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PERCEIVING HIERARCHICAL MUSICAL STRUCTURE IN AUDITORY AND VISUAL MODALITIES

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Abstract

When listening to music, humans perceive underlying temporal regularities. The most perceptually salient of these is the beat, what listeners would tap or clap to when engaging with music, and what listeners use to anchor the events in the musical surface to a temporal framework. However, we do not know if people perceive those beats in hierarchically ordered relationships, with some beats heard as stronger and others as weaker, as proposed by musical theory. These hierarchical relationships would theoretically be advantageous in orienting attention to particular locations in musical time, and facilitate synchronizing musical behavior such as performing or dancing. In two experiments, I investigated if listeners perceive multiple levels of beats structured hierarchically, and if they use that information to decide if metrically-structured metronomes match or mismatch music. In Experiment 1, musicians and non-musicians alike gave higher ratings of fit to metronomes that matched musical excerpts at two levels of a hierarchy over those that matched at only one or no levels. In Experiment 2, I had musicians and non-musicians rate the fit of auditory and visual metronomes to music, and administered tests of intelligence and musical aptitude to determine if these factors impacted metrical perception. Musicians and non-musicians rated visual metronomes similarly to auditory metronomes, once again giving highest ratings of fit to fully-metrically-matching metronomes over those that matched at one or no levels. Musical aptitude and intelligence did not relate to meter perception in any systematic way. With musicians and non-musicians alike able to match metronomes to music on two metrical levels, this suggests that perceiving a hierarchical structure of beats may be a natural way in which listeners organize their perception of time and make sense of the musical events they hear.

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Perceiving Hierarchical Musical Structure in Auditory and Visual Modalities

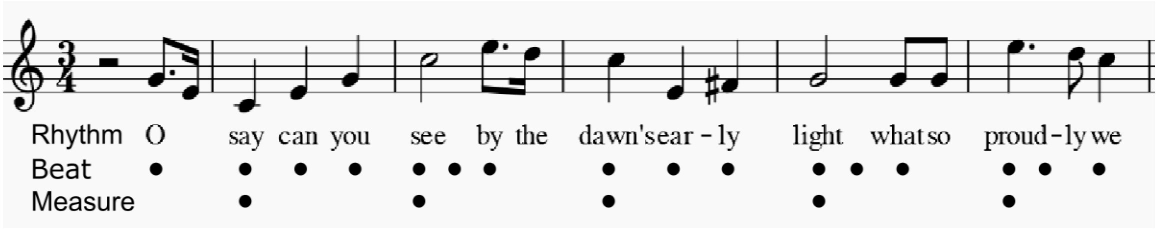
Imagine yourself at a concert for your favorite musical group. Whether it is classical, jazz, folk, rock, pop, or some other genre, you're caught up in the moment. Music enters your ears; a continuous stream of auditory input, yet you are able to effortlessly separate this stream into the sounds of different instruments, identify the melody, determine the speed of the music, and find the points in the music that you will clap along with. All the while, you watch the musicians move as they play their instruments, and effortlessly link their visual movements with the acoustic input of the music you hear. Your brain is performing complex calculations to make sense of this audio-visual, multimodal experience – yet you, the listener, are just enjoying the music and moving along, feeling this as an effortless phenomenon. How does our brain, through our sensory systems, make sense of these complex stimuli in a way that we perceive as simple and natural?

Music is a form of auditory communication, ubiquitous to every known human culture (Nettl, 2000). Just like speech, another human universal, music is an information-rich, complex auditory signal patterned in time. Thus, understanding speech or music requires extracting patterns in time (Krumhansl, 2000). Speech and music are not the only temporally patterned stimuli we experience: movement is also temporally patterned. Our eyes are involved in a musical experience, along with our ears. For example, we see a percussionist striking the drum head as we hear the snap of the snare, and we watch a violinist pull their bow across the strings as they play. Our multimodal experience of music starts as early as childhood. We learn to move our hands upward or downward along with the spider's actions in "The Itsy Bitsy Spider," (see video example; Super Simple Songs, 2008), and in "Ring Around the Rosie" we dance in a circle until the music tells us to "all fall down." As adults, we regularly clap, tap, or sway our bodies along with regular, repetitive events in music – and often experience this as pleasurable. The naturally multimodal nature of music makes it an excellent vehicle for comparing temporal processing and pattern-finding in audition and vision, as well as somatosensation and vestibulation.

Interestingly, the passage of time in music and other rhythmic patterns is not necessarily measured in the same manner as physical time. Constructs of musical time include rhythm, tempo, beat, and meter, which I define in the paragraphs to follow. These constructs have been the source of much interest to music theorists over the years (Cooper & Meyer, 1960; Creston, 1964; Hasty, 1997; Lerdahl & Jackendoff, 1983; Lester, 1986; London, 2012), and have inspired a burgeoning field of empirical research into music cognition over the last 25 years.

Rhythm. Rhythms are patterns of durations between inter-onset-intervals (IOIs) of events present in a physical auditory stimulus (e.g., speech, music, or any related pattern of sound; London, 2012). Listeners perceive the pattern of temporal onsets and events in a given rhythm as being connected or related to each other. In Figure 1, the specific timing of the musical notes in the Star Spangled Banner (America's national anthem; see LunaticAngelic, 2006) illustrates the rhythm of the musical piece. The onset and the duration of each note (held notes, spaces between notes, etc.) spell out the rhythm. A listener perceives these sound events as related to each other, and perceptually maps the musical events of the rhythm onto the temporal framework or grid of beats, based on the influence of duration and other musical variables (Cooper & Meyer, 1960).

Figure 1. Illustration of the sheet music of The Star Spangled Banner



Beat. The beat in music is a quasi-isochronous periodicity that marks the passage of time in music into equal durations (Lehrdahl & Jackendoff, 1983; Lester, 1986). Beats are reference points marking musical time into equal distances, and listeners relate the musical events they hear to this temporal grid of beats. In Figure 1, the perceptual and temporal location of the beats underlying The Star Spangled Banner is represented by the first row of dots under the notated musical score. Note that beats can exist where there are no musical events: in “The Star Spangled Banner”, two beats occur under “See” and “Light”, even though there is only one musical event (a held note) in each case (Figure 1). Yet a listener will still perceive a beat occurring in these locations, even when there are no new sound onsets.

There is usually a high level of inter-listener agreement on the location and temporal rate of the beat (Drake, Jones, & Baruch, 2000; Drake, Penel, & Bigand, 2000, Snyder & Krumhansl, 2001; Toiviainen & Snyder, 2003). When moving rhythmically to music, individuals will most often clap, tap, or sway to the beat. In Western music, the majority of musical pieces have an underlying beat, but, in rare cases, there are irregular, very slow, or very fast rhythms (more often in non-Western music) which do not promote the percept of a beat (Cooper & Meyer, 1960; Essens & Povel, 1985; London, 2002; Povel, 1981, 1984; Povel & Essens, 1985). The vast majority of music, however, promotes the percept of a beat.

Tempo. Listeners perceive musical events as passing by in time with a (usually) consistent underlying speed; this musical speed, often associated with the rate of the beat, is called tempo. Tempo has traditionally been quantified in “beats per minute,” relating the speed of the beats back to physical time, but this is not as straightforward a calculation as it seems. The underlying pulsation that a listener fixates on as the (perceived) beat is influenced many musical and extra-musical factors: how many events occur in a given span of musical time (event density; London, 2011), the listener’s familiarity with the musical piece or the type of music, how high or low in pitch the melody is (Boltz, 2011), where the listener focuses their attention in the musical stream, and a persistent tendency to perceive the beat as occurring approximately every 600 milliseconds (Drake, Gros, & Penel, 1999). Listeners may fixate on a different beat level than one intended by the performers or composers, or different listeners may subjectively perceive the tempo of the same piece as wildly different. Tempo is more than just the speed of the beat: the perceived tempo of the piece directly affects what the listener identifies as the (rate of the) beat they would tap or clap along with.

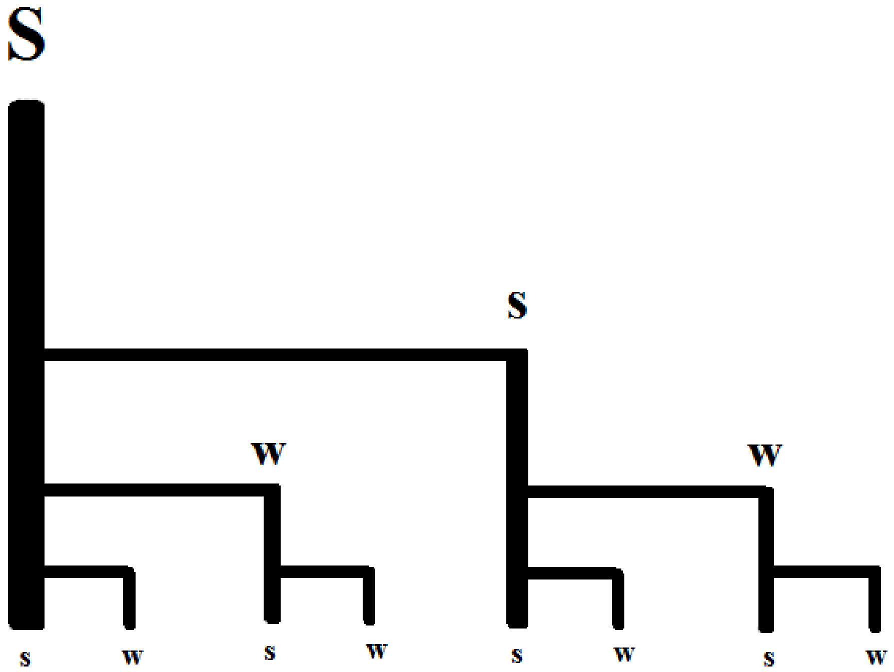
While acknowledging the complicated nature of tempo, a great deal of research has successfully used beats per minute as a (relatively) transparent measurement of musical speed. For a concrete (and albeit, simple) example of tempo, let us leave “The Star Spangled Banner” for a moment, and instead, focus on two examples of American pop music. Contrast the perceived musical speed of “Shout” by the Isley Brothers (video: GreatOldiesDJ, 2006) with “Imagine” by John Lennon (video: JohnLennonMusic, 2006). Most listeners would agree that you would tap or clap along to the beat in “Shout” faster than to the beat in “Imagine.” Thus, the tempo, or perceived speed of the beat, is faster in “Shout” than in “Imagine”.

Meter. If beats are the reference points in time which musical events are related to, meter organization of beats into regular, repeating patterns, where some beats are perceived as strong and others as weak, with these patterns nested hierarchically in each other (Lehrdahl &

Jackendoff, 1985; London, 2002). Meter inherently involves the perception of multiple levels of beats, as without multiple levels, beats cannot be perceived as relatively stronger or weaker than others (Lehrdahl & Jackendoff, 1985; Lester, 1986). Meter can also be thought of as a pattern of expectancies in time and a way of dynamically allocating attention towards events occurring at more salient (stronger) times (Jones & Boltz, 1989; Large & Jones, 1999).

Metrical structure specifies the direction and nature of the relationships among different levels of beats in the hierarchy. This hierarchical structure of meter can be visualized as an inverted tree, where the trunk represents the strongest hierarchical level, and each branch is a weaker level (Figure 2). These hierarchically nested levels of beats are commonly related in integer ratios to each other (at least, in most Western music; Cooper & Meyer, 1960; London, 2002).

Figure 2. Tree-like Illustration of a Metrical hierarchy. This tree illustrates a hypothetical metrical organization organized with four beats per measure and each beat subdivided into two subordinate beats. "S" indicates a strongly accented event and "w" a weakly accented event. Beats or events located on higher branches of the tree are perceived as stronger than events located on lower branches of the tree.



The relationship between rhythm and meter is bi-directional. The temporal location of phenomenal accents in a rhythm and other musical events (e.g. harmonic shifts, pitch changes, etc.) establish a listeners' perception of metrical structure, but an established metrical structure influences how the listener perceives the musical events (Lehrdahl & Jackendoff, 1985). Many different rhythms can share the same underlying metrical structure (Cooper & Meyer, 1960). For example, the base tango rhythm and samba rhythm both have the same metrical structure (beats nested in patterns of one strong beat followed by three weaker beats), but the rhythms are very different from one another. Conversely, a physically identical rhythm can be perceived differently based on the metrical framework it is presented in (Creston, 1964). Figure 3 illustrates an identical musical rhythm (pattern of IOIs between events; Figure 3A) that is perceived differently based on the implied metrical structure. Depending on the perceptual location of the beat (contrast 3B with 3C), the hierarchical relationships are different, with different hierarchical organizations at subordinate and superordinate levels, even though the physical rhythm is identical.

Figure 3. Identical rhythms interpreted differently depending on meter. The rhythm in 3.A. consists of four event onsets. Depending on how the listener interprets the grouping, the same rhythm can be heard as having three beats per measure (3B) or two beats per measure (3C).

While the metrical hierarchy can theoretically extend infinitely in either direction (beats extended over longer periods of time or divided into shorter periods of time), in practice, only two or three hierarchical levels of meter are generally perceived by a listener. Musical composers often indicate in their musical scores the intended metrical structure of a given musical piece; for example, if a strong beat is to be heard every two, three, or four beats. Each iteration of a single pattern of related strong and weak beats is notated and called as a measure (or bar) in (Western) musical notation: the first beat in a measure is the metrically strongest (accented) beat, and the remaining beats are weaker (unaccented). As shown in Figure 1, “The Star Spangled Banner” has three beats per measure, with the first beat (second level of dots) receiving a stronger metrical accent than the other two beats (note the lack of dots at the measure level), which are perceived as metrically weaker beats. In “The Star Spangled Banner”, these metrically stronger beats (first beats of the measures) are located at the lyrics “Say,” “See,” “Dawn,” and “Light.”

Organizing the temporal structure of music into hierarchical metrical patterns may facilitate group musical performances and dancing. Our attention may peak and we may perceive metrically strong beats as more perceptually salient weak beats (Large & Jones, 1999), making these metrically strong beats natural locations for synchronizing movements or people. For example, in partner dancing, if the leader initiates a dance movement on a weaker beat, at best the follower may be confused, and at worst, the leader may injure their partner or other surrounding dancers. Similarly, in group musical performances, starting the chorus two beats early (even if your entrance falls on the beat) will get you kicked out of the band.

Is there evidence that we perceive temporal patterns as alternations of strong and weak events? Our brains appear to automatically structure simple rhythmic sequences into hierarchical patterns (Bolton, 1894; Brochard, Abecasis, Potter, Ragot, & Drake, 2003; Ladinig, Honing, Haden, & Winkler, 2009; Temperley, 1963). Hearing the “tick tock” of a watch or clock – a strong-weak alteration pattern – is an example of (unconscious) subjective rhythmization. We perceive the physically identical signals as differentially accented. Subjective rhythmization illustrates hierarchical metrical grouping at a basic level: listeners are grouping physically identical signals (beats) into alternating patterns of strong and weak events. While automatic subjective rhythmization arises with very simple stimuli (e.g., the ticking of a clock, the continuous beeping of a car alarm, the clicks of a metronome), this may form the basis of the cognitive processes responsible for constructing and extracting the metrical structure from a rich and multi-layered musical piece.

Subjective rhythmization can also occur consciously: listeners can actively impose a metrical structure onto physically identical signals. When listening to a stream of physically identical isochronous tones and imagining them as organized with a strong beat every two beats or every three beats, listeners' EEG responses showed strong signals at the frequency of both the beat of the isochronous stimulus and at the frequency of the metrically accented beat of the group (Nozaradan, Peretz, Missal, & Moraux, 2011). This same neural resonance at the frequency of the beat and viewer-interpreted metrically higher levels of accent has also been found with visual displays of simple, isochronous flashing lights (Celma-Miralles, de Menezes, & Toro, 2016). Listeners' neural activity in higher oscillatory bands such as beta (20-30 Hertz) to chains of isochronous tones or repeating auditory rhythms also differs depending on the imagined strength of the beat, with greater responses relating to beats perceived as metrically strong (Fujioka, Ross, & Trainor, 2015; Fujioka, Zendel, & Ross, 2010; Iversen, Repp, & Patel, 2009; Paul, Sederberg, & Feth, 2015).

