preceding a predictable event, and is then decreased following the event. This might be reflective of endogenous mechanisms that dynamically direct attention to predicted points in time where events are expected to occur based on prior information. While it has been shown that modulations in beta bands are representative of efficient mechanisms for processing rhythmic stimuli, such as those with a perceptible beat pattern, few studies have investigated whether beta band activity is modulated during a *beat induction* task.

Future studies should aim to create a more comprehensive model of predictors for beat perception, which should account for not only slow-frequency modulation (i.e. SS-EPs) and fast-frequency modulation (i.e. beta band activity), but also source localization. It is unclear where this neural activity is being generated in the brain. In a recent study, intracranial electrodes were used to measure brain activity generated in the auditory cortex while participants imagined one of two beat patterns, similar to the experiment conducted in the 2011 paper by Nozaradan and colleagues (Nozaradan et al., 2016). Results demonstrated that not only did they find significant enhancements at beat-related SS-EPs, but this effect seemed to be coming predominantly from the auditory cortex. Still, they were unable to conclude whether other areas contributed to this effect. Previous research has suggested that not only is the auditory cortex involved in processing the beat in music, but so are other areas including the premotor cortex and cerebellum (Chen, Penhune, & Zatorre, 2008; Chen, Zatorre, & Penhune, 2006), as well as the supplementary motor area and basal ganglia Grahn & Brett, 2007; Grahn, 2012). It is certainly possible that a combination of these areas is contributing to the effects that have been demonstrated here. Future work should aim to utilize other tools that are better equipped to investigate the source of this activity, such as function magnetic resonance imaging (fMRI), magnetoencephalography (MEG), and transcranial magnetic stimulation (TMS). It is hypothesized that neural mechanisms for predicting when prominent auditory events are going to occur, such as those occurring on the beat, allow us to synchronize behavior, such as motor movement, with the rhythm. It is certainly then possible that motor areas play a large role in the modulation of oscillatory activity that, as we see here, can be used to reflect beat perception. One possible study could aim to target supplementary motor area (SMA) with repetitive TMS (rTMS) to attempt to knock out or temporarily "lesion" this area, and then have participants complete the beat induction task while recording EEG. I would predict that while control participants (TMS delivered to a control brain area that is not expected to contribute to beat perception) would demonstrate similar results as this study, the stimulated group would perform worse on the task and would also show less or no enhancement of beat-related SS-EPs.

While the results discussed here demonstrate that by adulthood, listeners can accurately maintain a beat percept once the auditory stimulus becomes beat-ambiguous, little is known about whether listeners at other stages of development, such as infants or children, are capable of this. The current paradigm was designed to be kid-friendly so that it can be used across a large age range. Future work aims to use this paradigm to explore subjective beat perception in child listeners and compare performance to adult listeners. Previous research has shown that children as young as 4 years old can perceive the beat (Anvari, Trainor, Woodside, & Levy, 2002). It is possible that because children can perceive the beat, they also have the ability to maintain the beat, and will thus perform well on the subjective beat task. However, it is also possible that the ability to maintain the beat without any physical support in the auditory stimulus relies on more complex cognitive processes that have not yet developed in young children. If this is the case, then we would expect young children to have lower performance on the subjective beat task. Future work aims to map the developmental timeline of subjective beat perception.

Overall, the current study provides evidence that beat induction can be related to neural activity recorded non-invasively, and this can be directly related to perception on a trial-to-trial basis. This study demonstrated that A) a rich musical stimulus can be used to induce a particular beat pattern in a beat-ambiguous rhythm, B) once a beat-pattern is induced, adult listeners with no music training are able to maintain that beat percept for an extended period of time (up to ~30 seconds), C) SS-EPs are enhanced at frequencies corresponding to the beat when the beat is accurately maintained for the entire beat-ambiguous rhythm, and D) trial-to-trial variation in accuracy on a beat induction task can be predicted by trial factors such as meter and tempo, as well as the amplitude of the beat-related SS-EP. This study provides the first evidence of a relationship between beat-related steady-state responses and perception. Future work should replicate this relationship, as well as further investigate the source of this neural activity in the brain.

