Quantifying Human Preferences for Polyrhythms

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Abstract

This study investigates the pleasantness ratings of polyrhythms formed by expressing the frequency ratios of common pitch intervals into metronomic pulse trains with corresponding tempo ratios. The study expands on prior work conducted by Razdan and Patel (2016) by addressing and improving design limitations of the 2016 study. Seventy-seven participants were asked to rate the perceived pleasantness of polyrhythms; in one condition, the faster metronome for the polyrhythms was set to 120 BPM, and in the other condition, the polyrhythms were condensed into 2-second cycle durations. We hypothesize that the pleasantness ratings for both of these sets of stimuli will resemble the pleasantness ratings for their pitch equivalents. When the polyrhythms are condensed into 2-second cycle durations, it ensures that the polyrhythms are maintained within participants' echoic memory. Therefore, we hypothesize that the pleasantness ratings for these polyrhythms in particular will represent more accurate evaluations of the polyrhythms. We also postulate that beat induction will be positively correlated with pleasantness ratings. Consistent with our hypotheses, pleasantness ratings of the polyrhythms are shown to be significantly correlated with their corresponding pitch counterparts, especially with respect to the polyrhythms condensed into 2-second cycles. Furthermore, the ability to perceive an underlying beat from a polyrhythm is positively correlated with the pleasantness ratings for the polyrhythm. Future work should now explore the parallel between the factors that seem to influence pleasantness ratings for rhythm and pitch, including beat induction and high degrees of harmonicity respectively.

Introduction

Pitch Perception

The word “consonance” stems from the Latin word *conosare*, which roughly translates to ‘sounding together.’ It specifically refers to the instance when sounds are combined and is used to identify sounds of harmonious agreement. In Western music, certain combinations of pitches – when played in isolation – are perceived as consonant, or pleasant, while other combinations of pitches are perceived as dissonant, or unpleasant.

Physicists, mathematicians, biologists and musicians alike have sought to understand why we perceive some sound combinations as consonant and others as dissonant. During the time of ancient Greece, philosopher and mathematician Pythagoras claimed that consonant pairs of notes have fundamental frequencies related by simple integer ratios. He argued that the simpler the frequency ratio between two tones, the more consonant it would be perceived (Crocker, 1963). While these Pythagorean-based views are relatively outdated, the relationship between simplicity and pleasing perceptual effects has retained influence (Bowling & Purves, 2015). There is still no conclusive reason, however, as to why simple ratios are more pleasing.

German scientist Herman Von Helmholtz is an important contributor to the current physical theories of consonance and dissonance. Helmholtz suggested that we could understand consonance and dissonance by observing the acoustic structures of the two pitches that make up an interval. Complex harmonic tones have a set of frequencies, which consists of a fundamental frequency and various upper harmonics, which are integer multiples of the fundamental (i.e. 120hz → 240hz →360hz). When two complex tones are played simultaneously, the brain perceives both sets of frequencies at once, which creates a composite sound of the frequencies. Helmholtz argues that when frequencies in this composite are close to each other (i.e. when harmonics of tone A lie close in frequency to those of tone B, which occurs when the ratio between two fundamental frequencies is complex) it creates 'roughness' (see Figure 1). This roughness is referred to as *beating,* because sound waves nearby in frequency drift in and out of phase with each other and the amplitude of the summed waveform oscillates, creating a warbling-like sound (Helmholtz, 1877).

When two tones have fundamental frequencies with simple ratios (e.g., the octave [2:1] or the perfect fifth [3:2]), the harmonics of tone A and B tend to perfectly align in frequency or be distant in frequency from each other, and consequently roughness is minimized and the composite tone is perceived as highly consonant (see Figure 2).

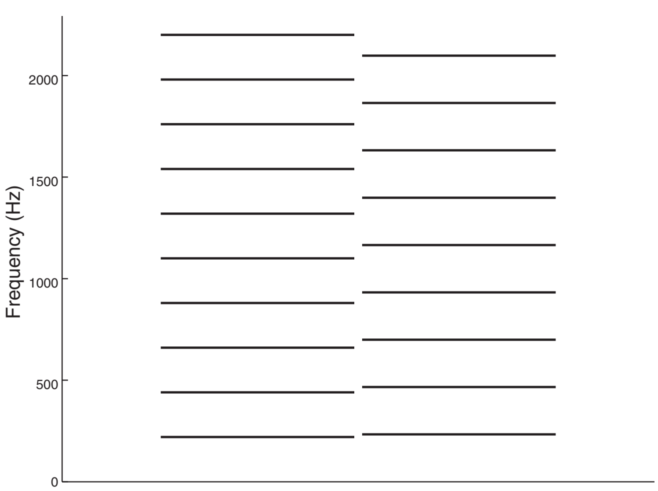


Figure 1. An illustration representing the fundamental and upper harmonics of a minor second with fundamental frequencies of A3 and A#3. The minor second is considered a highly dissonant pitch interval (Adapted from Patel, 2008).

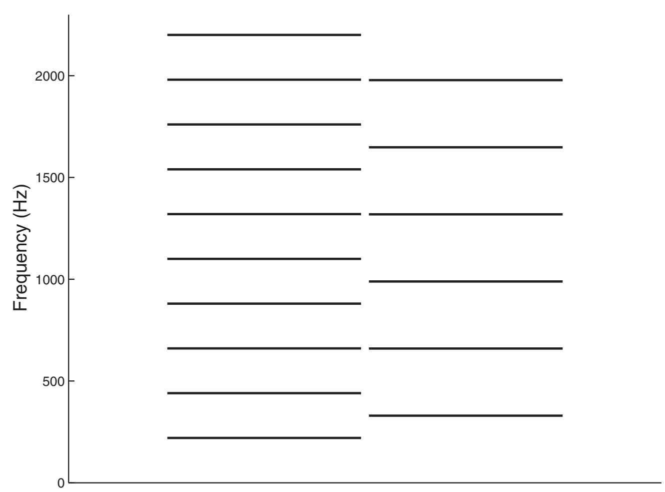


Figure 2. An illustration representing the fundamental and upper harmonics of a perfect fifth with fundamental frequencies of A3 and E4 . The perfect fifth is considered a highly consonant pitch interval (Adapted from Patel, 2008).

Helmholtz proposes that the more pairs of nearby frequencies a composite sound has, the greater the overall roughness of the sound. This is due to the beating between nearby frequencies. Generally, he suggests that the interactions of these nearby harmonics are the cause of dissonance and consonance (Helmholtz, 1877).

However, other theorists quickly raised issues with this physical framework. Stone and Lots (2008) discuss numerous examples in which Helmholtz's theory fails to explain components central to musical psychoacoustics. For example, experimental studies have shown that individuals with lesions in their auditory cortex lack the ability to evaluate consonance in a similar manner to normal patients (Peretz et al. 2011; Tramo et al. 2001). This indicates that specific neural pathways exist that are devoted to dissonance computations and thus can then be disrupted by selective brain damage (Tramo et al. 2001). This finding contradicts Helmholtz's suggestion (1877) that the source of musical perception is governed by peripheral mechanisms in the inner ear. In addition, Stone and Lots (2008) reference a study conducted by Itoh, Suwazono, and Nakada (2003) in which subjects of this experiment were exposed to pure tones, which are tones consisting of a single frequency without any overtones. Participants' EEG responses were measured and these measurements successfully provided electrophysiological evidence that matches behavioral preferences for simple frequency ratios. Given that pure tones were used in the experiment, it suggests that participants' preferences are not a result of the beating of harmonics, which undermines the foundation of Helmholtz's theory (1877).

Nineteenth century German scientist, Carl Stumpf proposed an alternative to Helmholtz's theory of consonance and dissonance. Stumpf investigated the degree to which our perception fuses the two tones of an interval into a single composite tone; he examined to what extent this composite sound resembles the spectrum of a single complex harmonic tone. Stumpf explains that when two frequencies are combined, if the composite set of frequencies matches the frequencies of a complex harmonic tone, the composite is considered to have a high degree of harmonicity. If a composite set of frequencies does not produce a frequency pattern that nicely fits a complex harmonic tone with evenly spaced harmonics, this composite is considered to have a low degree of harmonicity (Stumpf, 2012).

In a 2010 study, McDermott and colleagues measured ratings of pleasantness for all of the dyadic pitch intervals that exist in the Western music system (see Table 1).

Pitch Interval	**Example Pitch Interval (C4 as base pitch, 261.63hz)**	**Ratio Between Fundamental Frequencies**
Octave (O)	C4:C5	2:1
Minor Second (m2)	C4:C#4	16:15
Major Second (M2)	C4:D4	9:8
Minor Third (m3)	C4:Eb4	6:5
Major Third (M3)	C4:E4	5:4
Perfect Fourth (P4)	C4:F4	4:3
Tritone (TT)	C4:F#4	45:32
Perfect Fifth (P5)	C4:G4	3:2
Minor Sixth (m6)	C4:G#4	8:5
Major Sixth (M6)	C4:A4	5:3
Minor Seventh (m7)	C4:Bb4	16:9
Major Seventh (M7)	C4:B4	15:8

Table 1. The dyadic pitch intervals in the Western music system and their respective frequency ratio. Note that in equal-tempered music the ratios of the stated intervals are approximate.