Experimental investigation of the perception of metrical hierarchies of beats in complex auditory sequences like music is still relatively new. However, the ability of humans to perceive a beat in music (and other rhythmic stimuli) is well-documented. Listeners with and without formal musical training can perceive a beat in music or in simple rhythmic patterns. For example, people can tap in synchrony with simple, isochronous metronomes or to the beat underlying complex rhythmic patterns (Engström, Kelso, & Holroyd, 1996; Large, Fink, & Kelso, 2002; Mates, Müller, Radil, & Pöppel, 1994; Snyder, Hannon, Large, & Christiansen, 2006; Wing & Kristofferson, 1973; for reviews, see Repp, 2005; Repp & Su, 2013). Even people with no formal musical training can accurately tap to the beat in live or computer-generated music (Drake, Penel, & Bigand, 2000; Snyder & Krumhansl, 2001; Toiviainen & Snyder, 2003; van Noorden & Moelants, 1999). Listeners can successfully match a metronome-like stimulus with the beat of the music, or discriminate the tempo of various musical excerpts (Fujii & Schlaug, 2013; Hannon, Snyder, Eerola & Krumhansl, 2004; Iversen & Patel, 2008; Law & Zentner, 2012). Thus, while music training enhances a listener's sensitivity to the beat, perceiving and synchronizing to a beat in an auditory rhythm is a common ability that does not require musical training (Drake, Penel, & Bigand, 2000).

There is evidence of beat perception not only in behavioral responses, but in the brain activity of listeners. Cortical neurons appear to resonate with the frequency of the beat (and the metrical structure) in simple rhythms (Nozaradan, Peretz, & Moraux, 2012), not to the temporal onsets of the rhythmic pattern. Beta-band oscillatory activity follows the internal representation of a beat, with increases in beta-band power anticipating the physical arrival of a beat, and corresponding decreases in beta-band activity after a beat arrives (Fujioka, Trainor, Large, & Ross, 2009, 2012), rather than to each event in the rhythm. At a structural level, strong perceptions of beat are associated with higher levels of activation in the basal ganglia, particularly in the striatum, and the supplemental motor area (Grahn & Brett, 2007; Grahn & Rowe, 2013).

Auditory rhythms with clear metrical structures lead to different brain responses to identical events depending on the metrical strength of the event. Induced (internal) gamma-band oscillatory activity in the brain is stronger in response to omitted metrically strong tones than weak tones (Snyder & Large, 2005). When presented with strongly metrical auditory rhythms, neurons show resonant responses not only at the frequency of the beat, but also at frequency of the metrical structure implied by the rhythmic pattern (Nozaradan, Peretz, & Moraux, 2012). Deviations that disrupted the metrical structure of a musical piece resulted in large mismatch negativity responses in musicians and non-musicians (Vuust, Pallesen, Bailey, van Zuijen, Gjedde, Roepstorff, & Østergaard, 2005).

Listeners' perception of metrical structure is cued by more than just the temporal onsets in a rhythm. Musical phrasing, harmonic movement, perceived tempo, musical tonality shifts, note duration, loudness changes, and many other factors can strengthen or weaken a metrical interpretation of a musical piece (Hannon, Snyder, Eerola, & Krumhansl, 2004; Lerdahl & Jackendoff, 1983, 1985; London, 2002, 2011). People have an easier time finding and synchronizing to a beat in musical pieces than simple metronomes: adults and children synchronize to the beat more accurately when tapping to musical pieces than metronomes (Drake, Jones, & Baruch, 2000; Drake, Penel, & Bigand, 2000). Adding additional metrical levels (superordinate or subordinate) to an isochronous metronome increases tapping accuracy (Madison, 2014).

Visual information, such as hand gestures and body movement, can alter a listener's perception of music. Adding visual information like a bouncing ball or flashing light to an ambiguous auditory rhythm can enhance rhythm and beat extraction (Su, 2014b). Changing the speed of visual gestures accompanying sounds affects listeners' judgements of duration and speed of auditory information. Long, drawn-out movements engender longer duration ratings than quick, percussive movements for the same sound (Schutz & Kubovy, 2009; Schutz & Lipscomb, 2007; Su & Jonikaitis, 2011). When listeners were able to view the body movements of musicians, they perceived the music as more expressive than when they listened to the music without visuals (Davidson, 1993; Silveira, 2014; Vines, Krumhansl, Wanderley, Dalca, & Levitin, 2011; Vuoskoski, Thompson, Clarke, & Spence, 2014). This effect seems to hold across genres and instruments, with effects noted for solo clarinet and trombone performances with modern classical repertoire, and for a group performance of a brass quintet performing jazz.

Listeners' perception of the location of phrase breaks in the music changes with visual information (Vines, Krumhansl, Wanderley, & Levitin, 2006). Participants who watched a performer play a musical piece had increased physiological responses to the music over when they only listened to the piece (Chapados & Levitin, 2008). Finally, participants' perception of the tempo of a particular musical excerpt was influenced by how active a dancer's movements were: music paired with a vigorously animated dancer was rated as faster than the same music with a relaxed dancer (London, Burger, Thompson, & Toiviainen, 2016).

Beyond simply influencing the perception of (auditory) music, people can detect rhythmic patterns and a beat in visual-only patterns. People can tap synchronously with isochronous visual metronomes (Dunlap, 1910; Patel, Iversen, Chen, & Repp, 2005; Repp, 2003; for review, see Repp & Su, 2013). Watchers can also detect if the implied beat of a rhythmic sequence is speeding up or slowing down (Grahn, Henry, & McAuley, 2010; McAuley & Henry, 2010). Participants had an easier time detecting disruptions in visual rhythms with a strong beat-based structure than rhythms that did not promote the percept of a beat (Grahn, 2012).

In time perception tasks, people are more accurate at discriminating temporal intervals with the auditory system than the visual system (Goodfellow, 1934; Grondin, 1993, 2010; Grondin, Meilleur-Wells, Ouellette, & Macar, 1998), and timing information presented through the auditory system overwhelms conflicting information from other senses. This holds for both perception and production of temporal intervals. Listeners are better at discriminating between auditory than visual rhythms (Collier & Logan, 2000; Grondin & McAuley, 2009), and have an easier time perceiving a beat in auditory stimuli (Grahn, Henry, & McAuley, 2011; McAuley & Henry, 2010). People are also more accurate at tapping along with an auditory metronome or reproducing time intervals demonstrated with an auditory stimulus than a visual stimulus

(Bartlett & Bartlett, 1959; Grondin, 1993; Grondin, Meilleur-Wells, Ouellette, & Macar, 1998; Repp, 2003). If auditory and visual information are presented simultaneously as pacers, the auditory information dominates tapping behavior and perceptual judgments (Guttman, Gilroy, & Blake, 2005; Hove, Iversen, Zhang, & Repp, 2013; Pasinski, McAuley, & Snyder, 2016; Patel et al., 2005; Repp & Penel, 2002, 2004). When estimating the rate of temporal information in a multimodal context (i.e., a paired auditory flutter and visual flicker), observers estimate the visual rate to be close to the auditory rate when they conflict, but estimates of auditory rate are not altered by conflict in the visual flicker (Welch, DuttonHurt, & Warren, 1986).

The format of the visual stimuli used as pacers seems to influence participants' higher variability and lower accuracy in tapping tasks and visual rhythm perception tasks. Traditionally, the pacing stimuli used in visual tapping or time discrimination tasks have been clusters of flashing light-emitting diodes (LEDs) or simple colored squares on a computer monitor (e.g., McAuley & Henry, 2010; Patel et al., 2005, etc.). Flashing lights give precise temporal information but little to no spatial information. Participants synchronized more accurately to a visual metronome in studies using visual pacers that incorporated spatial and temporal motion, such as a bar moving across the screen, a bouncing ball, or a tapping finger than to a flashing light (Hove, Fairhurst, Kotz, & Keller, 2013; Hove, Spivey, & Krumhansl, 2010). This improvement in performance for visual pacers including spatial information, such as a (silent) bouncing ball, can bring synchronization variability within the same level as tapping tasks using auditory pacers (Gan, Huang, Zhou, Quian, & Wu, 2015; Iversen, Patel, Nicodemus, & Emmorey, 2015). Adding spatial information to perceptual tasks also aids performance for visual rhythm and beat perception tasks. Infants were able to discriminate between different rhythms when they were presented as a series of colored shapes appearing sequentially across the screen, but not when those same shapes were presented in a sequence from the same central location (Brandon & Saffran, 2011).

While there is evidence of people perceiving a beat in visual rhythms, there is not yet much evidence that people perceive those beats metrically, with some visual beats seen as accented and others unaccented. Dancers embody multiple levels of the metrical hierarchy in their movements, emphasizing some movements more than others (Naveda & Leman, 2010; Toiviainen, Luck, & Thompson, 2010). Metrical structure as suggested by a simple dance video presented simultaneously with an auditory target-detection task influenced reaction times, with participants responding slower to deviants occurring at the strongest metrical location in the (silent) dance video (Lee, Barrett, Kim, Lim, & Lee, 2015). This may be due to the strong metrical structure in the visual rhythm preferentially allocating attention to visual, not auditory, stimuli at the time of target appearance. Visual movements may also enhance attention to metrical structure in music: musicians may glean additional cues to metrical structure from the movements of other musicians, or from the gestures of a conductor in large ensembles (Luck & Toiviainen, 2006). However, are individuals consciously aware of the metrical structure implied or strengthened by visual information?

Meter is, by definition, the perception of multiple levels of beats related to each other hierarchically. Yet previous investigations of metrical perception have not examined the relative relationship among levels of beats. Matching metronomes to musical stimuli (Hannon et al., 2004) or detecting irregularities or disruptions to a rhythmic sequence (Geiser, Sandmann, Jäncke, & Meyer, 2010; Geiser, Ziegler, Jäncke, & Meyer, 2009; Ladinig et al., 2009) only gives us information about one level of meter. We know that listeners perceive events that fall on and off a beat differently (Hannon et al., 2004; Geiser, Sandmann et al., 2010; Geiser, Ziegler et al., 2009; Ladinig et al., 2009). What we do not know is if listeners perceive beats that are located in theoretically stronger metrical locations as stronger than surrounding beats. In one of the few studies that probed the relative strength of different metrical positions, musicians asked to perceive a continuation of a metrical pattern in absence of stimulation responded to probes differently based on the metrical location of the probe (Palmer & Krumhansl, 1990).

The majority of listeners seem able to perceive a beat in music, but the question remains if they perceive or attend to multiple levels of beats, structured metrically. If metrical structure is a way of dynamically shaping attention to locations in time (Jones & Boltz, 1989; Large & Jones, 1999), then this hierarchical organization of beats in time should be something all musical listeners use. Alternatively, if metrical hierarchies are more for synchronization of musical activities, then only individuals who are active participants in musical behaviors, such as singing, dancing, or instrumental performance, should show evidence of metrically organized beat perception. “Casual listeners” - people who listen to music regularly, but are not formally trained in music theory or performance – may not need to be sensitive to metrically strong and weak locations, and therefore may focus only a single level of beats. Most musicians, on the other hand, are explicitly taught to attend to the relative strength and location of beats in a metrical hierarchy, and receive training in music theory and written musical notation (which notates metrical structure at two levels) along with instrumental instruction. In ensemble rehearsals, conductors serve as a coordinator for the group, and physically indicate metrical structure at the beat and measure level. By comparing the metrical perception of actively playing, formally trained musicians with casual listeners, I may gain an idea of the contribution of formal training to hierarchical perception in rhythms above and beyond familiarity with a culture’s musical idiom.

In this thesis, I addressed three research questions. First, are listeners able to perceive two levels of metrical structure simultaneously? Second, is metrical perception something even casual listeners use, or does it require more intense engagement with music to develop? Third, can people compare metrical structure between simple visual images and music?

In Experiment 1 I investigated the first two research questions. If people perceive beats as hierarchically structured into patterns of strong and weak events, then they should be able to judge how well a metrically structured probe fits the music using more than one level of information. I asked participants to rate how well an auditory metronome containing two levels of metrical information (beat and measure level) matched a recorded piece of human-performed music. I manipulated how the beat-level and the measure-level of the metronome fit the music in a factorial fashion, creating conditions that matched or mismatched at both metrical levels or matched at one metrical level but not the other. I recruited participants with little to no formal musical training and participants who were trained musicians.

In Experiment 2, I probed meter perception with visual stimuli and with auditory stimuli. This requires participants to perceive metrical structure in visual patterns, and compare this visual metrical structure cross-modally with the metrical structure of the music. I asked trained musicians and casual listeners to make these judgments of fit between music and visual or auditory metronomes. This let me directly compare the effectiveness of probing metrical perception with auditory and visual stimuli.

Experiment 1

Method

Participants

Normal-hearing adults (ages 18-60) from the University of Nevada, Las Vegas (UNLV) subject pool, the UNLV music department, and greater Las Vegas community participated in Experiment 1. Non-musicians (*n* = 34; 19 female) came from the UNLV Psychology department undergraduate subject pool, and consisted of young adults aged 18-45 (*M* = 20 years, 9.5 months). I operationally defined musicians as individuals with (1) at least five years of formal musical training, (2) who had been actively participating in musical training for at least three years prior to their participation in the study, and (3) were actively playing and/or practicing music at their time of participation. Musicians (*n* = 22; 11 female) ranged in age from 18 to 62 (*M* = 33 years 0 months). As compensation for participating in the study, subject pool participants received experimental credit, and community participants received an entry into a raffle for a $40 gift card (odds 1:20 of winning).

If participants missed 25% or more of the trials in an experimental session (equivalent to one block of trials) their data were excluded from analysis. The data from two participants did not meet this standard due to participant error (*n* = 1) and experimenter error (*n* = 1). Two additional participants' data were also excluded; one for not meeting the group criteria for the musician group (fewer than five years formal musical training reported on the demographic questionnaire), and one for being over the age limit for the experiment (as reported on the questionnaire post-experiment). The final analysis included 32 participants in the non-musician group and 20 in the musician group, for a total of 52 participants. Please consult the table located in Appendix A for a complete demographic comparison between groups.