APPENDIX I

DEMOGRAPHIC QUESTIONNAIRE

(All information will be kept confidential)

*Today's Date:*______________*Experimenter:*________________
*Subject#:*____________*Run#:*_______*Time:*__________

Background Information

Age:________________

Participant Initials: ______________________

Sex: O Male O Female

Handedness: O Right O Left O Ambidextrous

Year in school: O Fresh. O Soph. O Jr. O Sr. O Non-degree seeking

Are you Spanish/Hispanic/Latino? (*Check one)*

O No, not Spanish/Hispanic/Latino
O Yes, Puerto Rican
O Yes, Mexican, Mexican-American, Chicano
O Yes, Cuban
O Yes, other Spanish/Hispanic/Latino:
____

What is your race? *Check all that apply*

☐ White
☐ Asian Indian
☐ Korean
☐ Native Hawaiian
☐ Samoan
☐ Black/African American
☐ Chinese
☐ Vietnamese
☐ Guamanian/Chamorro
☐ Some other race: __________________________
☐ American Indian/Alaska Native
☐ Filipino ☐ Japanese
☐ Other Asian: _________________________
☐ Other Pacific Islander: _________________

Mother's Highest Education Level?

O No H.S. diploma O H.S. diploma O Some college
O 4-year College degree O Graduate school degree O Technical school

Father's Highest Education Level?

O No H.S. diploma O H.S. diploma O Some college
O 4-year College degree O Graduate school degree O Technical school

Hearing & Medical History

Have you ever had frequent ear infections (more than three per year)?

O Yes, at what age(s)? ______________________
O No

Have you ever had pressure equalizing tubes in your ears?

O Yes, at what age(s)? ______________________
O No

Do you have a hearing impairment?

O Yes, describe: ___________________________
O No

Do you have a vision impairment?

O Yes, if so:
Is it corrected via contacts or glasses? O Yes O No
Are you currently wearing your corrective lenses? O Y
O No

Do you have a cold today? O Yes O No
Do you have an ear infection today? O Yes O No

Have you been in any unusually noisy environments?

O Yes, describe: ___________________________
For how long? ______________________
O No

Have you ever been diagnosed with a neurological/psychological disorder (ADHD, epilepsy, etc.)?

O Yes, please describe: ________________________
O No

If you are participating in an EEG study, please answer the following questions. Otherwise, s

Do you take any medications regularly?

O Yes, please list: ______________
O No

Have you ever had a serious head injury (concussion, unconsciousness, etc.)?

O Yes, please describe: ___________
O No

Language Information

Country of Your Birth: ______________________________

Country of Parents' Birth: Mother:________________Father:_

Language learned as child: ______________________________

Age English learned, if not first: ______________________________

Do you speak a language other than English?

O Yes, which ones? _____________
O No

Non-English language competence:

Language: _______________ O N/A O Beginner O Intermediate C
Language: _______________ O N/A O Beginner O Intermediate C
Language: _______________ O N/A O Beginner O Intermediate C

Do you consider yourself bilingual? O Yes O No

What do you consider your dominant/main language: ______________________________

What percentage of the time do you speak your main language(s) (e.g. 50%, 30%, etc.): ______________________________

Have you lived in any country outside of the United States of America?

O Yes
Where? ______________________
For how long? ________________
O No

Describe your exposure to music and/or dance there: ______________________________

Music Information

Do you sing or play an instrument? O Yes O No

How would you describe yourself as a musician (please choose ONE):

O Occasional Musician *(less than weekly*
O Recreational Musician *(weekly practice*
O Serious Amateur Musician *(extensive c activity)*
O Professional Musician (*paid to perform*

Type of music practiced (Classical/Jazz/Folk/etc.)? ______________________________

Instrument(s): ______________________________

Have you ever played an instrument in an ensemble (i.e. school band, orchestra, etc.)? O Yes O No

Type of Ensemble: (check all that apply)
O School Band O Private Institute Band O Self-Arranged Ensembl
O School Orchestra O Private Institute Orchestra O Other ______________

Beginning at what age? _________________ No. of years? _____________________________

Have you ever sung in an ensemble? O Yes O No

Type of Ensemble: (check all that apply)
O School Choir O School Theater Group
O Self-Arranged Ensemble O Other ___________________________

Have you ever taken private music lessons? O Yes O No

Beginning at what age? ___________________________________ No. of years? _____________________________

Solo or group lessons? (please describe if group): ____

Are you currently taking private lessons?
O Yes, days per week: _____________hours per day:____
Instrument: _______________________________________
O No

How often do you play/sing music on a weekly basis? O 1 day O 2-3 days O 4-5 days O 6-7 days