They successfully constructed sounds that varied in their amount of beating but not in harmonicity, in addition to creating sounds that varied in harmonicity but not in their amount of beating. This allowed the researchers to measure individuals’ aversions to beating and to harmonicity independently. In contrast to an aversion to roughness, results showed that the strength of participants' harmonicity preferences co-varied with the strength of participants' consonance preferences, which provides evidence in support of Stumpf's theory of consonance and dissonance (see Figure 3)[1].

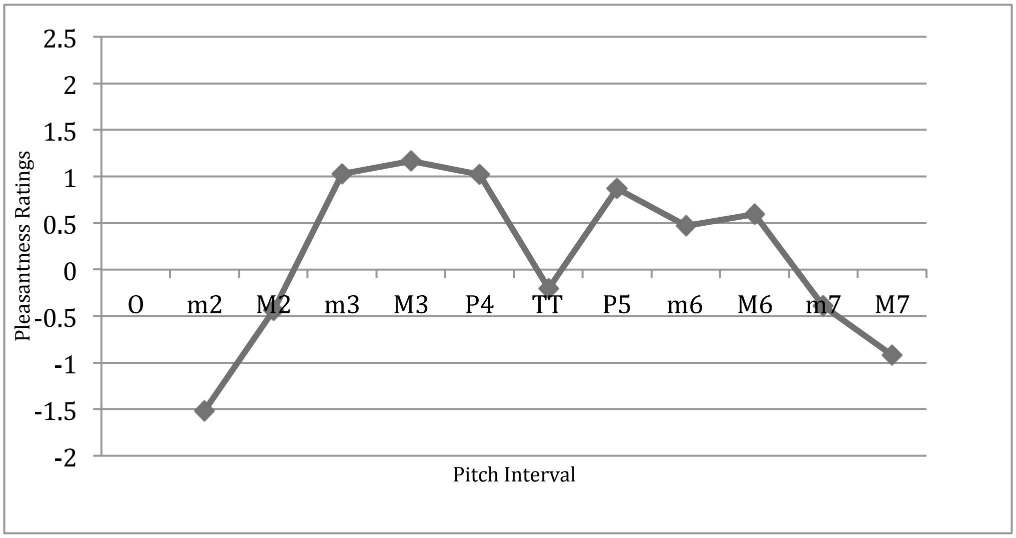


Figure 3. Mean pleasantness ratings for dyadic pitch intervals collected from McDermott et al. (2010)

However, while physical and mathematical theories for consonance are meaningful, they still do not properly explain the phenomenology of consonance nor do they explain why some tonal stimuli are more attractive than others (Bowling & Purves, 2015). It has been suggested that our perception of acoustic consonance and dissonance in pitch intervals reflects how well or how poorly the resulting sound matches the acoustic structure of the human voice. The human voice is one of the most important and relevant auditory stimuli in our environment. Similar to musical tones, vocalizations are also harmonic: vocal fold vibrations' produce sounds with a fundamental frequency along with harmonic overtones. We are attuned to the sounds of human voices because the voice facilitates language and the emotions that underlie the words we speak. Schwartz et al.

[1] Figure 3 displays McDermott et al. (2010) pleasantness ratings for the pitch intervals comprised of synthetic tones. These pleasantness ratings are displayed since the rhythmic stimuli used in this current study uses synthetic tones as well

(2003) extracted thousands of voiced segments and determined their spectra. They found that when frequency values of the segments were expressed as ratios and averaged across various human populations, popular musical intervals appeared as peaks in the distribution, demonstrating that intervals perceived as consonant are emphasized in vocal spectra.

Whether preference for consonance is rooted in acoustic properties important to the auditory system or is produced by enculturation, in which individuals learn to like specific pitch intervals and chords that are prevalent in their surrounding culture's music, still remains a matter of debate. Nevertheless, enculturation and acoustic-based explanations are not incompatible with one another. Conceivably, if a particular acoustic property were to underlie the distinction between dissonance and consonance, listeners could learn an aesthetic association with that property by hearing it repeatedly (McDermott et al., 2010).

Generally, there have been conflicting findings with respect to humans' innate preference for pitch consonance. Results from a study conducted by Zentner and Kagan (1996) found that two month-old infants prefer consonant intervals to dissonant ones, while Plantinga and Trehub (2013) found contrary findings in which the six-month-old infants in their study did not show preferences to consonant/dissonant pairs of stimuli. Existing research that explores dissonance cross-culturally has indicated that such preferences may be learned or at a minimum, easily adaptable (Jordania, 2006; McDermott, Schultz, Undurraga, & Godoy, 2016). Thus, these results also support a strong role for enculturation in consonance. However, they indicate that rather than learning to find specific arbitrary intervals or chords pleasing, listeners learn to like a general acoustic property, like that of harmonicity. In addition, nonhuman primates do not seem to have consonance preferences, which demonstrates that preference is not an inevitable consequence of the structure of the primate auditory system (McDermott & Hauser, 2004).

Rhythm Perception

While there is a considerable amount of research that explores pitch consonance and dissonance, research investigating consonance and dissonance with respect to the other temporal aspects of music, like rhythm, has been less investigated. Rhythm is an essential element of music that can be defined as patterns of duration and accentuation in acoustic sequences. Various specific rhythmic elements exist cross-culturally. In a 2015 study, Savage and colleagues analyzed a global set of 304 music recordings in order to examine what features of music are universal and which are culture-specific. While no absolute universals were found, the researchers uncovered a number of statistical universals especially within the rhythmic domain. This includes the use of beats that occur at equal time intervals, the use of few durational values, repetitive motivic patterns and phrase repetition (Savage et al. 2015). Furthermore, rhythm and beat perception abilities have been shown to exist early on in human development. Newborn infants have exhibited the ability to expect the onset of rhythmic cycles, even when the downbeat is not marked by stress, suggesting that beat perception is an innate ability (Winkler, Haden, Ladinig, Sziller & Honing, 2009).

Soley and Hannon's (2010) results showed that infants' rhythmic preferences are driven by culture-specific experience and a culture-general preference for simplicity. To elaborate, *meter*, which refers to the regular recurring patterns and accents of strong and weak beats of a rhythm (Benward & Saker, 2003), is simple and regular in Western music, as it contains metrical beat levels that include even divisions of time and sequential intervals related by ratios such as 1:1 and 2:1. In contrast, many other cultures (i.e. South Asia, Africa, Middle East) have meters that are more complex and irregular. In Soley and Hannon's (2010) study, they exposed American and Turkish infants to metrical patterns popular in their respective cultures. In addition, they exposed the infants to Balkan music, which follows a metrical pattern not often found in Western or Turkish music. Both American and Turkish infants preferred listening to the meter of their own culture, while also favoring the Balkan-meter sequence to the arbitrary-meter sequence. If familiarity was the only factor contributing to listening preferences, the Balkan and arbitrary meters should have been equally unfamiliar and thus indistinguishable to the infants. These results imply that simplicity may also have played some role in their preferences. Nevertheless, it was found that preferences for simplicity were overridden by cultural experience (Soley & Hannon, 2010).

Similar to pitch, rhythm is also a fundamental characteristic of language. Different languages are categorized according to their predominant rhythmic properties, and research has shown that infants utilize rhythmical characteristics to discriminate one language from another at birth (Ramus & Mehler, 1999). Furthermore, infants can use rhythm to detect the timing characteristics of speech (Fowler, Smith & Tassinary, 1986).

Bridging Pitch & Rhythm

Rhythm and pitch have different perceptual parameters but they are both events of temporality; they simply exist in different ranges of the time axis. For instance, we perceive the relationship between one train of clicks at 600hz and another at 400hz as a pitch interval of a perfect fifth, but if the click rates were to slow down to 6hz and 4hz respectively, we would perceive the relationship as a 3:2 polyrhythm.

Considering this parallel between pitch and rhythm in conjunction with research supporting the notion that both rhythm and pitch perception abilities are present in infancy, contribute to early language acquisition, are essential components of speech, and are crucial elements of music, it is natural to wonder if there are overlapping cognitive mechanisms responsible for the perception of both these musical fundamentals.

In a conference paper, Razdan and Patel (2016) sought to extend the research conducted by McDermott et al. (2010) and earlier research which investigated the cognitive overlap between pitch and rhythm processing (Pressing, 1983). Specifically, Razdan and Patel (2016) explored the relationship between ‘rhythmic consonance’ and harmonic frequency ratios.

The relationship between the perception of rhythmic ‘intervals’ and their corresponding pitch intervals has received little attention. Razdan and Patel (2016) explored a potential relationship between pitch and rhythm perception by exposing individuals to *polyrhythms*, which are rhythms that makes use of two or more rhythms played simultaneously. These polyrhythms were generated by expressing the frequency ratios of Western musical pitch intervals as rhythms. For example, a ‘rhythmic’ perfect fifth consists of two metronomes played simultaneously, in which the ratio of the tempi of the two metronomes are 3:2 (see Table 1, Column 3).