Stimuli and Materials

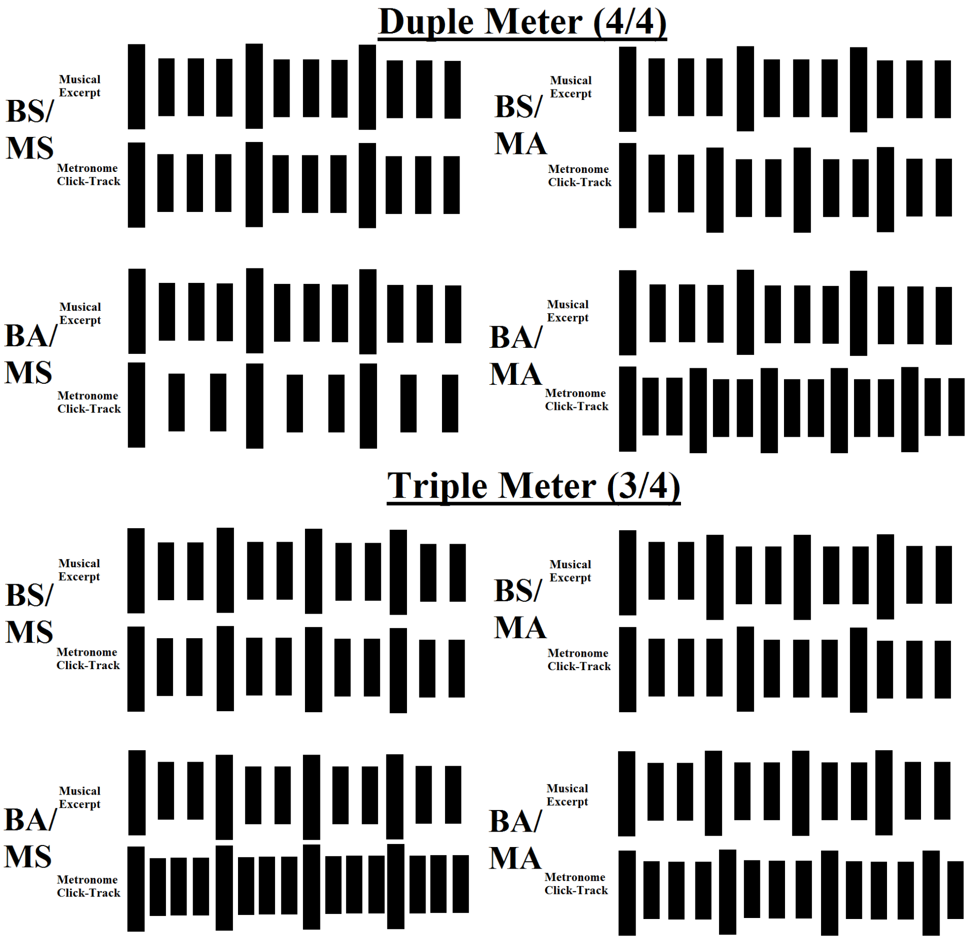
Auditory stimuli consisted of excerpts of ballroom dance music and auditory metronomes. The musical excerpts were taken from a compact disc (CD) set of instrumental music pieces intended for ballroom dancing (“Ballroom Dance Music,” Swiss Ballroom Orchestra, Blaricum CD Company, B.V.). Three pairs of musical pieces (six in total) were chosen for use in the experiment. Each pair contained one piece in duple meter (4/4) and one in triple (3/4) meter. The pairs of musical pieces were matched on average tempo, with pairs at 89, 104, and 124 beats per minute (BPM), respectively. The 89 BPM pair consisted of “Thornbirds Theme” (3/4) and “Meditation/Little Boat/One-Note Samba,” the 104 BPM pair consisted of “Great Waltz” (3/4) and “Brasil” (4/4), and the 124 BPM pair was “Skye Boat Song/Greensleeves/Amazing Grace” (3/4) and “Ole Guapa” (4/4). The musical pieces were chosen because of their similar base tempo, but they did not match exactly. To equate the average tempo of the music in each pair, I used the “Change Tempo” function in Audacity to equate their average BPM. This manipulation did not affect the expressive timing of the performance or the pitch of the musical track.

First, I determined the temporal location of the beats in each musical excerpt. I analyzed each complete audio file with the Bar and Beat Tracker plug-in from the Queen Mary VAMP plug-in set (Center for Digital Music, Queen Mary, University of London, London, England). The plug-in asks the user to enter the number of beats per measure, requiring the user to know this information before starting. After defining this parameter, the plug-in performs several analyses of the audio wave, as detailed by Davies and Plumbley (2006) and Stark, Davies, and Plumbley (2009). These analyses return the estimated location of the beats in the music, the measure-level grouping, and the estimated numerical position (e.g., 1, 2, 3, or 4) for each beat in a bar. Because the plug-in does not assume a steady isochronous beat, but relies on local source analyses, it finds the location of the beat based on audio information, and adapts to expressive timing and tempo variations inherent in any human musical performance. I used the location of the beats and their measure-level groupings in the musical excerpts as reference points to align the metronomes to the music based on the condition.

I used the metronome generator tool in Audacity (Dominic Mazzoni, 2014) to create the auditory metronomes. The metronomes consisted of 10ms sine-wave “ping” noises corresponding to MIDI tone 80 (G#5) for the beat and 92 (G#6) for the measure-level downbeat, with silence between clicks. The interval between the noise onsets (clicks) varied based on the condition of the relationship of the metronome to the music. While new metronomes were generated for each musical excerpt, the physical features of each metronome (i.e. the pitch and tone length) were identical. Only the temporal alignment of the metronome to the musical file differed among musical excerpts and conditions.

The fit of metronomes to each musical excerpt was manipulated to either match or mismatch the beat and the measure of the music, creating four possible metronome conditions (Figure 4). In the fully-matching condition (beat-synchronous measure-synchronous; BSMS), the beat- and measure-level tones in the metronome matched the temporal location of the the beat- and measure-level of the music. When the beat-level of the metronome matched the music, but the measure-level did not, (beat-synchronous measure-asynchronous; BSMA) condition, the metronome was always structured in a different metrical grouping from the musical excerpt (e.g. 3/4 to 4/4).

Figure 4. Visual illustration of the beat- and measure-level manipulations for musical excerpts in 4/4 and 3/4 metrical configurations. The large vertical bars represent measure-level downbeats, and the smaller vertical bars represent the non-accented beats in a measure. One full measure consists of a downbeat and all following regular beats. In each condition, the upper line represents the temporal locations of the downbeat and other beats in the music. The bottom line represents the temporal locations of the downbeat and other beats in the metronome (either visual or auditory).



When the beat of the metronome did not match the music but the measure did, (beat-asynchronous measure-synchronous; BAMS), the overall time-length of the measure in the metronome and the music were identical, but the beat in the metronome did not match the beat in the music, and were either faster or slower than the beat in the music. If neither the beat nor the measure level of the metronome matched the music (beat-asynchronous measure-asynchronous; BAMA), the metronome was in a different metrical grouping from the musical excerpt (e.g., 3 beats per measure in the metronome and 4 beats per measure in the music), and the tempo of the metronome was 6% faster than the music.

After creating the four types of metronomes and matching them to the musical excerpts, I performed an analysis of synchrony to compare the average levels of asynchrony between metronome and musical beat onsets. This attempted to ensure that the average synchrony at the beat-level between the metronome conditions was similar for beat-matching conditions and for beat-mismatching conditions. I compared the absolute value of the time-difference between a beat in the music and the corresponding (closest) beat in the metronome. For the manipulations of beat matching and mismatching across metronomes and musical excerpts, the average asynchrony for beat-matching conditions should be close to zero, and it should be much larger for beat-mismatching metronomes. This was the case: the two beat-matching conditions (BSMS and BSMA) did not differ in average asynchrony (*t*(10) = .046, *p* = .964), and the two beat-mismatching conditions did not differ in average asynchrony (*t*(10) = -1.17, *p* = .268) (see Table 2 for means and standard deviations).

Table 1. Analysis of Synchrony results between metronome beat position and music beat position.

Music Tempo and Meter	**BSMS**	**BSMA**	**BAMS**	**BAMA**
89 BPM; 4/4 Meter	0.254(±0.433)	0.173(±0.07)	141.191(±104.923)	165.475(±96.62)
89 BPM; 3/4 Meter	0.164(±0.146)	0.166(±0.148)	158.129(±114.917)	173.287(±97.776)
104 BPM; 4/4 Meter	0.159(±0.321)	0.186(±0.096)	126.505(±93.709)	144.503(±84.382)
104 BPM; 3/4 Meter	0.164(±0.278)	0.223(±0.214)	139.53(±98.921)	144.536(±84.402)
124 BPM; 4/4 Meter	0.173(±0.071)	0.161(±0.027)	111.112(±82.348)	125.424(±71.207)
124 BPM; 3/4 Meter	0.159(±0)	0.159(±0)	117.84(±83.348)	119.613(±71.112)

Participants listened to the musical excerpt and metronome simultaneously. To aid participants in perceptually separating the musical excerpt from the metronome, I presented the musical excerpts and metronomes dichotically, which aids in streaming the sounds into separate perceptual channels (Hartmann & Johnson, 1991). Half of the trials presented the music in the left ear, and the other half presented the music in the right ear. The left-right ear balance of the music and metronome was the same across all participants.

Participants heard four excerpts from each musical piece for each of the four metronome/music pairings from the six pieces (4 excerpts x 4 conditions x 6 musical pieces = 96). Each excerpt was five full measures of the musical piece in length. The number of metronome measures in the trial varied based on the metronome’s manipulation of beat and measure. For example, a fully matching metronome (BSMS) pairing contained five measures of the metronome and five measures of the music, matched identically in time and location. A beat-matching but measure-mismatching metronome (BSMA) for a musical excerpt with four beats per measure contained five measures of the musical excerpt and almost seven complete measures of the three beats per measure metronome (see Figure 4 for a visual depiction; BSMA). Trials varied between seven and fourteen seconds in length (*M* = 10.33 seconds) because of the different measure lengths and tempi of the musical stimuli. Six additional music/metronome pairings were created as practice stimuli for the training block. The practice stimuli consisted of other instrumental music pieces from the same record collection as the experimental stimuli, paired with metronomes that were either matching or mismatching at the beat- and measure-levels.

Procedure

All participants gave informed consent prior to participating in the experiment. The experimenter gave a short explanation of the task and procedure to the participant at the beginning of the experiment (please see Appendix A for text of verbal instructions to participants). The experimenter explained the task as an auditory matching task, where the participant would hear music and a second sound played at the same time, and would then rate how well the metronome (or "click-track") matched the music they heard. The experimenter told the participant, "There are no right or wrong answers; don't think too hard about it, just give us the answer that feels right to you." After providing a verbal explanation of the study (Appendix B), the experimenter read out loud the first computer screen of instructions to the participant, and then asked if the participant had any questions before beginning. Then, the participant proceeded through the practice phase and the experiment phase at their own pace. Throughout the experimental session, the experimenter remained in the room, and was available to answer any questions from the participant.

The task itself was performed on a desktop computer. Participants sat at individual desks with dividers between adjacent computers, approximately 70cm away from the monitor. To hear the music and metronome pairs, participants wore over-the-ear, sound-attenuating headphones (Sennheiser 280 Pro, Sennheiser Electronic Corporation, Old Lyme, CT) during the experiment. Participants could advance through the practice and instruction screens at will.

In the experiment, the trials were varied in length based on the duration of the musical excerpt and metronome pairing. Participants were not able to enter a rating until the music and metronome pair finished playing. The 96 trials in the experiment were divided into four blocks containing twenty-four test trials each. Block order and the order of trials within a block were randomized anew for each. Participants had the option to take a short break between blocks, but the timing was self-controlled. A custom program written in Presentation Software (Neurobehavioral Systems, Palo Alto, CA) controlled stimulus presentation and response collection.

Before starting the experiment, all participants completed a short training session. This introduced them to the idea that the metronome and the musical excerpt were separate, and that they were to decide how well the metronome matched the music. In the training session, participants listened to example musical excerpts and metronome pairs. Participants heard an examples of metronome/music pairings that would receive ratings of “4” (“Very Well”), “2 or 3”, and “1” (“Not Well At All”). The not-well-fitting metronome and music pairs were manipulated to be more mismatching than in the experiment proper (greater tempo difference between the metronome beat and the musical beat). Well-fitting examples had metronomes that matched the beat and measure level of music. None of the musical excerpts used in the training session were used in the test trials. First, participants passively listened to three examples of well- and not well-fitting metronome and music pairs along with explanation screens. They then listened to and rated three music and metronome pairs without feedback as an introduction to the format of the main experiment.

After a participant completed the practice, the experimenter asked the participant if they understood and were comfortable with the demands of the task. In the experimental blocks, each trial presented a single pairing of music and its corresponding metronome as described previously. The participant listened to the paired sounds in their entirety while the computer screen displayed the text “Listen to the sounds…” on the monitor. The computer did not accept any response or key input during the presentation of the sounds. After the paired musical excerpt and metronome finished playing, the computer monitor displayed a prompt asking the participant to enter their rating of fit, while showing the rating scale and anchor text on the screen as a reminder. Ratings were entered on the row of numbers at the top of a standard desktop keyboard.

After the participant entered their rating, there was a 600 ms blank screen, and the next trial began.

Ratings of fit were based on a Likert-type scale. The rating scale ranged from “1” (“Not Very Well At All”) through “4”, (“Very Well”). There was no mid-point in the scale that would correspond to “unsure” or “neutral.” This design was intentional. The lack of a midpoint forced participants to make a decision if the metronome fit the music or not. Furthermore, with no midpoint, the responses can be split into two groups, where responses of 1 and 2 indicate that to the participant, the metronome did not match the music, and 3 and 4 indicate the metronome did match the music, allowing greater flexibility in analysis.

Participants were warned they only had five seconds after the end of stimulus presentation to enter their ratings of fit. If a rating was not entered in that time window, the program automatically advanced to the next trial and presented the next musical excerpt/metronome pairing. Employing a limited time response window is a common practice in auditory judgment tasks, and it aims to ensure participants stay focused on the task. In this study, the total number of trials lost to automatically advancing trials was less than 1% of total trials. A limited response window also serves as a check on participant involvement; participants were excluded from data analysis if they missed more than 25% of the trials.

After the participant completed the experimental task on the computer, the experimenter administered the Auditory Experience demographic questionnaire to the participant (Appendix B). The Auditory Experience Questionnaire is a self-report measure that obtains demographic information, hearing history, musical experience, dance experience, and foreign language and cultural experiences. The entire experiment, including informed consent, the experimental task on the computer, and the demographic form took approximately 30 minutes to complete.

Planned Analyses

I was interested in the effect of three main variables on ratings of fit between the metronome and the music in this experiment: beat-level synchrony between metronome and music, measure-level synchrony, and formal musical training (as categorized by group). I entered average ratings of fit into a three-way, mixed model ANOVA, with group (musician vs. non-musician) as a between-subjects factor, and beat (synchronous vs. asynchronous) and measure (synchronous vs. asynchronous) as within-subject factors. Additionally, I planned to perform Bonferroni-corrected paired-samples and independent-samples *t* tests to compare differences between conditions (e.g. BAMA vs BAMS) within and between groups of participants.

To examine the impact of beat-level and measure-level matching made in ratings of fit, I created two difference scores per participant. The beat difference score combines the average ratings for both beat-matching metronome conditions (BSMS and BSMA) and subtracts from that the ratings of fit for both beat-mismatching metronome conditions (BAMS and BAMA). This difference score ignores measure-level matching and focused on the differences in ratings of fit driven by beat-level matching. The measure difference score takes the same approach, but adds together the average ratings for both measure-matching conditions (BSMS and BAMS) and subtracts from that the average ratings for both measure-mismatching conditions (BSMA and BAMA). These two difference scores allow me to investigate the relative effects of each factor (beat-level matching or measure-level matching) at an individual-differences level. I compared the two types of difference scores between groups with independent-sample *t*-tests.

Because an individual's musical history and training plays a large part in the perception of music, I then correlated the difference scores with demographic variables related to musical experience and dance experience. The specific variables I chose were hours of music listened to on a weekly basis, years of musical training, hours of music practiced per week (if applicable; not all participants were musicians), hours of music listened to per week, and years of dance training. While I intended to also include hours of dance practice per week, too few participants endorsed weekly dance practice to make a meaningful comparison.

Results

Mixed-Model ANOVA

To determine if participants' ratings of fit between metronome and music varied systematically based on my manipulations or their level of musical training, I entered the average ratings of fit as the dependent variable in a 3-way mixed-model ANOVA. Group membership (musician vs. non-musician) was a between-subjects variable, while beat synchrony (synchronous vs. asynchronous) and measure synchrony (synchronous vs. asynchronous) were within-subjects variables. The resulting *F* values and effect sizes (partial eta squared) are presented in Table 3.

Table 2. Effects of Beat, Measure, and Group membership on ratings of fit between metronome and musical excerpt.

Source	***F***	η_p^2
Beat	1273.48**	.962
Measure	18.85**	.274
Group	<1	.004
Beat * Group	4.12*	.076
Measure * Group	23.08**	.316
Beat * Measure	22.62**	.312
Beat * Measure * Group	1.94	.037

* $p < .05$. ** $p < .01$. *Note*: All *F*-tests on 1 and 50 degrees of freedom.