How many hours per day do you practice music (on average)? ____

How many hours per day do you play music for recreation (on average)? ____

Have you performed or taught music professionally (i.e. for pay)?
O Yes; for how many years? ____________________
O No

Dance Information

Do you dance (recreationally, formally, etc.)? O Yes O No

How would you describe yourself as a dance (please choose ONE):
O Occasional Dancer *(less than weekly dancing for fun or p*
O Recreational Dancer *(weekly practice or recreational dan*
O Serious Amateur Dancer *(extensive commitment to practi recreational dance activity)*
O Professional Dancer (*paid to perform and/or teach dance*

Type(s) of dance practiced:
O Folk O Ballet O Hip-Hop O Middle Eastern O Con
O Jazz O Asian O Ballroom OFlamenco/Latin O Con
O Tap O Lyrical O Other(s): _____________________

What age did you start dancing? _____ No. of years? ________________________________

Have you ever participated in formal dance lessons?
O Yes O No
Beginning at what age? _________________________
No. of years? ________________________________

Are you currently taking dance classes or lessons?
O Yes, hours per week: ____________________
Type of dance: _________________________

How often do you dance on a weekly basis? O 1 day O 2-3 days O 4-5 days O 6-7 days

How many hours do you practice dance per day (on average)?	____________________
How many hours do you dance recreationally per day (on average)?	____________________
Have you danced professionally (i.e. for pay)?	O Yes; for how many years? ______ O No

Other Information

Can you read music?	O Yes O No
Have you ever taken music courses at the university level?	O Yes, which course(s)? ______ O No
Do you have formal training in music theory (classes or self-taught)?	O Yes O No
If so, how many years?	O 0.5 O 1 O 2 O 3 O 4-6 O 7+
Do you have absolute pitch? (i.e. if someone played a note on the piano, you could name the note without looking)	O Yes O No O Don’t K
How many hours per week do you listen to music (on average)?	____________________
What types of music do you listen to?	____________________
How much music did you listen to growing up (i.e. hours per week)?	____________________
I have gotten goosebumps/shivers from listening to music before.	O Yes O No
Are any of your family members musicians?	O Yes, who: ______ O No
Are any of your family members dancers?	O Yes, who: ______ O No
During what other activities do you like to listen to music?	Please list: ______ ____________________
Do you exercise regularly?	O Yes O No
How many days per week do you exercise?	O 1 day O 2-3 days O 4-5 days O
Hours per day when you exercise:	____________________
Do you like to listen to music when you exercise?	O Yes O No
If so, what kind(s) of music?	____________________

Thank you for your participation!

APPENDIX II

IRB APPROVAL

UNLV Social/Behavioral IRB - Expedited Review
Continuing Review Approved

DATE:	January 13, 2017
TO:	Erin Hannon
FROM:	UNLV Social/Behavioral IRB
PROTOCOL TITLE:	[711149-13] Auditory Cognition in Adult Listeners
SUBMISSION TYPE:	Continuing Review/Progress Report
ACTION:	APPROVED
APPROVAL DATE:	January 13, 2017
EXPIRATION DATE:	January 12, 2018
REVIEW TYPE:	Expedited Review

Thank you for submission of Continuing Review/Progress Report materials for this protocol. The UNLV Social/Behavioral IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a protocol design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This IRB action will reset your expiration date for this protocol. The protocol is approved for a period of one year from the date of IRB approval. The new expiration date for this protocol is January 12, 2018.

PLEASE NOTE:
This protocol expired on January 9, 2017. Human subjects research is prohibited after that date and before the date of approval of this continuing review which is January 13, 2017. Upon approval, the research team is responsbile for conducting the research as stated in the protocol most recently reviewed and approved by the IRB.

Should there be *any* change to the protocol, it will be necessary to submit a **Modification Form** through ORI - Human Subjects. No changes may be made to the existing protocol until modifications have been approved.

ALL UNANTICIPATED PROBLEMS involving risk to subjects or others and SERIOUS and UNEXPECTED adverse events must be reported promptly to this office. Please use the appropriate reporting forms for this procedure. All FDA and sponsor reporting requirements should also be followed.

All NONCOMPLIANCE issues or COMPLAINTS regarding this protocol must be reported promptly to thi office.

This protocol has been determined to be a Minimal Risk protocol. Based on the risks, this protocol requires continuing review by this committee on an annual basis. Submission of the **Continuing Review Request Form** must be received with sufficient time for review and continued approval before the expiration date of January 12, 2018.