Razdan and Patel (2016) recruited individuals with at least 5 years of musical training or experience within the last 10 years to rate these 12 ‘rhythmic’ intervals for pleasantness, complexity, groove (how much the rhythm made you want to move) and beat induction (how strongly they gave rise to a sense of an underlying beat).

The most relevant finding of the study is that when 'rhythmic' intervals are created by translating frequency ratios of pitch intervals from the Western tonal system, the pleasantness ratings of the resulting polyrhythms are extremely similar to ratings previously reported for the corresponding pitch combinations (Figure 5).

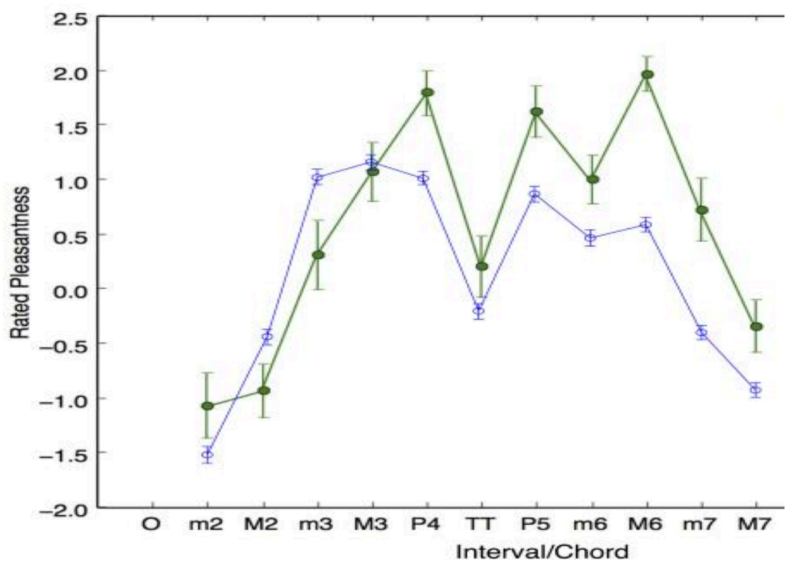


Figure 5. Average pleasantness ratings for rhythmic intervals overlaid on the pleasantness ratings of corresponding pitch intervals (synthetic tones) from McDermott et al. (2010). Blue lines indicate data from McDermott et al. 2010. Reprinted from *Rhythmic Consonance and Dissonance: Perceptual ratings of Rhythmic Analogs of Musical Pitch Intervals and Chords* (Razdan & Patel, 2016)

Ratings of pleasantness were also highly correlated with ratings of beat induction. A *beat* consists of a perceived underlying metronome-like pulse in a rhythm (Patel & Iversen, 2014) and it allows us to predict when sounds are going to happen. Without this ability, while listening to a rhythm or a piece of music, we would not be able to tap our fingers, bob our heads, or entrain body movements to music in a predictive way. The overall ability to track musical beat may reflect a process called neural entrainment – a phase-locking of neural oscillations to the rhythmic structure of music. Neural oscillations are slow increases and decreases in electrical activity and these oscillations have been shown to "entrain" to rhythmic stimuli, even stimuli with complex rhythmic frameworks such as polyrhythms (Stupacher, Wood & Witte, 2017). In addition to finding pleasantness ratings being directly correlated with ratings for beat induction, it should be noted that Razdan and Patel (2016) found that pleasantness ratings were inversely correlated with ratings of complexity.

From these observations, Razdan and Patel (2016) suggest that there may be common mechanisms responsible for driving both pitch interval and polyrhythm preferences, spanning the temporal spectrum from rhythm to pitch perception. Razdan and Patel (2016) refer to research conducted by Lots and Stone (2008) and Large et al. (2016) which propose frameworks for pitch interval perception based on nonlinear oscillatory models of neural activity.

Lots and Stone (2008) present a model of two neurons coupled in a nonlinear fashion being driven by an external pitch interval stimulus. Their results showed that the stability of oscillatory states induced by the 12 pitch intervals in Western music serves as an accurate predictor of preference ranking. Large et al. (2016) provides evidence showing that if we use such a nonlinear model, when looking for the most stable frequency ratios between 1:1 and 2:1, the 12 Western pitch intervals found in just intonation are successfully reproduced, which perhaps provides neurodynamic evidence as to why certain pitch intervals exist cross-culturally (Large et al, 2016).

With respect to rhythm, Large & Snyder (2009) and Large et al. (2015) speculate that human entrainment to a beat is also a consequence of nonlinear neurodynamic oscillatory effects. They suggest that the most popular patterns of metrical accent correspond to stable resonant states of neural oscillation, while a direct consequence of spontaneous oscillatory effects inherent in such nonlinear models is the internal sense of a beat that listeners experience.

While the timescales of rhythm perception and oscillatory timescales of individual neurons greatly differ, Large and Snyder (2009) suggest that their canonical model could be applied to entire brain regions as opposed to just pairs of individual neurons, especially in regions that are related to both auditory and motor feedback and processing in which activity levels are on the same timescale as rhythmic perception. Therefore, while the timescales of rhythm and pitch also greatly differ and while the specific regions or neural elements oscillating in each case may differ from one another, perhaps the same canonical nonlinear model can be used to explain perceived pleasantness of related stimuli in both temporal regimes.

Current Study

The goal of the present study is to further investigate human preferences for polyrhythms modeled on the mathematical properties of harmonically consonant and dissonant pitch intervals. Similar to Razdan and Patel (2016), this study exposes participants to a set of polyrhythms (consisting of two simultaneous metronomes made from short clicks) modeled on frequency ratios taken from Western musical pitch intervals. For these polyrhythms (or ‘rhythmic’ intervals) the tempo of the faster metronome is set to 120 BPM (beats per minute) and the tempo of the slower metronome is determined by the frequency ratio of the interval. (For example, for a 3:2 polyrhythm the slower metronome would occur at 80 BPM). Participants are asked to rate these polyrhythms on their perceived pleasantness and (on separate trials) to rate them on how strongly the rhythms give rise to an underlying beat.

One important difference between the current study and that of Razdan and Patel (2016) concerns the acoustics of the two metronomes in a polyrhythm. In Razdan and Patel (2016), the metronomes in the polyrhythms had clicks of slightly different duration (0.4 ms for metronome 1 and 0.2 ms for metronome 2[2], with the 0.4 ms clicks always being used with the 120 BPM metronome). This resulted in subtle but perceivable frequency variations in each polyrhythm because the 0.2 ms clicks sounded higher in frequency than the 0.4 ms clicks. For example, in the "rhythmic perfect fifth" this resulted in a varying frequency pattern as shown in Figure 6.

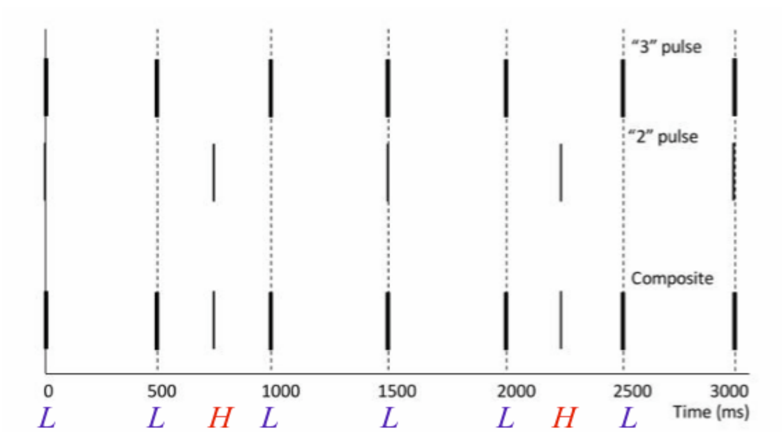


Figure 6. Two cycles and the beginning of a third cycle for a 3:2 polyrhythm with the faster metronome set to 120 BPM. Blue "L" indicates clicks of longer duration/lower frequency. Red "H" indicates clicks of shorter duration/higher frequency.

This frequency variation within each polyrhythm could potentially have influenced pleasantness judgments for the polyrhythms, and was thus a confound in terms of studying pure preference for rhythm patterns. In the current study, this potential confounding

[2] There is a typo within the Razdan and Patel (2016) paper in which it states that the duration of the clicks were 4ms and 2ms (A.D. Patel, pers.comm.). The correct values are reported in this thesis.

variable is addressed and appropriately changed so that there is no frequency variation between clicks within the polyrhythms.