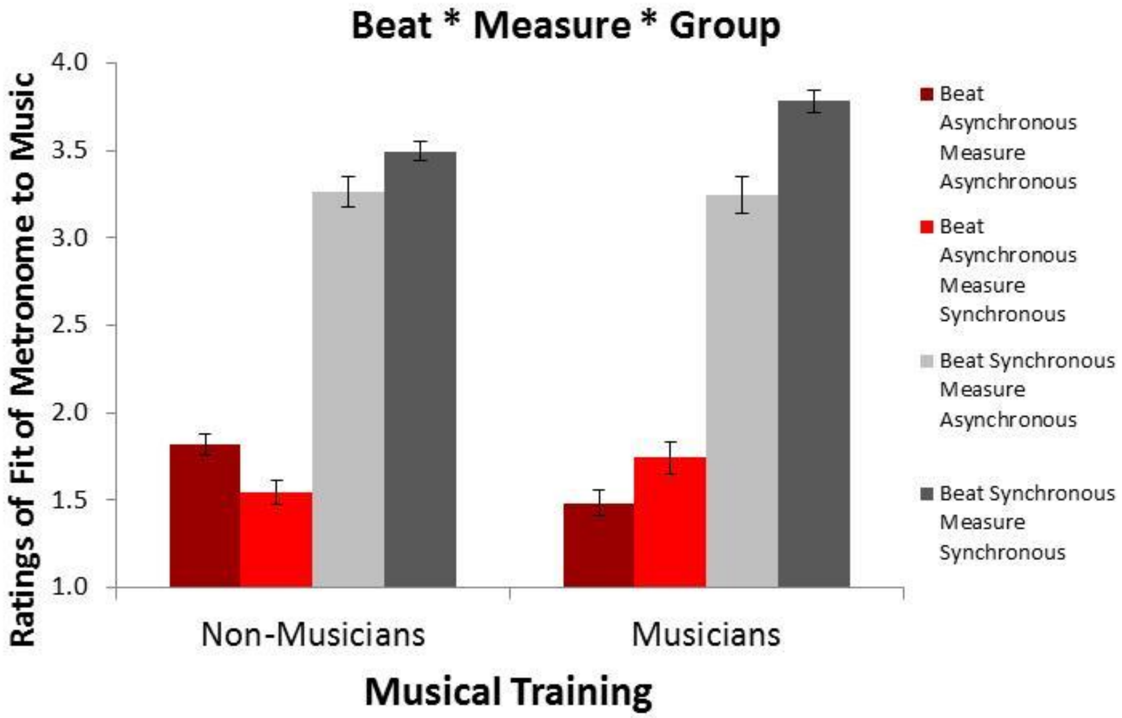
Beat and measure were significant main effects. Recall that participants gave their ratings of fit on a four-point scale, where “1” was “Not Well Fitting” and “4” was Well-Fitting; higher average ratings from participants indicate that they perceived the metronome fit the music better than those conditions with lower scores. Participants rated beat-synchronous metronomes (*M* = 3.45) as fitting better than beat-asynchronous metronomes (*M* = 1.65). However, beat also interacted with group membership and with measure. Musicians rated beat-matching metronomes (*M* = 3.51) higher than non-musicians did (*M* = 3.38), and musicians rated beat-mismatching metronomes lower (*M* = 1.61) than non-musicians (*M* = 1.68), suggesting that musicians more strongly differentiated between beat-level synchrony and asynchrony than non-musicians in their ratings of fit. The interaction between beat and measure shows that participants reacted to measure-level synchrony depending on whether the beat of the metronome matched or mismatched the music. When the beat of the metronome was synchronous with the music, participants rated fully-matching metronomes (BSMS; *M* = 3.64) as fitting the music better than measure-mismatching metronomes (BSMA; *M* = 3.26). However, when the beat of the metronome did not match the music, participants did not differ in their ratings of fit between fully asynchronous metronomes (BAMA; *M* = 1.65) and those that were synchronous at the measure-level (BAMS; *M* = 1.64).

The factor of measure-level matching did have a significant main effect on ratings, with participants rating the measure-synchronous metronomes (*M* = 2.64) higher than measure-asynchronous metronomes (*M* = 2.45). The difference in ratings and effect size for measure was weaker than for beat synchrony. However, the interaction between measure and group shows that only musicians rated measure-synchronous metronomes (*M* = 2.76) as better-fitting than measure-asynchronous metronomes (*M* = 2.37). Non-musicians rated measure-synchronous (*M* =

2.52) and measure-asynchronous (*M* = 2.54) metronomes as fitting the musical excerpts equally well.

Figure 5 illustrates the three-way interaction among beat, measure, and group. While this interaction was not statistically significant, it gives a clear illustration of the differences in ratings by metronome condition and by group. Adding measure-level synchrony to metronomes had different results based on group membership and beat-level synchrony. When the beat of the metronome was asynchronous, musicians rated BAMS metronomes (*M* = 1.74) as fitting the music better than fully asynchronous metronomes (BAMA; *M* = 1.48), while non-musicians rated BAMA metronomes (*M* = 1.82) as better-fitting than BAMS metronomes (*M* = 1.55). While musicians did not significantly differ in their ratings of BAMA and BAMS metronomes, *t*(19) = -1.812, *p* = .086, non-musicians did significantly rate BAMA metronomes as fitting the music better than BAMS metronomes, *t*(31) = 4.95, *p* < .001. Both groups reacted to the addition of measure-level synchrony in the same way when the beat of the metronome matched the music. Musicians rated BSMS metronomes (*M* = 3.78) as better fitting than BSMA metronomes (*M* = 3.24), *t*(19) = -5.49, *p* < .001. Non-musicians similarly rated BSMS metronomes (*M* = 3.49) as better fitting the music than BSMA metronomes (*M* = 3.26), *t*(31) = -4.13, *p* < .001.

Figure 5. Effects of group, beat, and measure on ratings of fit between metronome and music.



Between-group *t*-tests showed several significant differences between the ratings of musicians and non-musicians on the same metronome conditions. Musicians gave lower ratings of fit to fully- mismatching (BAMA) metronomes than non-musicians, *t*(50) = 3.60, *p* =.001. Musicians and non-musicians rated the beat-asynchronous but measure-synchronous (BAMS) metronomes similarly *t*(50) = -1.76, *p* =.085, but it was trending for musicians to rate BAMS metronomes as fitting the music better than non-musicians. The two groups also rated beat-synchronous but measure-asynchronous (BSMA) similarly, *t*(50) = 0.17, *p* =.908. Finally, musicians gave stronger ratings of fit to fully-matching (BSMS) metronomes than non-musicians, *t*(50) = -3.32, *p* =.002. The overall trend was for musicians' ratings to use a larger range and approach the end-points of the scale for fully asynchronous and fully synchronous metronomes than non-musicians. Musicians also trended towards giving higher ratings of fit when there was any synchrony at all in the metronomes (BAMS) as compared to non-musicians, who required beat-level synchrony to give higher ratings of fit.

Difference Scores

Beat difference scores consist of the sum of average ratings of beat synchronous conditions (BSMS and BSMA) minus the sum of average ratings of beat asynchronous conditions (BAMS and BAMA), showing the effect of beat-level matching regardless of measure-level matching. Both musicians (*M* = 3.80, *SD* = 0.488) and non-musicians (*M* = 3.39, *SD* = 0.813) had positive difference scores, indicating that both groups felt that beat synchronous metronomes matched the music better than beat asynchronous metronomes. However, musicians had larger positive difference scores than non-musicians, *t*(50) = -2.03, *p* = .048, suggesting that musicians were more sensitive to beat-level synchrony than non-musicians.

Measure difference scores were constructed similarly (sum of BSMS and BAMS minus the sum of BSMA and BAMA ratings) to beat difference scores. For measure difference scores, only musicians had a positive difference score (*M* = 0.793, *SD* = 0.770), with non-musicians averaging around zero (*M* = -0.040, *SD* = 0.484). Musicians' difference scores significantly differed from non-musicians, *t*(50) = -4.80, *p* < .001. This suggests that only the musician group consistently rated measure-matching metronomes as fitting the music better than measure-mismatching metronomes, regardless of the beat-level synchrony.

Correlations

I correlated the two difference scores (beat difference; measure difference) with demographic variables relating to the participants' experience and engagement with music and musical training. Results are shown in Table 4. For the beat difference score, only years of formal musical training was significantly correlated with it; those individuals with more years of formal musical training had higher beat difference scores. The measure difference score was significantly related to years of formal musical training and to hours of music practiced per week, with greater weekly practice and formal training relating to higher measure difference scores. The relationship between hours of practice per week and the measure difference score suggests that measure-level perception requires deeper, and possibly more active engagement with music than beat perception.

Table 3. Correlations among the difference scores for all participants and demographic variables related to musical experience and dance experience.

Measure	Beat Difference Score	Measure Difference Score	Years of Formal Musical Training	Hours Practicing Music/Week	Hours Music Listened to Weekly	Years of Dance Training
Beat Difference Score	-	-.007	.323*	.152	.047	.060
Measure Difference Score		-	.460**	.465**	.092	.012
Years of Formal Musical Training			-	.606**	.094	-.015
Hours Practicing Music/Week				-	.099	-.040
Hours Music Listened to Weekly					-	.310*
Years of Dance Training						-

all n = 52. * *p* < .05. ** *p* < .01.

Multiple Regressions

The average age of the musician group (*M* = 33 years) and non-musician group (*M* = 20 years, 9.5 months) differed markedly, as did the amount of musical training between groups. When participant age and years of musical training are examined alone, they both are have a positive relationship with beat and measure difference scores. These variables are confounded, as an individual who has lived longer has had more time to amass more years of formal musical training. However, increasing age decreases perceptual acuity and working memory capacity, so it is important to disentangle the effects of greater age from the effects of greater formal musical training. By statistically controlling for age while examining musical training and vice versa, the possibly opposite effects of these variables can be determined.

I performed two multiple regressions: one on the beat difference score and one on the measure difference score, using years of formal musical training and participant age as the predictor variables. The multiple regression on the beat difference score did not account for a significant amount of variance, $F(2,49) = 2.88$, $p = .066$, $R^2 = .105$ (adj. $R^2 = .069$). Controlling for participant age, years of formal musical training trended toward significance, $t(49) = 1.71$, $p = .094$, $\beta = .364$.

The multiple regression on the measure difference score did account for approximately 18-21% of the variance in participants' scores, $F(2,49) = 6.70$, $p = .003$, $R^2 = .215$ (adj. $R^2 = .183$). Years of formal musical training, when controlling for participant age, accounted for a significant portion of the variance in measure difference scores, $t(49) = 2.65$, $p = .011$, $\beta = .528$. When controlling for years of musical training, age did not significantly predict measure difference scores, $t(49) = -0.44$, $p = .662$, $\beta = -0.09$. It appears that in this case the age of the musician participants, when accounting for their increased levels of musical training, did not affect their performance in the task.

Discussion

In Experiment 1, I sought to answer two research questions. First, are listeners able to perceive multiple levels of the metrical hierarchy simultaneously and use that information in explicit judgments? Second, is it necessary to have formal education in music theory to perceive metrical structure, or can casual listeners with little to no formal musical training perceive meter in music and other rhythmically patterned sounds?

Both the musician and non-musician groups' ratings of fit varied depending on the beat- and measure-level matching between the metronome and the music. The fit of the metronome beat to the music strongly influenced both groups' ratings. The strong ratings of fit for beat-matching metronomes (regardless of measure-level information) support the prior finding that listeners can easily match a metronome with the beat of a piece of music (Iversen & Patel, 2008). Importantly, when the locations of the beat and the measure of the metronome matched the beat and measure of the music, those metronomes received the highest ratings of fit from both groups. Thus, listeners could perceive multiple levels of the metrical hierarchy simultaneously. The difference in ratings of fit between beat-only matching metronomes and beat- and measure-matching metronomes were stronger for musicians than non-musicians, but both groups used measure-level matching in their ratings of fit when the beat of the metronome matched the beat of the music.

Interestingly, measure-level matching between the metronome and music did not always result in higher ratings of fit from participants. If the beat-level of the metronome matched the music, the addition of measure-level matching increased the ratings of fit. However, when the beat-level of the metronome did not match the music, measure-level matching did not increase ratings of fit. If the measure level of the metronome matched the music but the beat level did not, non-musicians rated the fit of the metronome to the music very poorly; this condition received the lowest ratings of fit of all conditions from the non-musicians. Even fully-mismatching (beat and measure asynchronous) metronomes received higher ratings of fit from non-musicians than metronomes that mismatched the music at the beat level but matched at the measure level. The musician group did not differ in its ratings of fit for fully-mismatching metronomes and metronomes that matched at the measure-level but mismatched at the beat-level, rating both conditions as fitting the music poorly.

The lack of an effect for measure-level matching alone (or the unexpected lower ratings of fit than fully mismatching) could have been driven by the construction of this metronome condition. In the beat-mismatching but measure-matching metronome, the relative tempo mismatch between the metronome beat and the musical beat was greater than in the fully-mismatching (beat and measure asynchronous) metronome condition. The tempo of the metronome's beat in the fully mismatching condition was 6% faster than the tempo of the music. This is well above the approximately 2% just noticeable difference (JND) for multiple-interval sequences (Drake & Botte, 1993; Friberg & Sundberg, 1995). However, the tempo of the metronome in the beat-mismatching measure-matching condition was either 25% slower or 33% faster than the tempo of the music. This greater timing mismatch between the beat of the music and the beat of the metronome may have focused the listeners' attention more than the single point of synchrony at the head of each measure, thus driving the poor ratings of fit.

Both musically trained and untrained individuals used beat and measure levels of information in the metronomes and the music to make their judgments of fit. Some participants in the non-musician group did report limited amounts of formal musical training or musical participation, but almost two-thirds of the non-musician group (19 of 32 participants) reported no formal musical training at all (neither instrumental nor voice). This indicates that metrical perception does not require formal training to emerge. However, neither musicians nor non-musicians consistently used both levels of metrical information in their ratings of fit except when the beat-level of the music and the metronome were synchronous.

Meter perception thus may not require formal musical training to develop. It may, however, require some enculturation to the musical idiom of the music presented. Previous work on metrical perception comparing within culture and out of culture music suggests that exposure and familiarity with a particular musical idiom enhances sensitivity to metrical disruptions (Hannon, Soley, & Levine, 2011; Hannon, Soley, & Ullal, 2012; Hannon & Trehub, 2005; Hannon, Vanden Bosch der Nederlanden, & Tichko, 2012; Ullal, Hannon, & Snyder, 2015). Because the excerpts of music in this study were traditional ballroom dance styles found in American culture, this enculturation effect may have been indexed by the positive relationship between English as a first language and higher beat difference scores. Furthermore, the more musical engagement the non-musician group had on a weekly basis, as indicated by hours of music listened to per week, the higher the difference in ratings between beat-matching measure-mismatching metronomes and fully-matching metronomes (indexing sensitivity to both levels of the metrical hierarchy simultaneously).

While formal musical training may not be necessary for metrical perception, it does seem to enhance sensitivity to higher levels of the metrical hierarchy. When considering the whole group, years of musical training, hours of music practiced on a weekly basis, and the age of beginning musical training were all positively related to beat sensitivity (rating beat-matching metronomes as fitting the music better than beat-mismatching metronomes), measure sensitivity, and sensitivity to measure-level synchrony when the beat-level was asynchronous between the music and the metronome. However, within the musician group alone, no clear variables emerged as predictors of greater sensitivity to metrical structure. Prior investigations of musical meter had shown an advantage in performance for participants with formal musical training (Geiser, Jancke, Sandmann, 2010; Krumhansl & Palmer, 1990), but have rarely gone beyond simple demographic assessments of musicianship and years of training based on self-report.

Structuring rhythmic patterns into underlying patterns of alternating strong and weak beats may be an effective method of reducing mental processing load. As individuals with little to no formal musical training used beat and measure level information to make their judgments, it suggests untrained listeners are capable of attending to multiple levels of the metrical hierarchy simultaneously. If musical training was necessary, grouping of musical information into repeating strong-weak hierarchies would not be a natural way of organizing incoming temporal information. Because individuals who were simply enculturated into a musical culture (but not formally trained) show evidence of metrical perception, this provides a stronger argument for our sensory systems automatically sequencing incoming rhythmic information into hierarchically nested patterns.

In Experiment 1, I confirmed that listeners are able to perceive multiple levels of the metrical hierarchy simultaneously, and that formal musical training is not required to do this. However, several major questions remained unanswered. If the brain processes and chunks incoming temporal information into these nested hierarchies of meter, is this a modality specific (auditory only) or modality general (all senses) mechanism? Furthermore, grouping participants into active musicians versus non-musicians based on self-report does not quantify musical ability, which may naturally vary even in the absence or presence of formal musical instruction. Perhaps metrical sensitivity can be quantified through either musical aptitude or through general aptitude, such as verbal or non-verbal ability. A quantifiable measure of musical ability is needed to tease apart the effects of latent musical talent, enculturation, and formal training to see if metrical perception varies based on musical ability independently or in conjunction with formal musical education. If metrical perception is a general cognitive process, it may be related to intelligence or aptitude rather than specific to music-related knowledge and skills. In Experiment 2, I probed musical meter perception using visual and auditory stimuli, and I assessed musicians' and non-musicians' musical ability and general aptitude to tease apart what underlies metrical perception.