If you have questions, please contact the Office of Research Integrity - Human Subjects at IRB@unlv.ed or call 702-895-2794. Please include your protocol title and IRBNet ID in all correspondence.

Office of Research Integrity - Human Subjects
4505 Maryland Parkway . Box 451047 . Las Vegas, Nevada 89154-1047
(702) 895-2794 . FAX: (702) 895-0805 . IRB@unlv.edu

UNLV

UNLV Social/Behavioral IRB - Expedited Review
Continuing Review Approved

DATE:	November 21, 2017
TO:	Joel Snyder
FROM:	UNLV Social/Behavioral IRB
PROTOCOL TITLE:	[710883-30] Neural Mechanisms of Auditory and Visual Processing in Healthy Adults
SUBMISSION TYPE:	Continuing Review/Progress Report
ACTION:	APPROVED
APPROVAL DATE:	November 15, 2017
EXPIRATION DATE:	November 14, 2018
REVIEW TYPE:	Expedited Review

Thank you for submission of Continuing Review/Progress Report materials for this protocol. The UNLV Social/Behavioral IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a protocol design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This IRB action will reset your expiration date for this protocol. The protocol is approved for a period of one year from the date of IRB approval. The new expiration date for this protocol is November 14, 2018.

PLEASE NOTE:
Attached with this approval notice is the **official Informed Consent/Assent (IC/A) Form** for this study. Only copies of this official IC/A form may be used when obtaining consent. Please keep the original for your records.

Should there be *any* change to the protocol, it will be necessary to submit a **Modification Form** through ORI - Human Subjects. No changes may be made to the existing protocol until modifications have been approved.

ALL UNANTICIPATED PROBLEMS involving risk to subjects or others and SERIOUS and UNEXPECTED adverse events must be reported promptly to this office. Please use the appropriate reporting forms for this procedure. All FDA and sponsor reporting requirements should also be followed.

All NONCOMPLIANCE issues or COMPLAINTS regarding this protocol must be reported promptly to this office.

This protocol has been determined to be a Minimal Risk protocol. Based on the risks, this protocol requires continuing review by this committee on an annual basis. Submission of the **Continuing Review Request Form** must be received with sufficient time for review and continued approval before the expiration date of November 14, 2018.

If you have questions, please contact the Office of Research Integrity - Human Subjects at IRB@unlv.edu or call 702-895-2794. Please include your protocol title and IRBNet ID in all correspondence.

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Chen, J.L., Zatorre, R.J., & Penhune, V.B., (2006). Interactions between auditory and dorsal premotor cortex during synchronization to musical rhythms, *NeuroImage, 32*(4), 1771-1781.

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CURRICULUM VITAE

Karli Nave
nave@unlv.nevada.edu

EDUCATION:

Ph.D. (2019, *expected)*	University of Nevada, Las Vegas, NV Experimental Psychology, Emphasis: Development
B.S. (2014)	Michigan State University, East Lansing, MI Major: Psychology, Concentration: Cognitive Science
B.S. (2014)	Michigan State University, East Lansing, MI Major: Neuroscience, Concentration: Cognitive Science

ACADEMIC APPOINTMENTS:

- **Graduate Research Assistant,** 2017-2018
  University of Nevada, Las Vegas 2016-2017
  2015-2016
  2014-2015
- **Dean's Assistantship**, 2013-2014
  Michigan State University
- **Professorial Assistantship**, 2010-2012
  Michigan State University

HONORS AND RECOGNITION:

- **Barrick Graduate Fellowship** 2017-2018
  University of Nevada, Las Vegas
- **Summer Session Scholarship** 2017
  University of Nevada, Las Vegas
- **Student Travel Award** 2017
  International Conference for Music Perception and Cognition 2017 Meeting
- **Rebel Grad Slam 2016 – 1st Place Award** 2016
  UNLV 3-Minute Thesis Competition
- **College of Liberal Arts (COLA) Scholarship** 2016
  University of Nevada, Las Vegas
- **Student Travel Award** 2016
  International Conference for Music Perception and Cognition 2016 Meeting
- **College of Liberal Arts (COLA) Summer Research Stipend** 2016
  University of Nevada, Las Vegas
- **GPSA Research Fair – 2nd Place Poster** 2016