In addition to exposing participants to a set of rhythmic stimuli in which the faster metronome is set at 120 BPM, the current research investigates preferences for polyrhythms when the ‘rhythmic’ intervals are adjusted to a tempo such that each cycle for the polyrhythms are 2 seconds long in duration. As previously stated, the fastest click train for each ‘rhythmic’ interval in the research conducted by Razdan and Patel (2016) was set to 120 BPM (i.e. the rhythmic perfect fourth had one click train occurring at 120 BPM and the another occurring at 90 BPM, forming a 4:3 ratio in tempo). The concern with using 120 BPM as the fastest click train for the polyrhythms is that the cycle durations for the rhythmic minor second, major second, tritone, minor seventh and major seventh all exceed 4 seconds in duration. Human echoic memory is only capable of storing and retaining auditory information for 3-4 seconds (Cowan & Grove, 1990). Thus, the polyrhythms exceeding 4 seconds in duration in Razdan and Patel’s study (2016) may have been rated lower because subjects couldn’t contain the pattern in their working memory.

The cycle duration for any given polyrhythm is computed by multiplying the largest number in the tempo ratio by the period of the fastest click train. With respect to Razdan and Patel (2016), the period of the fastest click train was always .05s, since the fastest click train was set to 120 BPM. For example, the cycle duration for the rhythmic major second (9:8 ratio) was 9 * .05s = 4.5s (see Table 2 for cycle durations for each polyrhythm).

Interval	**Ratio Between Fundamental Frequencies**	**Cycle Duration (seconds)**
Octave (O)	2:1	1
Minor Second (m2)	16:15	8
Major Second (M2)	9:8	4.5
Minor Third (m3)	6:5	3
Major Third (M3)	5:4	2.5
Perfect Fourth (P4)	4:3	2
Tritone (TT)	45:32	22.5
Perfect Fifth (P5)	3:2	1.5
Minor Sixth (m6)	8:5	4
Major Sixth (M6)	5:3	2.5
Minor Seventh (m7)	16:9	8
Major Seventh (M7)	15:8	7.5

Table 2. Rhythmic intervals with their respective frequency ratio and cycle durations (faster metronome set to 120 BPM)

Another difference between Razdan and Patel (2016) and the current work pertains to subject characteristics. The earlier study focused on musically trained individuals who had at least 5 years of musical training in the past 10 years. The current study has no musical training requirement. This presents an opportunity to compare pleasantness and perceptual ratings of individuals with little vs. significant musical training/activity and allows us to observe how musical training may influence these ratings.

It is hypothesized that pleasantness ratings for both sets of rhythmic stimuli, that is, the stimuli in which the faster metronome is set to 120 BPM and the stimuli set to 2 - second cycle durations, will reflect McDermott et al.’s (2010) pleasantness ratings for the 12 western pitch intervals. In addition, it is hypothesized that the strength of beat induction will be correlated with higher pleasantness ratings. With respect to the effects of musical experience on the strength of consonance preferences, McDermott et al. (2010)

found that musical experience was significantly correlated with the strength of consonance preferences for pitch intervals, thus, it is expected that greater musical experience will also be correlated with greater strength for consonance preferences for these polyrhythms.

Methods

Participants

The participants of this study (n=77) had a mean age of 21.45 (SD 4.65), with a minimum age of 18 (min = 18, max = 60, with slightly over 60% being between 21 and 22 of age). 40 of the participants identified as male and 37 identified as female. On average, the participants had 4.26 years of musical experience within the past 10 years, with 31 out of the 77 participants having 5 or more years of musical experience in the past 10 years (the latter was the criterion used in Razdan & Patel for participants, and was used in the current study to define 'musicians' vs. 'nonmusicians').

Participants were recruited through recruitment materials including flyers, which were posted on Tufts' University's campus. In addition to this, participants were recruited through online sources, such as social media posts via Facebook. Participants were compensated $5 for their participation. The study was approved by the Tufts Institutional Review Board (IRB).

Materials

Participants listened to four blocks of stimuli. Each block consisted of either 13 or 12 rhythms. The blocks that consisted of 13 rhythms had 12 polyrhythms based on Western pitch intervals (see Table 1) plus one random rhythm. These blocks contained the stimuli in which the faster metronome of each polyrhythm was set to 120 BPM. Blocks that consisted of 12 rhythms were used when testing the polyrhythms condensed into 2-second cycles, because the 4:3 polyrhythm was omitted from these blocks since its tempo was the same as in the blocks where the faster metronome was 120 BPM. Therefore, blocks with 12 rhythms had 11 polyrhythms based on Western pitch intervals plus one random rhythm.

The polyrhythms were generated as .wav files (sample rate 44,1000 Hz) using a custom script in MATLAB. They were created by adding pairs of metronomic pulse trains aligned on the first pulse with tempo ratios that corresponded with the 12 pitch interval frequency ratios from Western tonal music (based on just intonation). Metronome clicks were square wave pulses of 1 ms in duration and 1 Volt in amplitude. At points where clicks in the two metronomes aligned (at the start of each cycle), the amplitudes of the clicks were summed, so that cycle-initial clicks were twice the amplitude of other clicks in the sequence. For the block of stimuli in which the faster metronome of the polyrhythm always had a tempo of 120 BPM, the random stimulus had a mean rate of events similar to a 120 BPM metronome, with a mean inter-onset interval (IOI) of 499 ms (SD = 134 ms, min = 281 ms, max = 753 ms). For the block of stimuli in which each polyrhythm's tempo was adjusted so that one cycle took 2 seconds to complete, the random stimulus had a mean rate of events similar to a 335 BPM metronome (the mean tempo of the faster metronome across the polyrhythms), with a mean inter-onset interval (IOI) of 179 ms (SD = 64 ms, min = 47 ms, max = 300 ms). In these randomly-timed stimuli, all clicks were of the same amplitude. Participants listened to all rhythms through a pair of Behringer HPM1000 Over-Ear Headphones at a comfortable listening level. The stimuli were administered through the PsychoPy software package.

After testing the first 28 participants, the timbre of the stimuli was altered slightly for the remaining 49 participants. This was done because a few participants in the initial 28 reported that the sounds of the individual clicks were unpleasant. To address this, the stimuli were filtered to make them less acoustically harsh by reducing energy at high and low frequencies and boosting mid-range energy using the Logic Pro X Version 10.1.1 Workstation (see Appendix A for information regarding specific modifications to stimuli including waveform images). The updated stimuli were then used for the following 49 participants.

Participants were given a questionnaire at the end of the experiment, which inquired about their age, gender, musical training and background (see Appendix B). It should be noted that a modification to the questionnaire was made after testing the first 28 participants. The modified questionnaire includes a question that asks participants to describe what their personal criterion was for evaluating the pleasantness of the rhythms (see Appendix C for modified questionnaire). In addition, the modified questionnaire asked participants to write down their gender identity rather than circling either Male or Female. This specific modification was made in order to create a more inclusive testing environment.

Procedure

Testing took place in quiet rooms. Upon their arrival, participants were handed a written consent form. Following their consent, participants were given a laptop and a pair of headphones and were told to follow the prompts presented on the computer screen.

Participants were told that this was an experiment on rhythm perception, in which they would be listening to a series of rhythms and giving the rhythms perceptual ratings. They were told that there were no right or wrong answers, and that the researchers were simply interested in how they perceived these sounds. The first 28 participants were not given any examples. For the next 49 participants (after filtering of the metronome clicks), each heard an example of the 3:2 polyrhythm at 120 BPM before and after filtering. They were told that these two stimuli had the same rhythm, but differed in the sound of the clicks, and were instructed to base their pleasantness ratings in this experiment on the pattern of the rhythm, not on the sound quality of the clicks. No practice runs were done in which listeners heard rhythms and made perceptual ratings.

Each participant heard 4 blocks of rhythmic stimuli: The first block consisted of the 13 polyrhythms in which the fastest metronome of the polyrhythm was set to a tempo of 120 BPM. The second block consisted of the same polyrhythms in which the tempo for each rhythm was adjusted so that the cycle duration was 2 seconds long. Each rhythm within the first block and the second block played for 8 seconds. After each rhythm, participants were asked to, “rate how pleasant it was to listen to, on a scale of -3 (very unpleasant) to 3 (very pleasant).” Only integer responses were allowed, and participants were encouraged to use the full range of the scale. After each rating, the participant was presented with the subsequent rhythm. Rhythms were presented in random order for both the first and second block.

In the third and fourth block, participants listened to the rhythmic stimuli and were told, “If you find yourself perceiving a beat (even weakly), please tap that beat using the left mouse button.” Participants’ clicking data was recorded as they tapped along to the rhythm. After each trial, the participants were then asked to, “rate how strongly it gave rise to a sense of a steady underlying beat, on a scale of 1 (no sense of beat) to 7 (very strong sense of a steady beat)”. Each rhythm in the third and fourth block played for 16 seconds. In this part of the experiment, the polyrhythms were presented in fixed order. This fixed sequence was created by randomly alternating between polyrhythms in the two conditions (120 BPM and 2-second cycles). This was done in order to avoid exposing participants to a polyrhythm with the same frequency ratio at different tempi back-to-back (e.g., 3:2 at 120 BPM and as a 2s cycle). After the fixed order was established, the first 13 polyrhythms were presented in the third block and after a short break, the remaining 12 polyrhythms were presented in the fourth block (see Appendix D for the order of stimuli).