Experiment 2

Method

Participants

Thirty-three normal hearing adults from the UNLV psychology subject pool (*n* = 16, 11 female) and the UNLV music department and greater Las Vegas community (*n* = 17, 7 female) participated in Experiment 2. Subject pool participants were not recruited with specific criteria, and the resulting group consisted of participants with little to no formal musical training (*M* = 1 year). The musician group was recruited from the Las Vegas community. For inclusion in the group, had to have a minimum of five years of formal musical training (*M* = 20 years 4 months). Demographic data on the two groups is contained in Table 4. Musicians in Experiment 2 were recruited based on the same operational definition of musicianship used in Experiment 1. One participant in the musician group was not included in the final data analysis due to withdrawing from the study after the first session, and no demographic data is available for that participant.

Table 4. Demographic comparisons between musician and non-musician groups in Experiment 2.

Demographic Variable		**Non-Musicians**	**Musicians**
Sample Size (Females)		16 (11)	16 (7)
	Age Range	19-29	18-50
Average Age (SD)		21.56 (+/- 3.03)	31.18 (+/- 8.83)
Hispanic Participants		4	2
Races	Caucasian	9	12
	Black/African American	2	2
	Chinese	0	1
	Filipino	1	1
	Middle Eastern	2	0
English as a First Language		10	14
Age Learned English if not First Language		8.8 (2.59)	9
Speak More than One Language		8	8
Lived Outside the US		3	3
Frequent Ear Infections		2	3
Pressure Equalizing Tubes as a Child		1	0
Family History of Hearing Impairment		2	2
Had A Cold		1	0
Had an Ear Infection		0	0
Ever Taken Private Music Lessons		4	16
Years of Musical Training		3.34 (3.95)	18.55 (12.52)
Average Age of Starting Lessons (SD)		11 (1.73)	9.44 (3.52)
Currently Taking Private Music Lessons		0	7
Currently Practicing Music		1	16
Average Hours Music Practice/Week		<1	13.69 (11.06)
Have Absolute Pitch		2	4
Ever Taken Dance Lessons		2	6
Average Age of Starting Dance Lessons		8.5 (7.78)	20.17 (14.05)
Years of Dance Training		1.06 (3.75)	1.22 (2.77)
Hours of Music Listened to/week		14.94 (17.59)	18.56 (11.84)

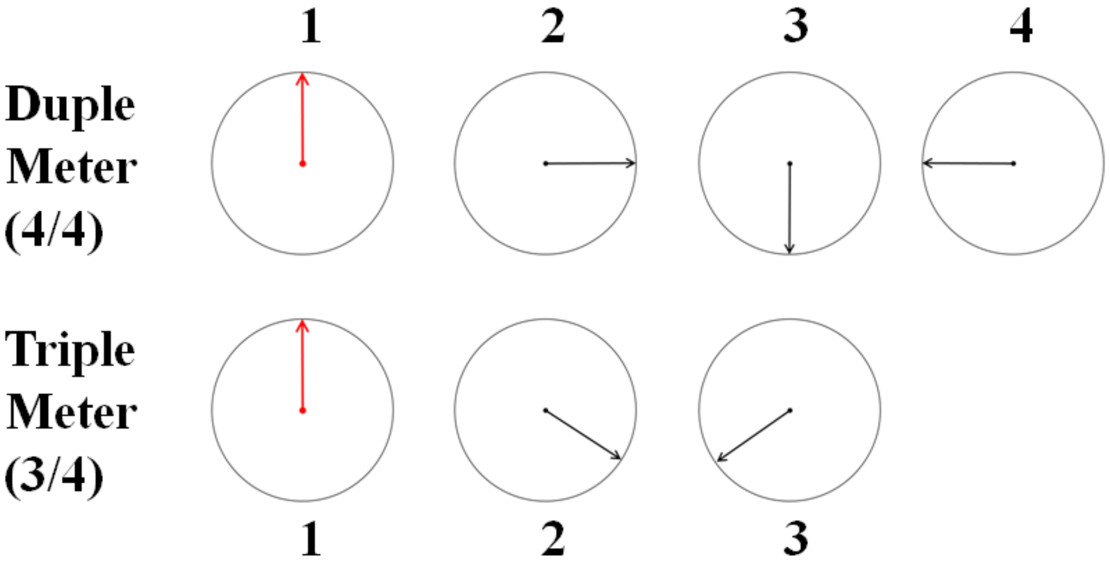
Because post-hoc power analyses of the data collected in Experiment 1 indicated high effect sizes for the main effects of beat and measure, the sample size in Experiment 2 (16 per sample) was smaller than Experiment 1 (34 non-musicians and 20 musicians). A priori power calculations for Experiment 2 using the effect sizes obtained in Experiment 1 suggested that only sixteen participants per group were needed to obtain $\beta > .8$ for the main effects. Experiment 2 also used a within-subjects design for comparison between the auditory and visual modalities, which increased observed power while decreasing the required number of participants.

All participants gave informed consent prior to participation in this study. The participants who were recruited through the Subject Pool received course credit as compensation. Participants from the larger community received entry into two raffles for a $40 gift card to iTunes or Starbucks, one entry for each session they completed (odds 1:20 of winning for each draw, with two draws performed).

Stimuli

Experiment 2 contained auditory and visual metronomes paired with the same musical excerpts used in Experiment 1.The auditory metronomes paired with the music were identical to those used in Experiment 1. The visual metronomes were created using the temporal information from the auditory metronomes. First, I determined the exact temporal onset of each beat in the auditory metronome. I created a time-log of the exact beat and measure-level downbeat temporal locations of the four metronome conditions. Then, I created three- or four-frame visual metronomes in Microsoft PowerPoint (Microsoft Corporation, Seattle, WA). Each visual metronome was a white circle with a black outline, resembling a clock face, presented on a white background. The overall size of the image containing the metronome was 960 x 720 pixels in size, and the computer monitor had a resolution of 1680 pixels by 1050 pixels. With an approximate viewing distance of 70 centimeters, the metronome and surrounding white frame subtended a visual angle of 15.5°. As the metronome ticked out the time, an arrowed line jumped from point to point, stopping at the quarters or thirds of the circle. A central dot anchored the line with the arrow, and the arrow connected to the circle's outline (Figure 6).

Figure 6. Illustration of visual metronomes.



For each beat of the visual metronome, the arrowed line advanced to the next position on the clock face. The arrow moved discretely from beat to beat, remaining in its location until the next beat, where it appeared to "jump" (or discretely move) to the next location on the circle, creating apparent motion while still keeping the locations discretely fixed (as in Grahn, 2012). The downbeat was always positioned at the top of the circle, in the same position as 12 on a typical wall clock. The line was black for all weak beats (non-measure downbeats), and was red and slightly thicker in width to indicate the measure-level “downbeat”. It switched colors between frames. Each frame of the visual metronome appeared at the corresponding onset times of the auditory metronome clicks (but with no sound). This created a visual analog to the auditory matching or mismatching of the beat and measure information between the metronome and musical excerpts.

Experiment 2 contained 96 pairs of musical excerpts and auditory metronomes, and 96 pairs of musical excerpts and visual metronomes (6 musical pieces x 4 excerpts/piece x 4 beat and measure synchrony/asynchrony conditions). As in Experiment 1, training stimuli for visual metronomes were created using the auditory metronome training stimuli (with the auditory metronome removed from the audio track). Metronome modality remained constant in an experimental session, with participants experiencing only one metronome modality per session. Within a modality, stimuli were arranged into blocks and block order and stimulus order within a block were randomized across participants. The presentation of the visual and auditory metronomes and musical excerpts was administered by a custom program written in Presentation Software as in Experiment 1.

Measures

In Experiment 2, participants completed a measure of verbal and non-verbal intelligence and a measure of musical ability in addition to the demographic questionnaire used in Experiment 1. To assess verbal and non-verbal intelligence, participants completed two subtests of the Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II; Wechsler & Hsiao-Pin, 2011). Participants took the Gordon Advanced Measures of Music Audiation (AMMA; Gordon, 1986) to provide an objective measure of their musical ability.

All participants completed the Vocabulary and Matrix Reasoning sub-tests of the WASI-

II. The Vocabulary sub-test is a measure of verbal intelligence, and the Matrix Reasoning sub-test is a measure of non-verbal intelligence and problem solving. Verbal intelligence and non-verbal intelligence can also be compared to the constructs of crystallized intelligence (verbal) and fluid intelligence (non-verbal). Taken together, the two subtests yield an estimate of general cognitive ability. In the Vocabulary sub-test, participants are asked to define a set list of words. In the Matrix Reasoning sub-test, participants select the figure or image from a larger set that completes a larger incomplete pattern. The WASI-II was administered verbally by the experimenter, and each sub-test took approximately 10 minutes per participant. Scores on the WASI-II are normed for individuals ages 6 to 90, so participant age (in years) was used to convert their raw scores on the subtests to age-normed *t*-scores. When interpreting *t*-scores for the WASI-II, higher scores indicate higher performance (i.e. higher verbal or non-verbal intelligence).

The AMMA is a single test with questions that are parceled out into a rhythm sub-test and a melody sub-test. The AMMA aims to provide an objective measure of musical ability, regardless of the influence of musical training. The test is normed for use from high school age through college, and has different norms for college music majors and college non-music majors (Gordon, 1990; McCrystal, 1995). As all musicians indicated they were either current music majors or had completed a music degree, they were all scored as “College Music Majors.” All non-musicians indicated they were not pursuing a music major, and were scored as “College Non-Music Majors”. The version of the AMMA used in this experiment was computer-administered and computer scored. It took participants approximately 15 minutes to complete the entirety of the AMMA. The computer provided normed scores, percentile rankings, and raw scores for overall performance and the rhythm and melody sub-tests. Higher raw scores on the

AMMA and higher percentile ranks indicate higher performance. Because musical training does impact raw scores on the AMMA, I used normed scores from the two subtests in the data analyses.

Procedure

Experiment 2 spanned two one-hour experimental sessions. Participants waited a minimum of 48 hours between each session, with this break designed to avoid carryover effects between the auditory and visual modalities (as observed in Grahn, Henry, & McAuley, 2010). It weakened participants' memory of the musical excerpts, which were identical in both sessions (visual and auditory metronomes). The experimental sessions were counterbalanced, with half of each group of participants (musicians and non-musicians) encountering the auditory metronome version of the task first, and half receiving the visual metronome version of the metronome first. All participants took the WASI-II on their first session and the AMMA on their second session, with the experimental task performed first and the testing second each session.

All participants granted informed consent to participate in the study prior to inclusion. During the consent process, the experimenter told the participant this experiment was a study of rhythm perception, and the experiment was intended to find out how people feel sounds and rhythms in music match when the rhythms are in sound (auditory) or in sight (visual). The experimenter also told the participant they would take a vocabulary quiz (the WASI-II Vocabulary subtest), a pattern completion task (the WASI-II Matrix Reasoning subtest), and a music quiz (the AMMA). The experimenter reminded participants that they were free to ask questions at any time, and that their questions would be answered as best as possible during the study and fully answered after study completion.

The participant completed the music and metronome rating task first in both experimental sessions. For the rating task the participants sat in front of a computer monitor approximately 70 cm away and wore sound attenuating, over-the-ear headphones (Sennheiser 280 Pro, Sennheiser Electronic Corporation, Old Lyme, CT) as in Experiment 1. Before the participants began the experimental tasks, the experimenter read a short description of the aim of that experimental session (visual or auditory as appropriate; see Appendix A for experimenter instructions for the auditory and visual conditions) and read the first computer screen of instructions to the participants. Participants heard the auditory metronomes and music presented dichotically as in Experiment 1, and heard the musical excerpts binaurally while performing the visual metronome condition.

The custom programs for stimulus presentation and response collection were kept as similar as possible between the two modalities, with only minor changes in the wording between the visual and auditory metronome versions to accommodate the different modalities. The same four-point Likert rating scale as in Experiment 1 was used in Experiment 2. The five-second time-out from Experiment 1 was also used again. As in Experiment 1, the total number of missed trials was less than 1% of the total trials across all participants. Participants would have been excluded if they missed more than 25% of the trials in a given metronome modality session, but no participants met this criteria.

After completing the computer task, participants completed the WASI-II (first experimental session) or AMMA (second experimental session). All participants completed the WASI-II on the first session and the AMMA on the second session, regardless of group membership or modality of experimental task order. This was to avoid priming musical expectations or activating musical stereotypes for the second session in the group that had the AMMA first, but not the group that took the WASI-II first. For the WASI-II, the participant and the experimenter moved to a separate room and the experimenter administered the Vocabulary and Matrix Reasoning sub-tests to the participant. In the second session, participants moved to a different computer in the same room and completed the AMMA. All instructions on the AMMA were computer-narrated. After completing the AMMA, participants filled out the demographic questionnaire (see Appendix B). Each session, including the beat/measure perception task and the AMMA/WASI-II administration, took approximately 50-55 minutes.

Planned Analyses

In Experiment 2, I wanted to compare participants' ability to detect beat- and measure-level synchrony between music and metronomes when the metronomes were either visual or auditory. Would participants use beat- and measure-level information differently depending on the modality of the metronome? I submitted participants' average ratings of fit between the metronome and musical excerpt into a 2 (modality: auditory or visual; within-subjects) x 2 (beat: synchronous or asynchronous; within-subjects) x 2 (measure: synchronous or asynchronous; within-subjects) x 2 (group: musician or non-musician; between-subjects) mixed-model ANOVA. Comparisons among groups, modalities, and manipulations were compared with *t*-tests either between or within groups.

All participants took standardized measures of intelligence (WASI-II) and musical aptitude. To determine if there were any overarching group differences, I conducted a 2 (group membership) x 4 (subtest identity) mixed-model ANOVA on normed scores from the WASI-II (using standardized scores) and AMMA subtests (using percentile ranks).

Would musical aptitude or general intelligence factors (as measured by the AMMA and WASI-II, respectively) predict sensitivity to beat- or measure-level synchrony above and beyond formal musical training? I submitted beat difference scores and measure difference scores for the auditory metronomes and visual metronomes to a series of multiple regressions, with WASI-II and AMMA sub-test scores, years of musical training and hours of music practice per week as the predictor variables.

Results

ANOVAs

Combined Metronome Modalities 4-Way ANOVA

How does musical training, measure- and beat-level synchrony between metronome and music, and metronome modality affect participants' ratings of fit between metronome and music? I submitted participants' average ratings of fit per metronome condition to a 4-way mixed-model ANOVA, with group membership as a between-subjects variable, and metronome modality, beat-level synchrony, and measure-level synchrony as within-subjects variables. The results from the four-way mixed-model ANOVA are presented in Table 5.

Table 5. Effects of Modality (auditory and visual), Group (musician and non-musician), beat (synchronous and asynchronous) and measure (synchronous and asynchronous) on ratings of fit of metronome to musical excerpt.

Source	***F***	**η_p^2**
Modality	4.28*	.125
Beat	378.67**	.972
Measure	9.24**	.236
Group	3.11	.094
Modality * Group	1.78	.056
Modality * Beat	19.38**	.392
Modality * Measure	<1	.007
Beat * Group	8.24**	.215
Measure * Group	18.40**	.380
Beat * Measure	65.85**	.687
Modality * Beat * Group	2.08	.065
Modality * Measure * Group	<1	.007
Modality * Beat * Measure	3.83	.113
Beat * Measure * Group	<1	.008
Modality * Beat * Measure * Group	<1	.006

* $p < .05$. ** $p < .01$. *Note:* All F tests conducted on 1 and 30 degrees of freedom.