University of Nevada, Las Vegas

- **Rebel Grad Slam 2015 – Finalist** 2015
  UNLV 3-minute Thesis Competition
- **Student Conference Travel Award** 2015
  Graduate and Professional Student Association, UNLV
- **Student Travel Award** 2015
  Society for Music Perception and Cognition 2015 Meeting
- **College of Liberal Arts (COLA) Summer Research Stipend** 2015
  University of Nevada, Las Vegas
- **Edward Lovinger Psychology Scholarship** 2014
  University of Nevada, Las Vegas

PUBLICATIONS:

- Hannon, E.E., Lévêque, Y., **Nave, K.M.,** & Trehub, S. (2016). Language-specific rhythms are exaggerated in children's songs: A corpus analysis and perceptual study. *Frontiers in Psychology, 113 (48), 5212-5226.*

MANUSCRIPTS IN PREPARATION:

- **Nave, K.M.** & Hannon, E.E. (in review). Contemporary Approaches to Neuroscience in Music. In *The Science and Psychology of Music: From Mozart at the Office to Metallica at the Gym.*
- Hannon, E.E., Nave-Blodgett, J., & **Nave, K.M.** (in review). Musical rhythm and development: Current knowledge and future directions. *Child Development Perspectives.*
- **Nave, K.M.,** Hannon, E.E., & Snyder, J.S. (approved pre-registered report). Registered Report: Replication of Nozaradan, Peretz, Missal and Mouraux (2011). *Perspectives on Psychological Science.*
- **Nave, K.M.,** Hannon, E.E., & Snyder, J.S. (in preparation). Subjective beat perception in musical rhythms in adult listeners.
- Hannon, E.E. & **Nave, K.M.** (in preparation). Infants classify wordless, sung melodies based on language of origin.
- **Nave, K.M.**, Gordon, R. L., & McAuley, J.D., (in preparation). Rhythm discrimination predicts phonological awareness and grammatical competence in children ages 4 to 7 years.
- McAuley, J. D., Henry, M. J., Rajarajan, P., & **Nave, K.M**. (in preparation). Does moving in synchrony with sound affect what you hear? Phillips-Silver and Trainor (2007) revisited.
- McAuley, J.D., **Nave, K.M.**, & Syzek, B. (in preparation). Effect of tempo on the beat-based advantage in rhythm discrimination.

TEACHING EXPERIENCE:

- **Guest Lecturer**, Psychology 316: Foundations of Cognitive 2015

Psychology (Title: Language and Cognition)

- **Teaching Assistant,** Psychology 316: Foundations of Cognitive Psychology (undergraduate seminar, UNLV) 2015
- **Teaching Assistant,** Psychology 210: Introduction to Statistics (undergraduate seminar, UNLV) 2014
  In charge of teaching the SPSS lab portion of the class.
- **Guest Lecturer**, Psychology 330: Developmental Psychology, Infancy and Childhood (Title: Context Effects and Media in Development) 2014
- **Teaching Assistant,** Psychology 330: Developmental Psychology, Infancy and Childhood (undergraduate seminar, UNLV) 2014

PROFESSIONAL ORGANIZATIONS:

- American Psychological Association
- Association for Psychological Science
- Association for Research in Otarlaryngology
- Society for Music Perception and Cognition
- Society for Research in Child Development

RESEARCH INTERESTS:

- Auditory Neuroscience, Cognitive Development, Music Cognition, Rhythm Perception and Production, Music and Language Connections, Beat and Meter Perception in Music

INVITED TALKS:

- **Invited Panelist – Communications Certificate Program** 2017
  Graduate Professional Student Association (University of Nevada, Las Vegas)
- **Invited Panelist – Pursuing Graduate School** 2017
  Society for Music Perception and Cognition 2017 biennial meeting
- **Invited Talk – Professor's Choice Class** 2016
  Osher Lifelong Learning Institute (Las Vegas, NV)
  Do babies have the beat?: An EEG approach to music perception in infants.
- **Invited Panelist – Graduate School in Psychology** 2016
  Psy Chi, University of Nevada, Las Vegas

PRESENTATIONS:

- **Nave, K.M.**, Hannon, E.E., Snyder, J. *Musical rhythms induce long-lasting beat perception in older children but not younger children.* Podium presentation at Society for Music Perception and Cognition biennial meeting, San Diego, CA; 08/2017.
- **Nave, K.M.**, Cirelli, L., Thiede, A., Hannon, E.E., Snyder, J., Trainor, L.J. *Steady state responses to musical beat induction in 6- and 12-month olds.* Poster at Society for Music Perception and Cognition biennial meeting, San Diego, CA; 08/2017.
- **Nave, K.M.**, Hannon, E.E., Snyder, J. *Development of self-sustained musical beat*

perception. Poster at Society for Research in Child Development biennial meeting, Austin, TX; 04/2017.