Due to equipment problems, no beat induction ratings were recorded for 3 participants. Thus in this study, pleasantness ratings were analyzed for 77 participants and beat induction ratings were analyzed for 74 of these participants. Additionally, for the first 28 participants, no beat induction rating was stored for the 5:4 polyrhythm in the condition in which the faster metronome of the polyrhythms was set to 120 BPM. Thus for this polyrhythm in this condition, the mean beat induction rating was computed based on the remaining 49 participants.

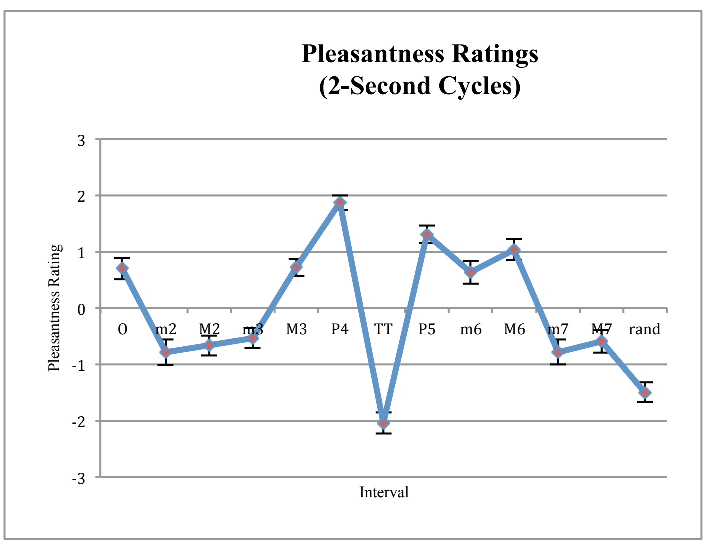
After all four blocks of stimuli the participants completed a written questionnaire, which included questions such as “What was your personal criteria for ‘pleasantness’?” and “Please list what instruments, including voice, you have studied and for how long.” After completing the questionnaire, the participants were handed a debriefing form and given $5 compensation.

Results

Analyses were first conducted on all subjects' data collapsed together. Since the timbre of the polyrhythms' pulse trains were manipulated after testing the first 28 participants, subsidiary analyses were also conducted on the first 28 participants and the following 49 participants separately. The pattern of results was highly similar across the two groups of participants, (see Appendix E), thus providing justification for combining data across participants.

Mean pleasantness ratings for the rhythmic stimuli condensed into 2-second cycle durations are shown in Figure 7a. Mean pleasantness ratings for the rhythmic stimuli in which the faster metronome is set to 120 BPM are shown in Figure 7b. For a comparison of these pleasantness ratings, see Figure 8a and Figure 8b.

a



b

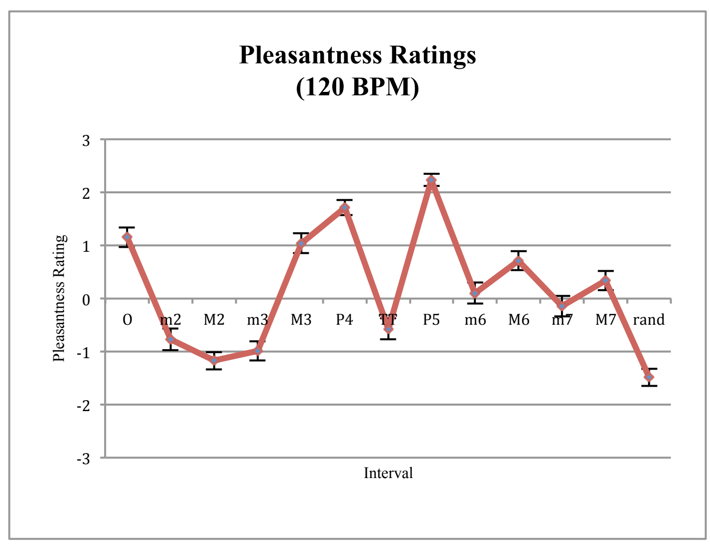


Figure 7. a) Mean pleasantness ratings for polyrhythms condensed into 2-second cycles (data from all participants; Error bars represent standard error); b) Mean pleasantness ratings for polyrhythms in which the faster metronome is set to 120 BPM (data from all participants; Error bars represent standard errors)

a

b

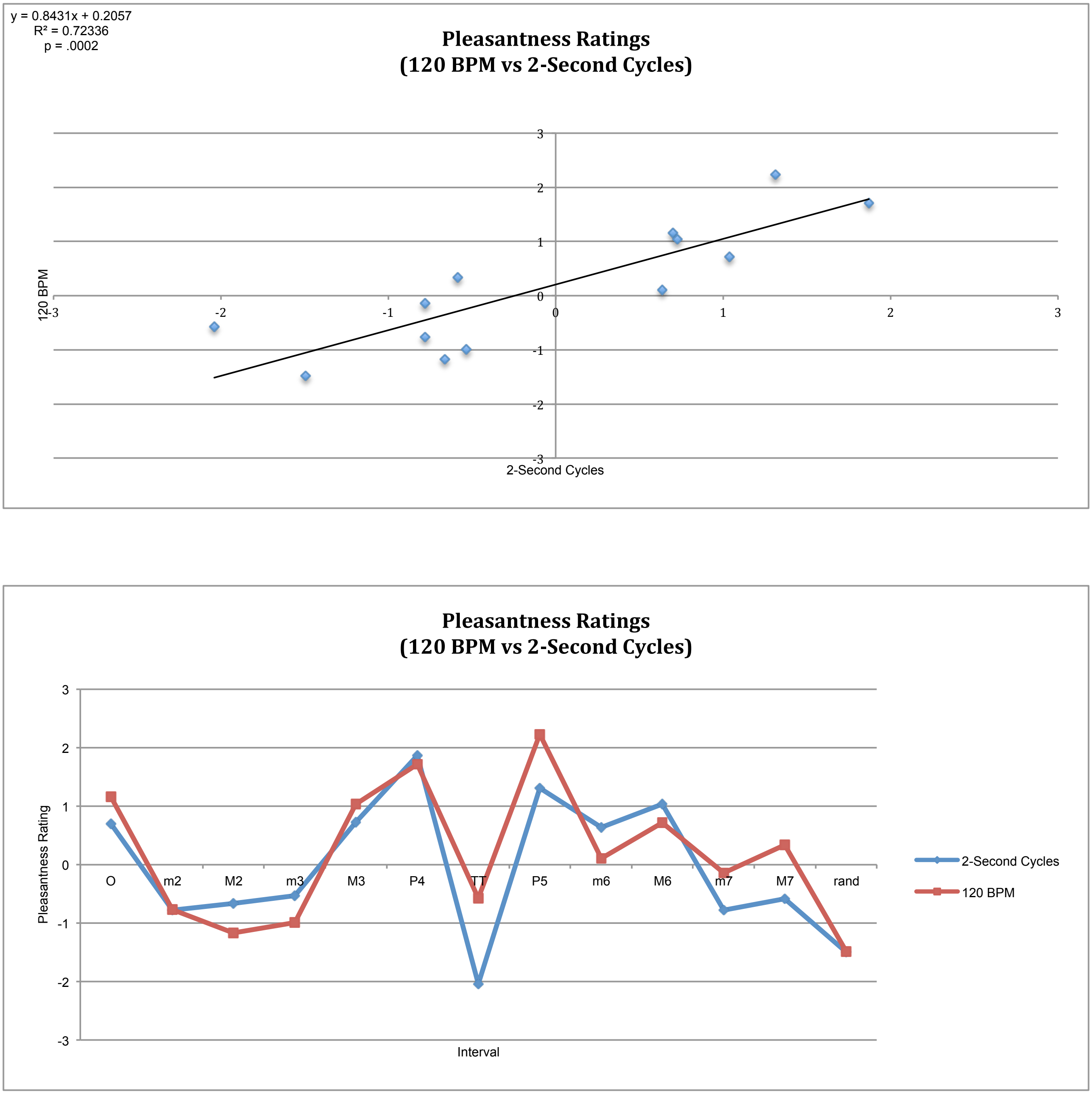


Figure 8. a) Relationship between mean pleasantness ratings of polyrhythms in which the faster click train is set to 120 BPM and mean pleasantness ratings of polyrhythms condensed into 2-second cycles; b) the same ratings represented so that the shape of the pleasantness ratings can be observed

The relationships between the polyrhythms condensed into 2-second cycles, the polyrhythms in which the faster metronome is set to 120 BPM, and McDermott et al.'s pleasantness ratings of the corresponding pitch intervals (2010) are shown in Figure 9 and Figure 10 respectively. There is a significant correlation between the pleasantness ratings for the rhythms condensed into 2-second cycles and the ratings of the pitch intervals on which they are modeled (p = .0262) (see Appendix F for numerical data). While the relationship between pleasantness ratings for the rhythms in which the faster metronome is set to 120 BPM and the pleasantness ratings from the McDermott et al. (2010) study for corresponding pitch intervals does not reach statistical significance, the ratings have a very similar trend and shape pattern (see Figure 10) (see Appendix F for numerical data). It's important to note that these correlations do not include our pleasantness ratings for the 'rhythmic' octave since McDermott et al. (2010) did not test the octave pitch interval in their experiment.