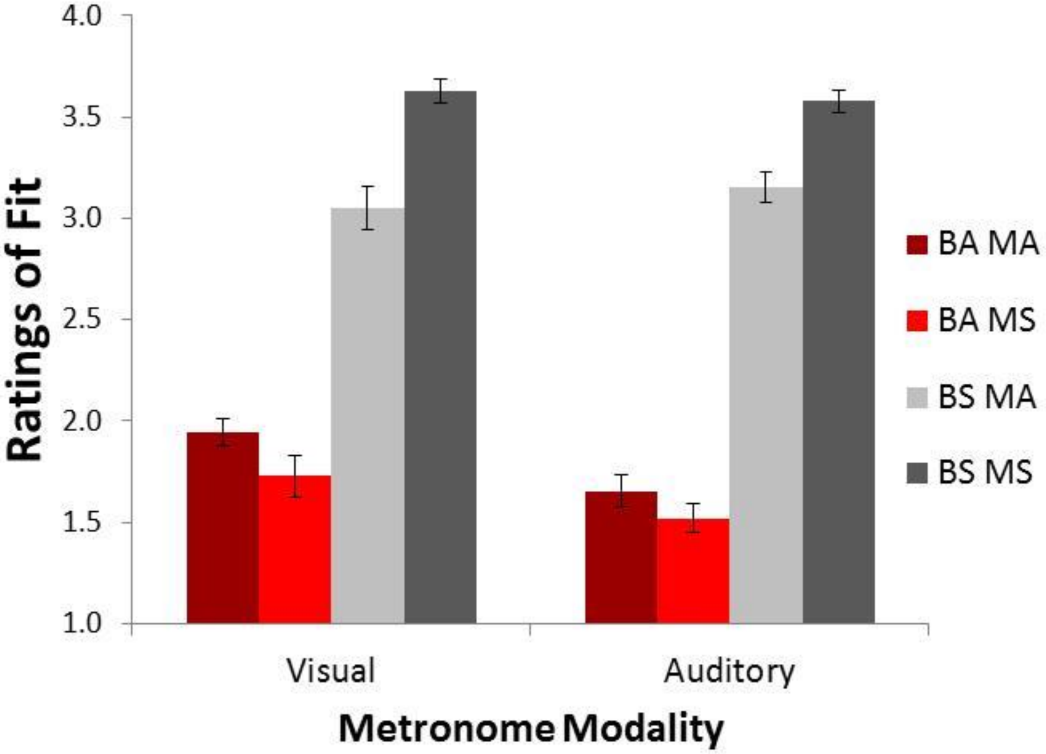
The manipulations of metronome modality, beat, and measure all had significant main effects. For modality, participants rated visual metronomes ($M = 2.59$) as fitting the music better than auditory metronomes ($M = 2.48$). However, metronome modality interacted with beat, with participants giving higher ratings of fit to beat-asynchronous visual metronomes ($M = 1.84$) than to beat-asynchronous auditory metronomes ($M = 1.59$). Participants rated beat-matching metronomes in the visual ($M = 3.34$) and auditory ($M = 3.37$) modality similarly.

The main effect of beat was that participants rated beat-synchronous metronomes ($M = 3.35$) as fitting the music better than beat-asynchronous metronomes ($M = 1.71$). Beat significantly interacted with group and with measure. Musicians gave higher ratings of fit ($M = 3.40$) to beat-synchronous metronomes than non-musicians ($M = 3.30$), and musicians gave lower ratings of fit ($M = 1.52$) to beat-asynchronous metronomes than non-musicians ($M = 1.91$). The interaction between beat and measure changed ratings of fit as well. When the beat of the metronome was asynchronous, participants rated fully asynchronous (BAMA) metronomes (*M* = 1.80) as better-fitting than beat-asynchronous measure-synchronous metronomes (BAMS; *M* = 1.62). However, when the beat of the metronome was synchronous, participants rated fully-synchronous (BSMS; *M* = 3.60) metronomes as better-fitting than beat-synchronous but measure-asynchronous (BSMA; *M* = 3.10) metronomes.

The main effect of measure was similar to beat, but not as strong in the ratings. Participants rated measure-synchronous metronomes (*M* = 2.61) as fitting the music better than measure-asynchronous metronomes (*M* = 2.45). The interaction between measure and group was driven by opposite results in musicians and non-musicians. Musicians rated measure-synchronous metronomes (*M* = 2.66) as fitting the music better than measure-asynchronous metronomes (*M* = 2.27), whereas non-musicians rated measure-asynchronous metronomes (*M* = 2.64) as fitting the music better than measure-synchronous metronomes (*M* = 2.58). Musicians seemed to be more sensitive to measure-level synchrony regardless of beat-level synchrony, while non-musicians appeared to need beat-level synchrony to detect measure-level synchrony.

A three-way interaction among modality, beat, and measure approached conventional significance levels (*p* = .060). While participants gave similar ratings for beat-matching metronomes in the auditory (BSMS *M* = 3.58, BSMA *M* = 3.15) and visual (BSMS *M* = 3.63, BSMA *M* = 3.05) modalities, they differed when the beat was asynchronous. Participants gave higher ratings of fit for beat-asynchronous visual metronomes (BAMA *M* = 1.95; BAMS *M* = 1.73) than auditory metronomes (BAMA *M* = 1.66; BAMS *M* = 1.52). This suggests that participants were less sensitive to beat and measure asynchrony in visual metronomes than in auditory metronomes, but did rate synchronous metronomes as better fitting in either modality.

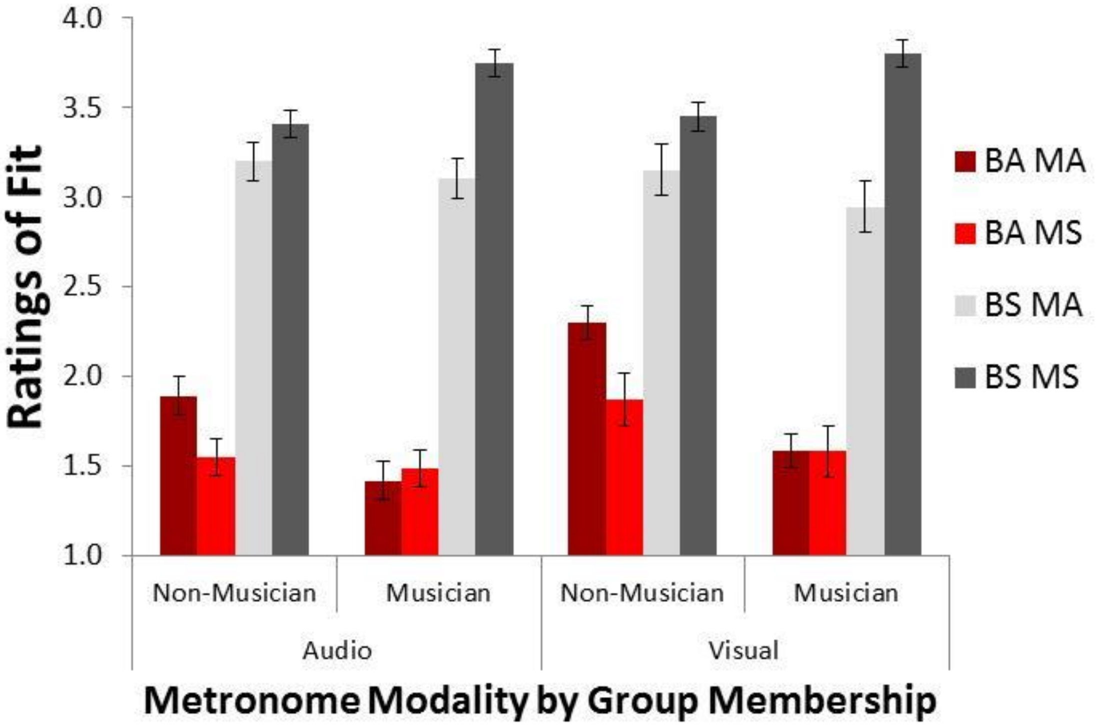
Figure 7. Effects of metronome modality, beat synchrony, and measure synchrony on ratings of fit between metronome and music.



While the higher-order interaction among beat, measure, modality, and group did not reach significance, Figure 8 illustrates the interaction and patterns of ratings of fit. Interestingly, musicians and non-musicians both showed similar patterns of ratings in the visual and auditory modalities that were consistent within groups and different across groups. Musicians showed similar ranges of ratings across the metronomes modalities, but non-musicians were more restricted in their range of ratings for visual metronomes than auditory metronomes, rating all beat-asynchronous metronomes as fitting the music better in the visual modality than they did the identical auditory metronomes.

Figure 8. Ratings of beat and measure manipulated metronomes by metronome modality and

group membership.



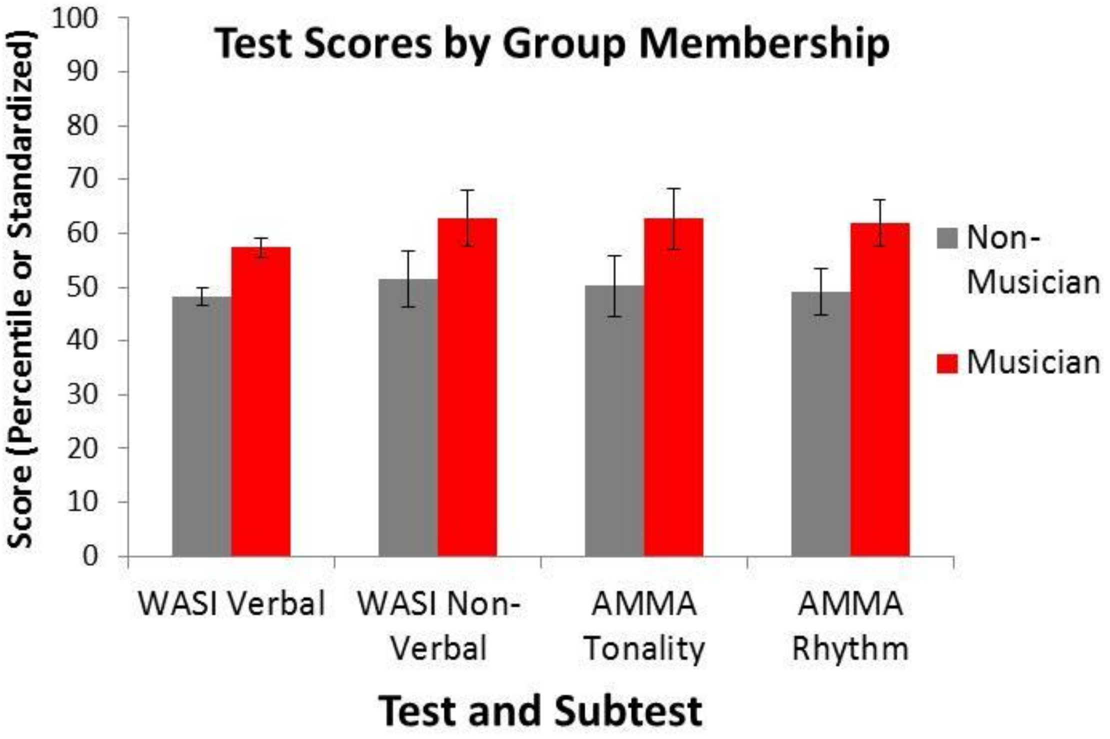
Musicians rated beat-asynchronous metronomes similarly regardless of measure-level synchrony in both modalities (auditory BAMA-BAMS: *t*(15) = -0.61, *p* = .550; visual BAMA-BAMS: *t*(15) = 0.04, *p* = .972). Non-musicians did, however, rate fully-asynchronous (BAMA) metronomes as better-fitting than BAMS metronomes in both metronome modalities (auditory BAMA-BAMS: *t*(15) = 3.89, *p* = .001; visual BAMA-BAMS: *t*(15) = 4.69, *p* < .001).

When the beat of the metronome matched the music, both musicians and non-musicians rated fully synchronous (BSMS) metronomes as better fitting than BSMA metronomes. Musicians gave higher ratings of fit to BSMS over BSMA metronomes for both auditory and visual metronomes (auditory BSMA – BSMS: *t*(15) = -5.74, *p* < .001; visual BSMA-BSMS: *t*(15) = -5.61, *p* < .001). Non-musicians similarly rated auditory and visual BSMS metronomes as fitting the music better than BSMA metronomes (auditory BSMA – BSMS: $t(15) = -2.48$, $p = .026$; visual BSMA-BSMS: $t(15) = -2.34$, $p = .034$).

2-Way Test Scores ANOVA

To compare group performance on the measures of intelligence and musical aptitude, I submitted test scores from the AMMA and the WASI-II to a two-way mixed-model ANOVA. Group (musician or non-musician) was a between-subjects variable and subtest (WASI-II verbal or non-verbal and AMMA rhythm and tonality) was a within-subjects variable. The scores reported have been converted to normalized scores based on the normative data provided with each test. For each subtest, a score of 50 represents the 50th percentile. There was no main effect of test identity, $F(3,90) = .51$, $p = .68$, $\eta_p^2 = .017$. As a whole group, participants scored roughly equally on all four subtests. However, there was a significant main effect for group, $F(1,30) = 7.46$, $p = .010$, $\eta_p^2 = .199$. Musicians scored higher on all four subtests than non-musicians, as illustrated in Figure 8. Test and group did not interact significantly, $F(3,90) = .10$, $p = .963$, $\eta_p^2 = .003$. The group difference between musicians and non-musicians was about 10 percentage points, with musicians scoring around the 60th percentile and the non-musicians scoring at the 50th percentile on average. While this is less than ideal, as it suggests that musicians systematically differed from non-musicians as a group, it also raises interesting questions as to why musicians are different than non-musicians.

Figure 9. Percentile and normed rank scores on the WASI-II Vocabulary and Matrix Reasoning Subtests and the AMMA Tonality and Rhythm Subtests.



Multiple Regressions

I performed a series of four multiple regressions on beat and measure difference scores to determine if any of the demographic variables or the measured intelligence and musical aptitude scores predicted beat-level or measure-level sensitivity. Because different metronome modalities may have tapped different processes, I separated the beat and measure scores by metronome modality, creating an auditory version of each and a visual version of each. All four standard multiple regression models used the WASI-II Verbal scores, WASI-II Non-Verbal scores, the AMMA Rhythm scores, AMMA Tonality scores, hours of music practice per week, years of musical training, and hours of music listened to per week as predictors. See Table 7 for overall model results.

Table 6. Standard multiple regression models, overall significance and explained variance for the four dependent variables.

Dependent Variable	***F***	***P***	R^2	**Adj.** R^2
Auditory Beat Difference Score	0.85	.562	.205	-.037
Auditory Measure Difference Score	4.04	.005	.551	.451
Visual Beat Difference Score	1.10	.397	.250	.022
Visual Measure Difference Score	4.08	.005	.554	.418

Auditory Metronome Beat Difference Score.

The overall multiple regression on auditory beat difference scores did not predict a significant amount of variance (see Table 7). None of the predictor variables accounted for a statistically significant portion of the variance in the auditory beat difference scores. Beta values ranged from -0.247 to 0.252, and *p* values ranged from .318 to .947.

Auditory Metronome Measure Difference Score.

For measure difference scores using auditory metronomes, the multiple regression model accounted for a significant portion of the variance in scores However, the Rhythm AMMA score was the only significant predictor, $t(23) = 2.40$, $p = .025$, $\beta = 0.457$. Higher scores on the rhythm subscale of the AMMA predicted higher measure difference scores with auditory metronomes. No other predictors reached significance; all other *p*'s ranged from .158 to .788; all other β's ranged from -0.153 to 0.270.

Visual Metronome Beat Difference Score.

The overall multiple regression model did not explain a significant portion of the variance in the visual metronome beat difference scores. None of the individual predictors accounted for enough unique variance to reach statistical significance. Significance values on all predictors ranged from .127 to .515.

Visual Metronome Measure Difference Score.

In the multiple regression predicting measure difference scores for visual metronomes, the model successfully predicted between 41-55% of the variance. No predictors reached statistical significance individually, but several trended toward significance. Hours of practice per week approached significance as an individual predictor, $t(23) = 1.98$, $p = .060$, $\beta = 0.368$, with higher amounts of practice predicting higher measure difference scores. Hours of music listened to on a weekly basis also approached significance, $t(23) = -1.96$, $p = .063$, $\beta = -0.313$. Interestingly, lower levels of musical listening predicted higher measure difference scores. Years of musical training trended toward significance as an individual predictor, $t(23) = 1.74$, $p = .095$, $\beta = 0.323$, with more musical training predicting higher measure difference scores. None of the other predictors approached significance, with *p*-values ranging from .317 to .846.