- **Nave, K.M.** *Do babies have the beat?: An EEG approach to music perception in infants.* Rebel Grad Slam 3-minute thesis competition, UNLV; 11/2016
- **Nave, K.M.**, Hannon, E.E., Snyder, J. *Musical rhythms induce long-lasting beat perception in listeners with and without musical experience.* Podium presentation at International Conference for Music Perception and Cognition Biennial Conference, San Francisco, CA; 07/2016.
- **Nave, K.M.**, Hannon, E.E., Snyder, J. *Musical rhythms induce long-lasting beat perception in non-musicians.* Podium presentation at 2nd Annual Rhythm and Timing Symposium, East Lansing, MI; 04/2016.
- Hannon, E.E., **Nave, K.M.**, Vanden Bosch der Nederlanden, C.M., & Black, L *A developmental perspective on rhythm processing in music and language.* Invited talk in Rhythm: Development, Evolution and Cognition workshop at the 11th International Conference on the Evolution of Language, New Orleans, LA; 03/2016.
- **Nave, K.M.**, Hannon, E.E., Snyder, J. *Musical rhythms induce long-lasting beat perception in listeners with and without musical experience.* Poster at GPSA Research Fair, UNLV; 03/2016.
- **Nave, K.M.**, Hannon, E.E., Snyder, J. *Musical rhythms induce long-lasting beat perception in listeners with and without musical experience.* Poster at Association for Research in Otolaryngology Annual Conference, San Diego, CA; 02/2016.
- **Nave, K.M.** *Subjective beat perception in musical rhythms in adult listeners.* Master's thesis proposal, UNLV; 12/2015.
- **Nave, K.M.** *Our brains have rhythm!: An EEG approach to music perception in adult listeners.* Rebel Grad Slam 3-minute thesis competition, UNLV; 11/2015
- **Nave, K.M.**, McAuley, J.D., Gordon, R. *Musical rhythm discrimination and language development in children ages 4 to 7 years.* Podium presentation at Society for Music Perception and Cognition Biennial Conference, Nashville, TN; 08/2015.
- McAuley, J.D., **Nave, K.M.**, Rajarajan, P. *Rhythmic movement seems unlikely t affect auditory encoding of ambiguous rhythms.* Symposium presentation at Society for Music Perception and Cognition Biennial Conference, Toronto, Ontario; 08/2013.
- **Nave, K.M.**, Smith, L., Abid, A., McAuley, J.D.. *Is the effect of movement on auditory encoding of rhythm an artifact of demand characteristics?* Poster presentation at Midwest Undergraduate Cognitive Science Conference, Bloomington, IN; 04/2013.
- McAuley, J.D., Syzek, B., **Nave, K.M.,** Mastay, B., Walters, J. *Discrimination of slow rhythms mimics beat perception impairments observed in Parkinson's disease*, Poster presentation at International Conference for Music Perception and Cognition Biennial Conference, Thessaloniki, Greece; 07/2012.
- McAuley, J.D., Henry, M.J., Rajarajan, P., **Nave, K.M.** *Effect of movement on the metrical interpretation of ambiguous rhythms: Phillips-Silver and Trainor (2007) revisited*, Podium presentation at Society for Music Perception and Cognition Biennial Conference, Rochester, NY; 08/2011.

REVIEWING:

- **Judge for Office of Undergraduate Research Competition** 2017
  OUR Fall 2017 Lightning Talk Competition for Undergraduates
- **Reviewer for Association for Psychological Science** 2016
  APS Student Research Award
- **Reviewer for Association for Psychological Science** 2015
  APS Student Research Award

CAMPUS INVOLVEMENT & SERVICE:

- **Graduate Student Mentor** 2017
  Outreach Undergraduate Mentoring Program (OUMP) 2016
  2015
- **Developmental Emphasis Representative,** 2017
  Experimental Psychology Student Council 2016
  2015
- **Third-Year Cohort Representative,** 2016
  Experimental Psychology Student Council
- **First-Year Cohort Representative,** 2014
  Experimental Psychology Student Council
- **Executive Board Member** 2014-2017
  Michigan State University Alumni Association of Las Vegas

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