a

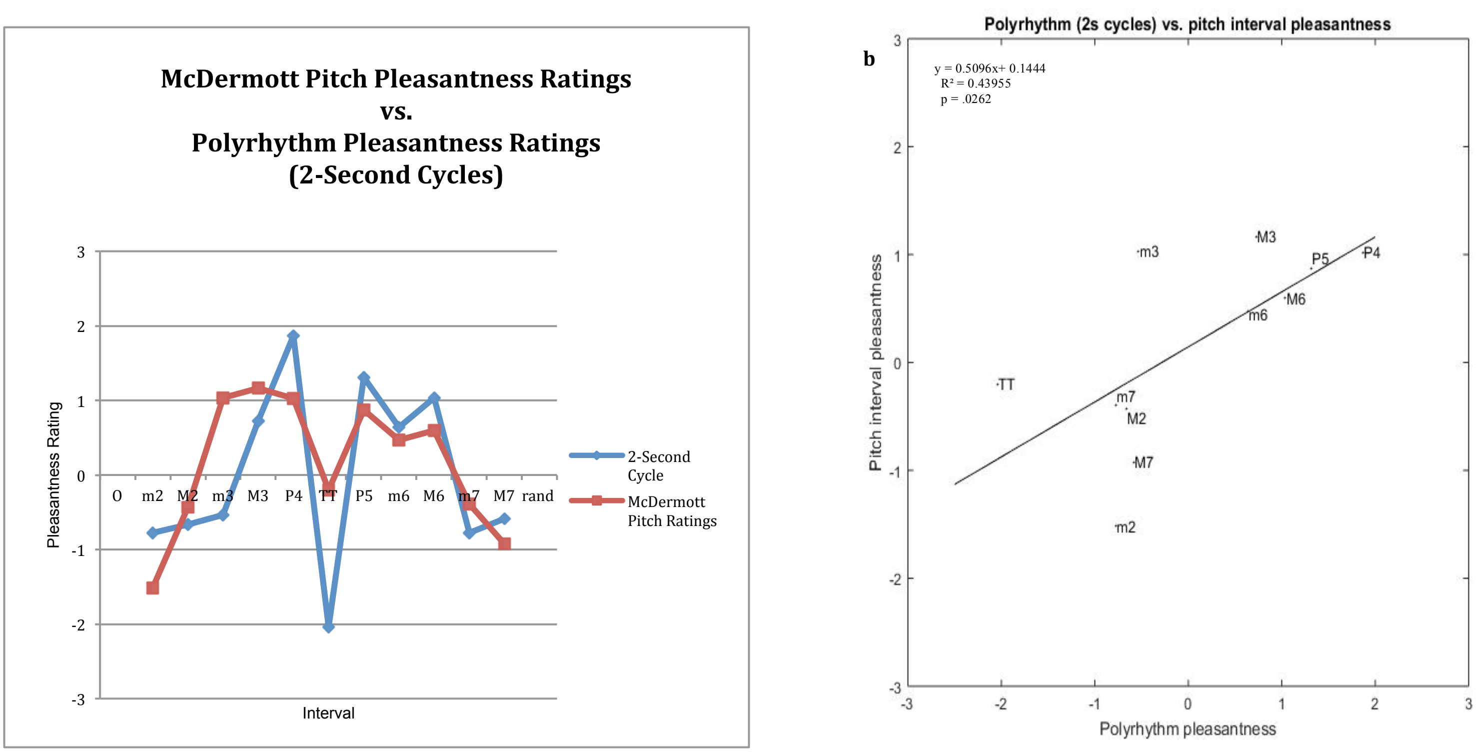


Figure 9. a) Relationship between mean pleasantness ratings of pitch intervals from McDermott et al. (2010) and mean pleasantness ratings of polyrhythms condensed into 2-second cycles; b) the same ratings represented so that the correlation can be observed.

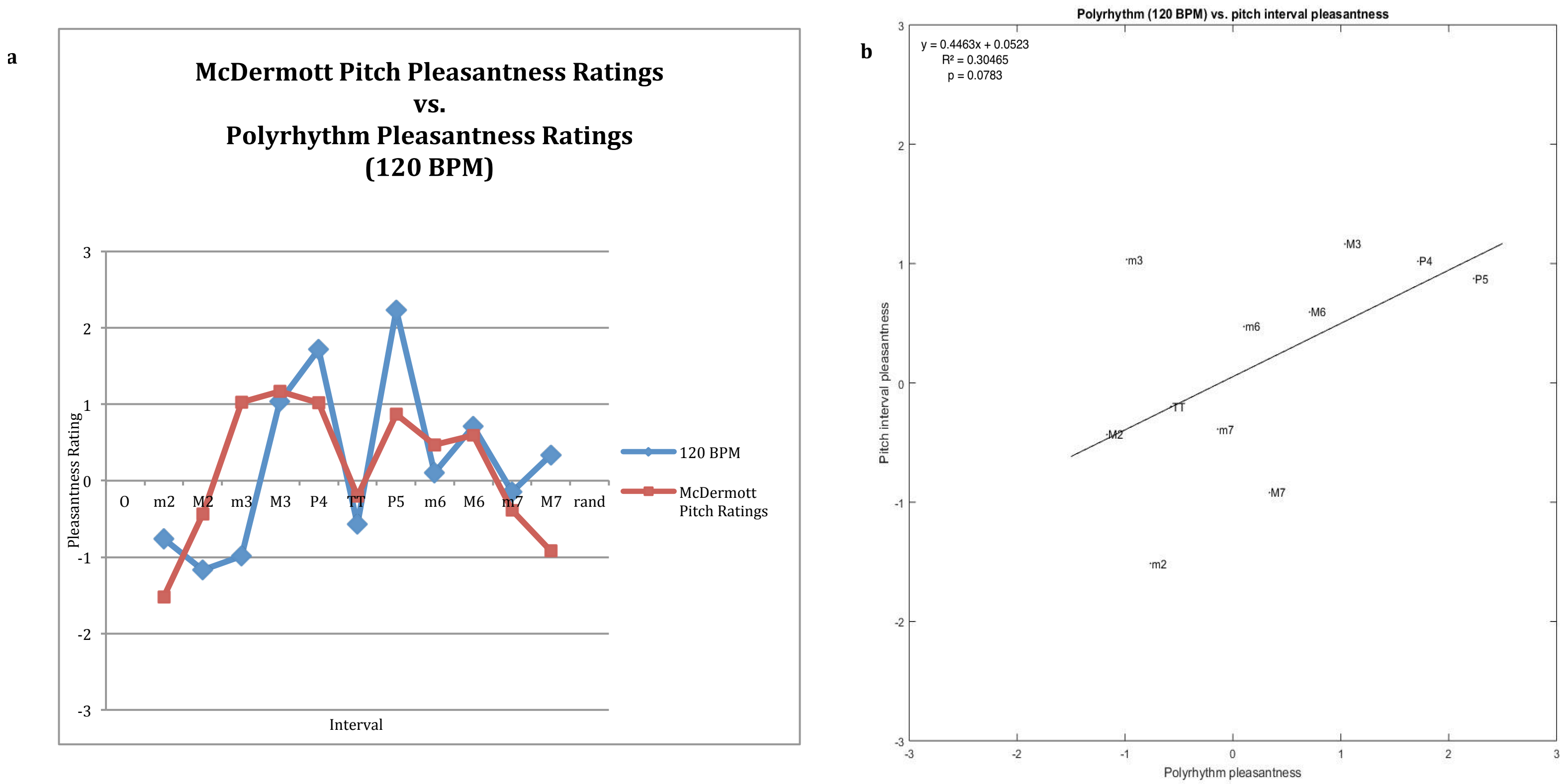


Figure 10. a) Relationship between mean pleasantness ratings of pitch intervals from McDermott et al. (2010) and mean pleasantness ratings of polyrhythms in which the faster metronome is set to 120 BPM; b) the same ratings represented so that the correlation can be observed.

Figure 11 and Figure 12 shows the relationships between participants' judgment of the strength of an underlying beat (referred to as beat induction) in a polyrhythm and its pleasantness rating for the polyrhythms in which the faster metronome was set to 120 BPM and for polyrhythms condensed to 2-second cycles respectively. Beat induction is strongly related to pleasantness ratings for both sets of stimuli (120 BPM: $p = <0.0001$) (2s: $p = 0.0001$).