Age and Musical Training on Difference Scores.

As in Experiment 1, the average age of the musician group (M = 31 years, 2 months) and non-musician group (M = 21 years, 7 months) were markedly different. To statistically control for the effects of age when examining the impact of musical training, and to control for musical training when examining the effects of age, I performed four multiple regressions on the auditory metronome and visual metronome beat difference scores and measure difference scores, using participant age and years of musical training as predictors.

The regression on auditory beat difference scores did not account for a significant amount of the variance in scores, $F(2,28) = 1.27$, $p = .296$, $R^2 = .083$. Similarly, the regression of age and years of musical training on visual beat difference scores was not statistically significant, *F*(2.30) = 1.40, *p* = .264, R^2 = .091.

The overall multiple regression on auditory measure difference scores did explain approximately 29-34% of the variance in participant scores, *F*(2,30) = 7.26, *p* = .003, R^2 = .342 (adj. R^2 = .295). When statistically controlling for participant age, years of musical training accounted for a significant portion of the variance in measure difference scores, *t*(30) = 2.35, *p* = .026, β = 0.831, with more years of musical training related to higher measure difference scores. Participant age, when controlling for years of musical training, did not significantly predict a unique portion of the variance, *t*(30) = -0.82, *p* = .422, β = -0.289.

Similarly, the multiple regression of participant age and musical training on visual measure difference scores predicted approximately 35-39% of the variance in scores, *F*(1,30) = 9.18, *p* = .001, R^2 = .396 (adj. R^2 = .353). When statistically controlling for age, years of musical training predicted a significant portion of unique variance, *t*(30) = 3.47, *p* = .002, β = 1.18, with greater amounts of musical training related to higher visual measure difference scores. Even controlling for musical training, participant age also predicted a significant portion of unique variance, *t*(30) = -2.04, *p* = .051, β = -0.694, with younger participants having higher scores and older participants having lower measure difference scores.

Discussion

In Experiment 2, I presented individuals with and without formal musical training with auditory and visual metronomes that matched or mismatched the metrical structure of the music. If structuring incoming rhythmic input in a hierarchical fashion is a domain-general mechanism for temporal perception, the same pattern of metrical perception from the auditory modality should be seen in other senses. I attempted to quantify musical ability with an objective assessment, and I also looked for a relationship among verbal and non-verbal intelligence and meter perception. I found that musicians and non-musicians showed similar patterns of metrical perception across modalities, and that neither musical ability nor intelligence was strongly related to metrical perception.

Musicians and non-musicians responded to the auditory metronomes in Experiment 2 in the same way they responded in Experiment 1. Both groups rated beat-mismatching metronomes as fitting the music poorly, and beat-matching metronomes as fitting the music well. When the auditory metronomes matched the music at both the beat- and measure-level, they received the highest ratings of fit from both groups. The effect of measure-level matching in the absence of beat-level matching decreased ratings of fit for non-musicians, and did not alter ratings of fit as compared to the fully-mismatching metronomes from musicians. The replication of the findings in Experiment 1 strengthens the argument that listeners are capable of extracting multiple levels of the metrical hierarchy from musical excerpt and from isochronous patterns such as the metronomes.

In some of the first evidence of hierarchical structuring of musical information in the visual system, all participants successfully extracted both beat- and measure-level information from the visual metronomes and matched them to the metrical structure in the music. All participants rated beat-matching visual metronomes as fitting the music better than beat-mismatching metronomes. As with the auditory metronomes, both the musician group and the non-musician group rated fully-matching (beat- and measure-level) visual metronomes as fitting the music better than the metronomes that matched only at the beat-level. As with the auditory metronomes in Experiment 1 and the current experiment, the difference was stronger in the musician group than in the non-musician group, but both groups rated fully-matching metronomes as fitting the music better than beat-matching alone metronomes.

The ability of participants to match the beat of the visual metronome to the beat of the music aligns with research showing stronger beat perception and sensorimotor synchronization with visual stimuli with high amounts of spatial information (Brandon & Saffran, 2011; Grahn 2012, Hove, Fairhurst, et al., 2013; Hove, Iversen, et al., 2013; Hove, Spivey, & Krumhansl, 2010; Iversen et al., 2015; Su, 2014b). The visual metronomes appeared as clocks that discretely "ticked" from one beat to the next like a clock, incorporating both spatial (place) and temporal (rate) information.

While on average, all participants gave higher ratings of fit to fully-matching metronomes over those that matched only on the beat, musicians differentiated between one and two levels of metrical matching in their scores more strongly than non-musicians. Two possible explanations come to mind to explain the greater discrimination between beat-matching only and beat- and measure-matching metronomes by musicians in the visual metronome condition. First, musicians may have more experience with translating visual stimuli into musically relevant information. Many musicians engage in group performances, often with a conductor indicating the beat of the music in a visual manner with the gestures of the baton. Musicians are better at extracting metrical information and beat information from movements of a conductor than non-musicians, possibly because of this experience (Luck & Toiviainen, 2006; Luck, Toiviainen, & Thompson, 2010). Alternatively, formal musical training and instruction in the idea of metrical hierarchies may bestow perceptual benefits to any modality where a beat can be perceived or bias individuals to perceive rhythmic information in a hierarchically structured format. When presented with metrically-structured rhythmic patterns through vibrotactile stimulation, individuals with formal musical training were more successful at extracting beat and meter information even in the absence of auditory cues, suggesting that beat can be perceived in multiple senses (Huang et al., 2012).

The non-musicians and musicians differed on average intelligence and musical aptitude as a group. On average, musicians scored 10 points higher in standardized scores and percentile rankings for both verbal and non-verbal intelligence and musical aptitude. Formal musical training consistently relates to higher reported measurements of verbal vocabulary, memory, and ability (Brandler & Rammsayer, 2003; Foregard, Winner, Norton, & Schlaug, 2008). However, the differences in intelligence and musical aptitude between the groups did not consistently explain individual differences in performance on the ratings task. Higher scores on the AMMA only significantly predicted measure-level perception with visual metronomes, and neither verbal nor non-verbal intelligence related in any systematic way to meter perception. While the average age and education levels of the musician and non-musician groups did differ (musicians were older and more educated than non-musicians), the WASI-II and AMMA norming processes take into account age and musical training. The observed differences for musical aptitude between groups may be the result of self-selection effects: individuals with higher musical aptitude may have chosen to pursue musical careers or have continued with their musical education and practice, whereas individuals with some musical experience but lower ability may have abandoned music practice and adopted other pursuits.

Overall, very few variables predicted individual differences in sensitivity to metrical structure. Scores on the rhythm subtest of the AMMA, which one would expect to correlate with meter perception, only significantly predicted visual measure-difference scores. Even traditional self-report measures of musicianship and musical seriousness, such as hours of practice per week and years of musical training did not significantly predict differences in meter perception. As there were clear differences in ratings between musicians and non-musicians, some element of musical training seems to enhance metrical perception. However, just what aspect of musical training aids rhythm processing and metrical perception is not immediately obvious. Perhaps it is more active engagement in musical production and performance that influences meter perception, and not just accumulated years of musical training. Perhaps a threshold of seriousness in musical study must be reached. Current engagement in musical behavior, as measured by hours of practice per week, seemed to have more influence on metrical perception than accumulated years of musical training, suggesting that active engagement may be more important than past training. Overall, the lack of influence of traditional variables that are used to represent musicianship on metrical perception suggests that, at least for rhythm perception, we may need to re-think how we define “musician”.

General Discussion

In these two experiments, I sought to answer three major questions: are listeners capable of perceiving multiple levels of hierarchical structure in music (musical meter), is musical training necessary for meter perception, and are listeners able to perceive metrical structures in visual patterns. In Experiments 1 and 2, participants listened to rich, ecologically valid excerpts of human-performed music, and experienced auditory or visual metronomes with metrical information that either matched or did not match the metrical information present in the music. Listeners rated how well the metronomes matched the music, ideally using the metrical match between the metronome and the music to decide their ratings of fit.

Beat-level matching between the metronome and the music was the strongest driver of ratings of fit for all participants. Musicians and non-musicians alike are well able to match the beat of an isochronous metronome to simple or complex musical stimuli (Fujii & Schlaug, 2013;

Patel & Iversen, 2008; for a review, see Repp & Su, 2013). The strong influence of beat-level matching between the metronomes and music on ratings of fit replicates this finding in a perceptual task.

All listeners rated the fully (beat and measure) matching auditory metronomes as fitting the music better than those that matched at only one metrical level (either only beat level or only measure level) or those that did not match the metrical structure of the music at all. Musicians and non-musician groups used beat and measure information in their ratings of fit, but the ratings from participants in both groups were more strongly influenced by beat-level matching of the metronomes to the music than by measure-level matching. The measure-level information in the metronomes influenced their ratings of fit most strongly when the beat level matched between the metronome and the music. Thus, listeners successfully attended to multiple levels of the metrical hierarchy, but did not attend to both levels with equal weight.

Listeners successfully extracted the metrical structure from complex pieces of human-performed music to compare against the metrical structure of isochronous visual or auditory sequences. The perception of metrical structure is enhanced by additional information above rhythmic cues alone (Snyder et al., 2006). Previous studies of metrical perception have used simple isochronous patterns (Fujioka et al., 2010, 2015; Nozaradan et al., 2011, Paul et al, 2015; Snyder & Large, 2005) or rhythmic patterns with tones or a single instrument (Geiser et al., 2010; Huang et al., 2013; Iversen et al., 2009; Nozaradan et al., 2012). Other studies have used melodic and harmonic combinations with multiple instruments, but have been computer-generated and thus the timing is perfectly isochronous (Geiser et al., 2009; Hannon & Johnson, 2005; Hannon, Soley, et al., 2012; Hannon & Trehub, 2005; Hannon, Vanden Bosch der Nederlanden, et al., 2012). Yet human musical behavior is not strictly isochronous, and the beat in musical performances is at best quasi-isochronous (Clarke, 1985; Desain & Honing, 1994). Metrical perception is a robust phenomenon if listeners are able to successfully extract the metrical structure from complex music with expressive timing variation, as individuals did in the current studies.

In this study, participants successfully perceived beat- and measure-level information in visual metronomes and matched the visual metronomes to the music. In Experiment 2, musicians and non-musicians successfully extracted beat-level information from visual metronomes, rating those that matched the music at the beat-level as fitting better than the visual metronomes that did not match the beat of the music. This replicates the findings of beat perception and sensorimotor synchronization at the beat level with visual stimuli possessing both spatial and temporal information (Grahn, 2012; Hove, Fairhurst, et al., 2013; Hove, Spivey, & Krumhansl, 2010; Su, 2014; Su & Pöppel, 2012). Furthermore, when the beat of the visual metronome matched the music, both musicians and non-musicians rated the fully (measure and beat) matching metronomes as fitting the music better than metronomes that matched the beat but not measure of the music. Musicians showed the strongest evidence of this, but it was present in the ratings of non-musicians as well.

Both the musically trained and the musically untrained groups used both levels of metrical information in the metronomes in their ratings of fit, but formal musical training enhanced metrical perception. Listeners in both groups rated fully matching auditory and visual metronomes as fitting the music better than those that matched only at the beat. The difference in ratings of fit was strongest for musicians, but non-musicians showed the same pattern of preference for fully metrically matching metronomes over metronomes that matched the music only at the beat level. Adding in multiple levels of metrical information to an isochronous stimulus improves tapping accuracy for listeners with varying levels of musical training (Madison, 2014), suggesting that listeners are capable of perceiving the metrical hierarchy at some level, regardless of musical training. Similarly, American listeners were able to detect disruptions to the metrical structure of both simple and complex rhythms, even though they were less familiar with complex metrical structure (Hannon, Soley, & Ullal, 2012). The stronger preference for metrically matching metronomes in musicians fits with previous investigations that found perceptual advantages in detecting metrical disruptions for musically trained individuals over musically untrained individuals (Geiser, Sandmann, Jäncke, & Meyer, 2010).

The perception of metrical structure in visual metronomes may be related to participants' familiarity with the incorporation of hierarchical structure into music-induced movement. Professional dancers in samba and Charleston styles incorporate movements that echo multiple levels of meter in the music they dance to (Naveda & Leman, 2010). Musicians embody multiple levels of musical meter when moving to the music (Toivianinen, Luck, & Thompson, 2010), as do individuals with no dance or musical training (Burger, Thompson, Luck, Saarikallio, & Toiviainen, 2014). Even if participants could not explicitly articulate the idea of meter or hierarchical patterning, they may be familiar with visual representations of multiple levels of musical meter.

While musicians' ratings of fit for visual and auditory metronomes in Experiment 2 stayed in roughly the same range, non-musicians showed a reduction in range of their ratings. The fully mismatching and beat-mismatching but measure-matching visual metronomes received higher ratings of fit from non-musicians than the identical auditory metronomes. The visual metronome condition required participants to make cross-modal judgments of synchrony: the music was heard, but the metronome was seen. When humans integrate information from multiple senses, there is a window of time in which stimuli that are presented at different times are considered to be simultaneous to the perceiver: the temporal integration window (TIW). Drummers and pianists have narrower temporal integration windows than non-musicians and singers (Krause, Pollok, & Schnitzler, 2010; Lee & Noppeny, 2011). Furthermore, experience with music and musical training enhances musicians' ability to detect audiovisual asynchronies (Petrini, Dahl, et al., 2009; Petrini, Russel, & Pollick, 2008). Non-musicians may perceive smaller stimulus-onset asynchronies between visual and auditory information as synchronous, whereas musicians experience them as asynchronous.

While musical training did confer benefits to metrical perception, even non-musicians used beat- and measure-level information when matching the metronomes to the music. This suggests that perceiving hierarchical structures underpinning patterns of events in time – meter – is a general mechanism that does not require formal musical training. However, it may require repeated exposure to metrically structured input, like the music of an individual's culture. Starting as early as infancy, we find it easier to detect rhythmic disturbances in familiar metrical patterns (Hannon, Soley, & Levine, 2011; Hannon, Soley, & Ullal, 2012). Exposure to unfamiliar music and metrical structure improves detection of metrical disruptions in young children, but not as much in older children and adults (Hannon, Vanden Bosch der Nederlanden, & Tichko, 2012). Adults also have an easier time tapping to music structured in metrically familiar ways (Snyder, Hannon, Large, & Christiansen, 2006; Ullal-Gupta, Hannon, & Snyder, 2014), and tap at higher levels of the metrical structure for culturally familiar over unfamiliar music (Drake & El Heni, 2003).

The results of these experiments demonstrated that listeners are capable of perceiving multiple levels of the metrical hierarchy, but more work is required to determine if this is a general cognitive mechanism. Listeners only judged two different metrical structures: three beats or four beats per measure, and all of the beats in each measure were of equal duration. Other musical cultures, such as Turkish, Balkan, North African, and Northern Indian music use more complex metrical structures, with beats of unequal duration in the same measure. As these more complex metrical structures are still metrically structured, listeners should theoretically be able to perceive the metrical structure in these complex forms. Further work is needed to determine if listeners are able to make use of multiple levels of metrical structure when the music is less familiar, or if familiarity and enculturation is necessary for perceiving and attending to multiple levels of the metrical structure.

Participants in the current study demonstrated that they were able to extract beat and measure information out of visual metronomes and match these metrical structures across modalities to the metrical structure of the music. However, we still do not know if people are able to extract metrical information out of complex visual patterns, even in the absence of auditory input. Without music, can listeners decide if a dancer is moving in a particular metrical pattern? While analyses of motion-capture recordings of people moving to music confirm that dancers embody different levels of meter in their movements (Burger et al, 2014; Naveda & Lehman, 2010; Toiviainen, Luck, & Thompson, 2010), it has not been conclusively established that viewers are aware of this structure. However, metrical structuring of visual information may alter attentional allocation and thus performance. In a target detection task, participants responded the slowest to targets that fell on the metrically emphasized locations in a video of a popular dance (Lee et al., 2015).