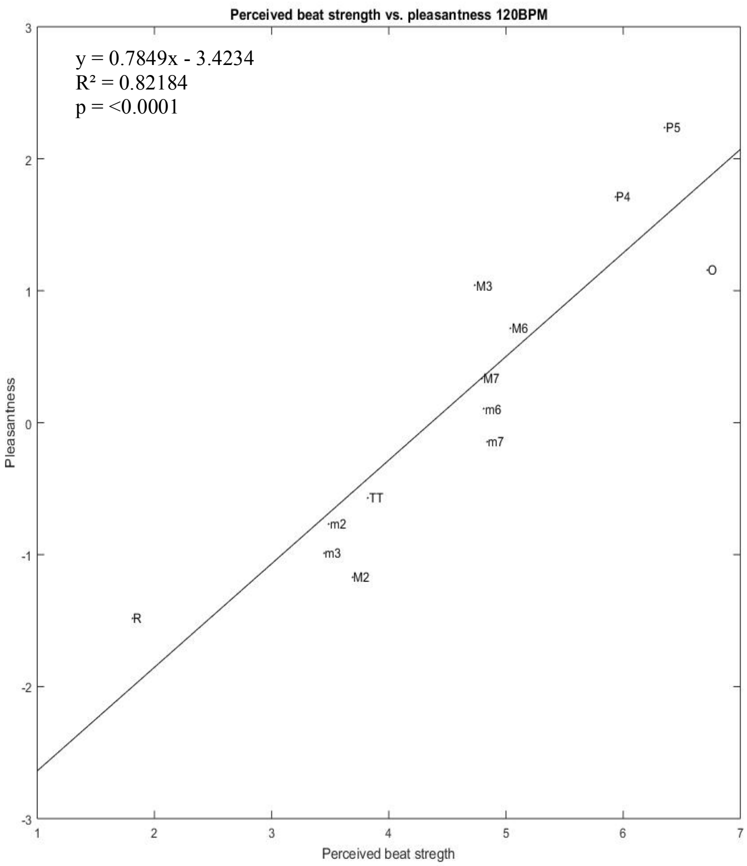


Figure 11. Relationship between mean pleasantness ratings for polyrhythms in which the faster metronome is set to 120 BPM and mean ratings of beat induction for polyrhythms in which the faster metronome is set to 120 BPM.

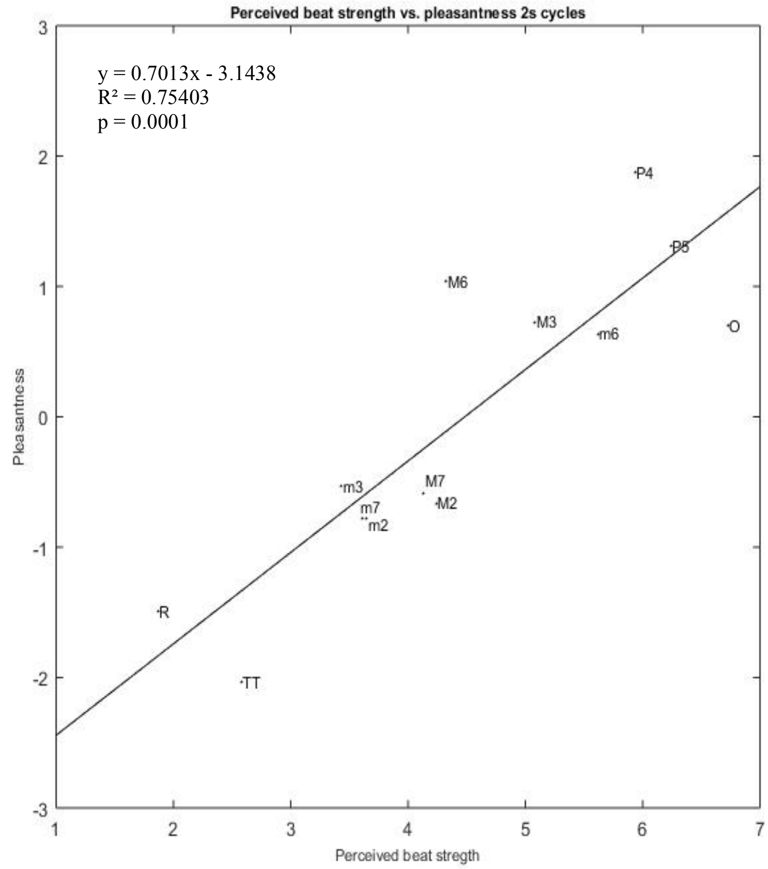


Figure 12. Relationship between mean pleasantness ratings for polyrhythms condensed into 2-second cycles and mean ratings of beat induction for polyrhythms condensed into 2-second cycles.

For the purposes of investigating how musical experience may influence perceived pleasantness of the rhythms, Figure 13 and Figure 14 displays the relationships between musicians and non-musicians' pleasantness ratings for the polyrhythms in which the fastest metronome is set to 120 BPM and their ratings for the polyrhythms condensed into 2-second cycles respectively. Figure 15 and Figure 16 displays the relationship between musicians and non-musicians' pleasantness ratings and their ratings for beat induction for the polyrhythms condensed into 2-second cycles and for the polyrhythms in which the faster metronome is set to 120 BPM respectively.

A ‘musician’ is defined as a participant who has 5 or more years of musical experience in the past 10 years. A ‘non-musician’ is defined as a participant with less than five years of musical experience in the past 10 years. Five years of musical experience in the past 10 years was used as the division between being a ‘musician’ and ‘non-musician’ since it is unsuitable to perform a median split on years of musical of experience in the past 10 years for this data. This is because there was a high percentage of participants with 4 years of musical experience in the past 10 years, and performing a median split would cause approximately half of the participants with 4 years of musical experience in the past 10 years to be placed arbitrarily in the ‘non-musician’ category and the other half of the participants with 4 years of musical experience to be placed in the ‘musician’ category. In addition to this, prior research has also used 5 years of musical experience in the past 10 years to separate those with significant musical experience from those without (Razdan & Patel, 2016). This provides further justification for using 5 years as the separation point. As can be seen in Figure 13 and Figure 14, the pleasantness ratings for polyrhythms are very similar for musicians and non-musicians.

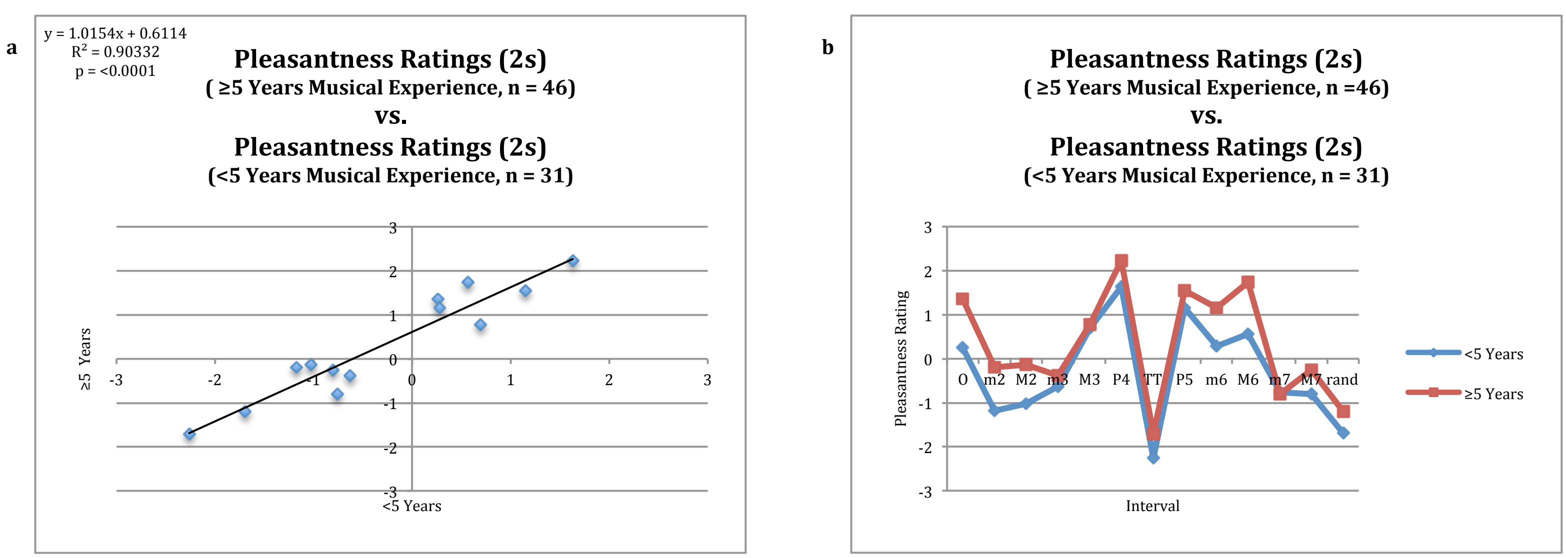


Figure 13. **a) A comparison between mean pleasantness ratings of polyrhythms condensed into 2-second cycles for participants with greater than five years of musical experience and participants with less than five years of musical experience in the past 10 years; b) the same ratings represented so that the shape of the pleasantness ratings can be observed**