Listeners with and without formal musical training successfully perceived and used multiple levels of hierarchical temporal organization at the same time to make judgments of fit.

While familiarity and formal musical training enhanced the accuracy and sensitivity of the metrical perception, formal training was not a necessary prerequisite for meter perception. Participants were further able to match metrical structure cross-modally and use beat- and measure-level information in auditory and visual metronomes and match them to the metrical structure of complex, human-performed music with its varied and non-isochronous timing. This lends support to the idea that our sensory systems automatically structure the temporal information underlying rhythmic stimuli into hierarchical relationships, with some temporal locations perceived as stronger and other locations perceived as weaker. From here, further inquiries can determine the capacities and limits of metrical perception across vision and audition, and if metrical perception requires familiarity or enculturation with the idiom it is presented in.

Appendix A

Table 7. Demographic information from participants in Experiment 1.

Demographic Variable		**Non-Musicians**	**Musicians**
Sample Size (Females)		32 (19)	22 (11)
Age Range		18-45	18-62
Average Age (SD)		20.79 (5.3)	33.05 (+/-13.61)
Hispanic Participants		7	3
Races	Caucasian	16	21
	Korean	2	0
	Black/African American	4	0
	Chinese	1	1
	American Indian	0	1
	Filipino	6	2
	Japanese	0	1
English as a First Language		23	22
Age Learned English if not First Language		4.62 (2.13)	n/a
Speak More than One Language		20	11
Lived Outside the US		8	8
Frequent Ear Infections		2	2
Pressure Equalizing Tubes as a Child		4	1
Family History of Hearing Impairment		2	0
Had A Cold		0	2
Had an Ear Infection		0	2
Ever Taken Private Music Lessons		15	22
Years of Musical Training		5.35 (3.63)	19.41 (13.64)
Average Age of Starting Lessons (SD)		10.5 (3.59)	10 (3.56)
Currently Taking Private Music Lessons		0	10
Currently Practicing Music		2	20
Average Hours Music Practice/Week		n/a	13.8 (12.12)
Have Absolute Pitch		4	4
Ever Taken Dance Lessons		10	12
Average Age of Starting Dance Lessons		6.9 (3.9)	17.04 (11.48)

Years of Dance Training	6.1 (6.09)	5.88 (14.01)
Hours of Music Listened to/week	19.82 (13.25)	14.91 (9.68)

Note: This includes all participants, prior to data analysis. Two participants whose demographic information is included here were not used in data analysis.

Appendix B

Experimenter Instructions to participant.

Experiment 1, Experiment 2 (Auditory Metronomes):

“We're interested in how well people feel that sounds and music match up when we play them to you together. In this experiment, you'll be hearing music and click tracks presented to you over headphones, and we'll be asking you how well you think the two sounds matched or fit together. There are no right or wrong answers; don't think too hard about it, just give us the answer that feels right to you. You will start out with some practice trials that will explain the rating scale and the sounds to you, and then move on to the rest of the experiment once you are ready. In the experiment, you will listen to a sound, and after it is finished you have about five seconds to enter your response as to how well you felt the sounds fit together. If you do not get an answer in, it's okay – just focus on the next set of sounds you hear, and forget the previous sounds. If you have questions, please ask them now, or ask me during a break in the experiment. If you have a cell phone, please set it to “silent” and keep it out of sight during the experiment. Now, I'm going to read to you the instructions on the screen, and when you are ready, you may begin.”

Experiment 2 (Visual Metronomes):

“We're interested in how well people feel that sounds and images match up when we play them to you together. You'll be hearing music over headphones and seeing images on the computer screen, and we'll be asking you how well you think the sounds and images “matched” or fit together. There are no right or wrong answers; don't think too hard about it, just give us the answer that feels right to you. You will start out with some practice trials that will explain the rating scale and the sounds and images to you. Once you’re ready, you’ll move on to the rest of the experiment.

On each trial, you’ll hear the sound and see the visual image. Afterward you have about five seconds to enter your response as to how well you felt the sounds fit together. If you do not get an answer in, it is okay – just focus on the next set of sounds and images you hear, and forget the previous sounds and images. If you have questions, please ask them now, or ask me during a break in the experiment. Now I'm going to read to you the instructions on the screen, and when you are ready, you may begin.”

Appendix C

Auditory Experience Questionnaire

(All information will be kept confidential)

*Today's Date:*________ *Experimenter:*_____

*SS#:*__________ *Run#:*________ *Time:*___________

Sex: ○ Male

○ Female

Participant Initials: ____________________

Year: ○ Fresh. ○ Soph. ○ Jr. ○ Sr. ○ Non-degree seeking

Background Information

Age:	______________________________
Are you Spanish/Hispanic/Latino? (*Check one)*	○ No, not Spanish/Hispanic/Latino ○ Yes, Puerto Rican ○ Yes, Mexican, Mexican-American, Chicano ○ Yes, Cuban ○ 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
☐ Other Asian: ______________________
☐ Other Pacific Islander: _____________
☐ Japanese

Parent's Highest Education Level?	○ No H.S. diploma ○ H.S. diploma ○ Some college ○ 4-year College degree ○ Graduate school degree ○ Technical school

Hearing History

Have you ever had frequent ear infections (more than three per year)?	○ Yes, at what age(s)? ________________________ ○ No
Have you ever had pressure equalizing tubes in his/her ears?	○ Yes, at what age(s)? ________________________ ○ No
Does your family have a history of hearing impairment?	○ Yes, describe: _____________________________ ○ No
Do you have a cold today?	○ Yes ○ No
Do you have an ear infection, currently?	○ Yes ○ No
Have you been in any unusually noisy environments?	○ Yes, describe: _____________________________ For how long? _____________________________

○ No

Musical Information

Have you ever taken private music lessons?	○ Yes ○ No
Type of music practiced (Classical/Jazz/Folk)? ____________________	Instrument(s): ____________________
Beginning at what age? __________	No. of years? ____________________
Solo or ensemble? (please describe ensembl type):	____________________
Are you currently taking private lessons?	○ Yes ○ No
Do you currently practice music on a regular basis?	○ Yes, hours/week ____________________ ○ No
Have you ever taken music courses at the university level?	○ Yes, which course(s)? ____________________ ○ No
Do you have absolute pitch?	○ Yes ○ No
Have you ever taken dance lessons or participated in formal dance (Folk dance/Hip-Hop/Ballroom)?	○ Yes ○ No
Type of dance(s):	____________________
Beginning at what age? __________	No. of years? ____________________
Currently taking dance lessons or participating in formal dance	○ Yes ○ No
If yes, please describe:	____________________
How many hours per week do you listen to music?	____________________
Type of music?	____________________

Language Information

Country of Birth:	____________________
Country of Parents' Birth:	____________________

Language…

a. learned as child: ______________________________

b. age English learned, if not first: ______________________________

Do you speak a language other than English ○ Yes ○ No, what other language(s)?

____

a. Non-English language competence ○ Beginner ○ Intermediate ○ Advanced/Fluent

Have you lived in any country outside of North America? ○ Yes, where? ______________________

How long? ______________________

○ No

Please describe your exposure to music there: ______________________________

Thank you for your participation!

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Wing, A. M., & Kristofferson, A. B. (1973). Response delays and the timing of discrete motor responses. *Perception & Psychophysics, 14*(1), 5-12.

Curriculum Vitae

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B.A.	University of Maryland, Baltimore County, 2012 Psychology, summa cum laude
B.A.	McDaniel College, 2006 Music Theory/Composition, summa cum laude
A.A.	Carroll Community College, 2003 Fine Arts, summa cum laude

AREAS OF RESEARCH INTEREST:

Auditory Perception
Audiovisual Synchrony Perception
Time and Sequence Perception
Music Cognition
Cognitive Neuroscience

PUBLICATIONS:

Provine, R.R., Cabrera, M.O., **Nave-Blodgett, J.** (2013) Red, yellow, and super-white sclera: Uniquely human cues for healthiness, attractiveness, and age. *Human Nature, 24*(2): 126-136.

Provine, R.R., Cabrera, M.O., **Nave-Blodgett, J.** (2013) Binocular symmetry/asymmetry of scleral redness as a cue for sadness, healthiness, and attractiveness in humans. *Evolutionary Psychology, 11*(4): 873-884.

Provine, R.R., **Nave-Blodgett, J.,** Cabrera, M.O. (2013) The emotional eye: Red sclera as a uniquely human cue of emotion. *Ethology, 119*: 993-998.

CHAPTERS AND ENCYCLOPEDIA ENTRIES:

Snyder, J.S., Vanden Bosch der Nederlanden, C. M., & **Nave-Blodgett, J.** (2015). Music

Perception. In: *SAGE Encyclopedia of Theory in Psychology*.

MANUSCRIPTS IN PRESS:

MANUSCRIPTS UNDER REVIEW:

Hannon, E. E., Schachner, A.D., **Nave-Blodgett, J.** (submitted). Babies know bad dancing when they see it: Older but not younger infants discriminate between synchronous and asynchronous audiovisual musical displays. *Developmental Science.*

MANUSCRIPTS IN PREPARATION:

Nave-Blodgett, J., Hannon, E. E., & Snyder, J. S. (in preparation). We've got the beat: The development of metrical perception and the effects of training and enculturation.

CONFERENCE PRESENTATIONS:

Nave-Blodgett, J., Hannon, E.E., & Snyder, J.S. (2016). Auditory and visual beat and meter perception in children. *To be presented at the upcoming International Conference on Music Perception and Cognition (ICMPC) 14,* San Francisco, CA.

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Nave-Blodgett, J., Hannon, E. E., & Snyder, J.S. (2015). Do people hear multiple levels of metrical hierarchies in music? *Presented at the Society for Music Perception and Cognition biannual convention, August 1-5, 2015,* Nashville, TN.

Nave-Blodgett, J., Hannon, E. E., & Snyder, J.S. (2015). Do people hear multiple levels of metrical hierarchies in music? *Presented at the GPSA Research Forum, March 21, 2015,* University of Nevada, Las Vegas.

Nave-Blodgett, J., Hannon, E. E., & Snyder, J.S. (2015). Do people hear multiple levels of metrical hierarchies in music? *Presented at the New England Sequencing and Timing (NEST) Conference, March 7, 2015,* University of Massachusetts, Amherst.

POSTER PRESENTATIONS:

Nave-Blodgett, J., Hannon, E.E., & Snyder, J.S. (2016, August). Perception of auditory and visual disruptions to the beat and meter in music. *To be presented at the upcoming International Conference on Music Perception and Cognition (ICMPC) 14,* San Francisco, CA.

Lyons, K.L., Jensen, J.R., **Nave-Blodgett, J.,** Hannon, E. E., & Snyder, J.S. (2016, April). Auditory beat and meter perception in children. *Presented at the Psi Chi Spring Research Fair,* University of Nevada, Las Vegas.

Lyons, K.L., Jensen, J.R., **Nave-Blodgett, J.,** Hannon, E. E., & Snyder, J.S. (2016, March).

Auditory beat and meter perception in children. *Presented at the Undergraduate Student Research Forum,* University of Nevada, Las Vegas.

Nave-Blodgett, J., Snyder, J.S., & Hannon, E.E. (2016, February). Perception of auditory and visual disruptions to the beat and meter in music. *Presented at the Association for Research in Otolaryngology Midwinter Meeting 2016,* San Diego, CA.

Nave-Blodgett, J., Hannon, E.E., & Snyder, J.S. (2014, May). Simultaneous use of beat and meter information in a musical rhythm matching task. *Presented at the UC Merced Center for Human Adaptive Systems and Environments (CHASE) Summer School I: The Dynamics of Music and Language*, University of California, Merced.

Provine, R.R., Cabrera, M.O., Spangler, S., **Nave-Blodgett, J.,** Dorizan, S., Kennedy, I., Koehler, J. (2011, November). When the whites of the eyes are red, yellow and super-white: A uniquely human communication medium. *Presented at the Society for Neuroscience meeting*, Washington DC.

Spangler, S., Koehler, J., Cabrera, M., **Nave-Blodgett, J.,** Dorizan, S., Kennedy, I. (2011, April). Hiccupping: Who does it and when? *Presented at the Undergraduate Research and Creative Achievement Day*, University of Maryland Baltimore County.

HONORS AND AWARDS:

2016-2017	Patricia Sastaunik Scholarship, University of Nevada, Las Vegas Total: $2500
Summer 2016	UNLV Summer Scholarship Total: $2000
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Spring 2016	UNLV Graduate and Professional Student Association Research Forum Honorable Mention speaker
Winter 2015	UNLV Graduate and Professional Student Association Travel Scholarship Total: $675
Fall 2015	Rebel Grad Slam 3 Minute Thesis Competition Finalist; Semifinals 1st place; Qualifiers 1st place & Audience Choice Total: $200
2015-2016	Patricia Sastaunik Scholarship, University of Nevada, Las Vegas Total: $2500
Summer 2015	Society for Music Perception and Cognition 2015 Conference Student Research Award Total: $250
Summer 2015	Liberal Arts Ph.D. Student Summer Faculty Research Award Total: $3000
Spring 2015	UNLV Graduate and Professional Student Association Research Forum Honorable Mention speaker
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Fall 2014	Rebel Grad Slam 3 Minute Thesis Competition Finalist; Semifinals 2nd place; Qualifiers 3rd place
2013, 2014, 2015	Graduate Access Scholarship, University of Nevada, Las Vegas Total: $2000
2012	Distinguished Scholar Award in Psychology, University of Maryland, Baltimore County
2006	Departmental Honors in Music, McDaniel College

ADDITIONAL TRAINING:

Summer 2014	UC-Merced CHASE Summer School: Dynamics of Music and Language

PROFESSIONAL ACTIVITIES:

2015-present	Reviewing for the following journals under the supervision of Joel S. Snyder: *Journal of Experimental Psychology: Human Perception and Performance* *Psychomusicology: Music, Mind, and Brain*
2016	Member of Scientific Advisory Board, 9th International Conference for Students of Systematic Musicology, 2016
Summer 2015	Provided instruction in Electrophysiological Methods: Army Research Laboratory: Human Research and Engineering Directorate, the Environment for Auditory Research

ACADEMIC APPOINTMENTS:

8/2015-present	*Graduate Teaching Instructor*, Instructor of two sections of Introduction to Psychology (PSY-101) per semester.
8/2014-5/2015	*Graduate Assistant*, Teaching Assistant to Jefferson Kinney and James Hyman, University of Nevada, Las Vegas
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8/2013-5/2014	*Graduate Assistant*, Research and Teaching Assistant to Erin E. Hannon, University of Nevada, Las Vegas.

PROFESSIONAL MEMBERSHIPS:

Association for Psychological Science
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SERVICE POSITIONS:

6/2016-present	*President*, Experimental Student Committee, University of Nevada, Las Vegas
9/2014-present	*Outreach Undergraduate Mentoring Program,* Graduate student mentor for undergraduates applying to graduate school, University of Nevada, Las Vegas
6/2015-6/2016	*Secretary*, Experimental Student Committee, University of Nevada, Las Vegas
5/2014-6/2016	*Applicant Housing Liaison*, Experimental Student Committee, University of Nevada, Las Vegas
9/2013-6/2016	*Cohort Representative*, Experimental Student Committee, University of Nevada, Las Vegas

TEACHING EXPERIENCE:

8/2015-present	*Instructor of Record*, Introduction to Psychology (survey course). Syllabus available upon request.
8/2014-5/2015	*Teaching Assistant,* Sensation and Perception
8/2013-5/2014	*Teaching Assistant*, Developmental Psychology
5/2009-6/2013	*Substitute Teacher, Carroll County Public Schools*: taught grades K-12, with a focus on middle and high-school classes; major areas of expertise were science, math, and music.
10/2008-5/2009	*Special Education Instructional Assistant*: Served as a one-on-one personal assistant in classroom settings, managed and executed IEP

RESEARCH EXPERIENCE:

8/2013–present	*Graduate Student, University of Nevada, Las Vegas*, Las Vegas, NV with Joel S. Snyder, Ph.D., and Erin E. Hannon, Ph.D.
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