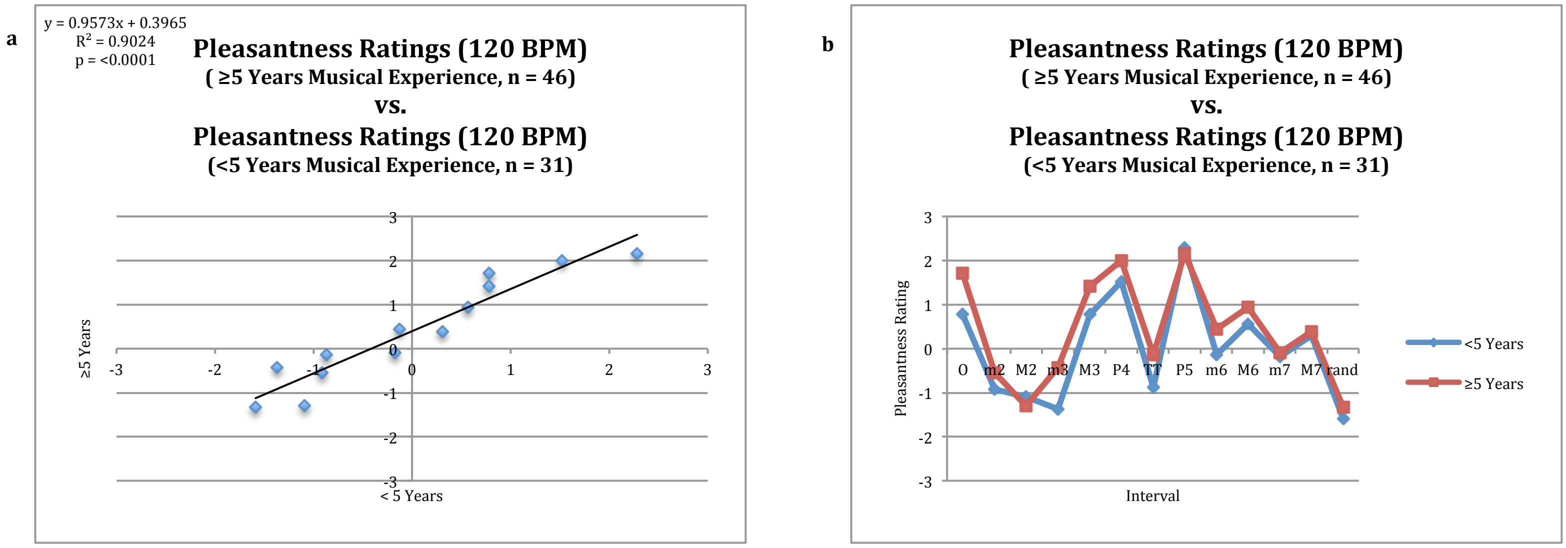


Figure 14. **a) A comparison between mean pleasantness ratings of polyrhythms in which the faster tempo is set to 120 BPM for participants with greater than five years of musical experience and participants with less than five years of musical experience in the past 10 years; b) the same ratings represented so that the shape of the pleasantness ratings can be observed**

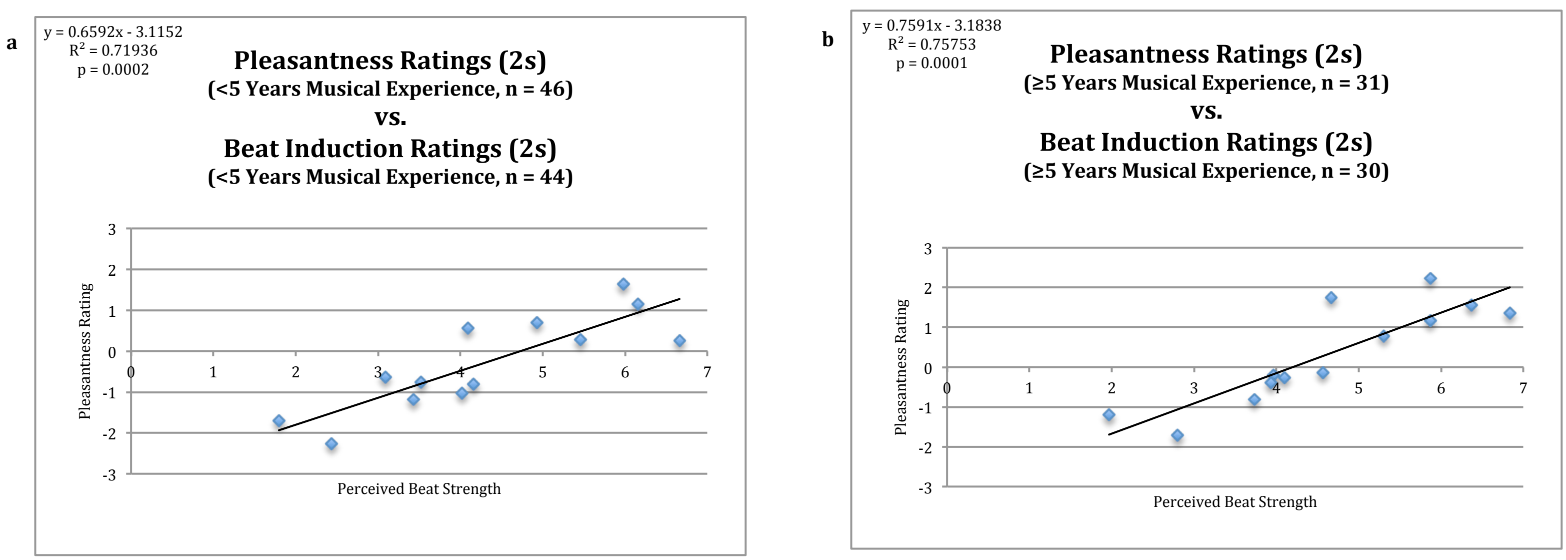
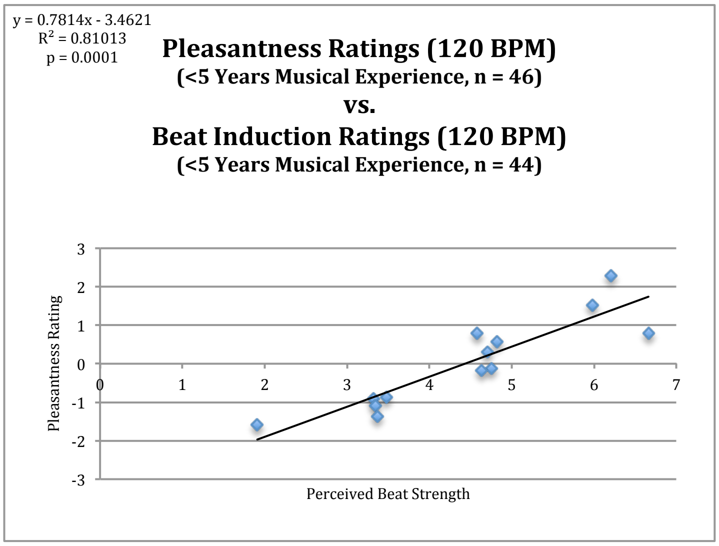


Figure 15. a) Relationship between mean pleasantness ratings for polyrhythms condensed into 2-second cycles and mean ratings of beat induction for polyrhythms condensed into 2-second cycles for participants with less than 5 years of musical experience b) the same relationship for participants with greater than or equal to 5 years of musical experience

a



b

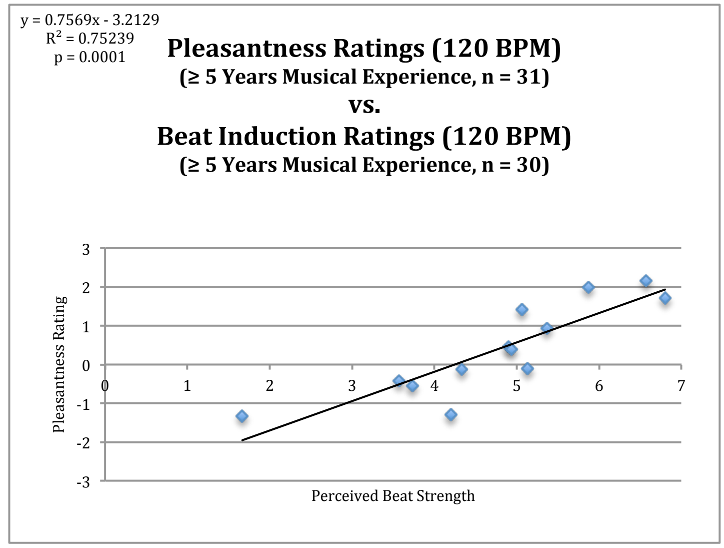


Figure 16. a) Relationship between mean pleasantness ratings for polyrhythms in which the faster metronome is set to 120 BPM and mean ratings of beat induction for polyrhythms in which the faster metronome is set to 120 BPM for participants with less than 5 years of musical experience b) the same relationship for participants with greater than or equal to 5 years of musical experience. Ratings for beat induction for the 5:4 polyrhythm was taking from n = 16 for the musicians and n = 33 for the non-musicians.

In order to determine if pleasantness ratings for the polyrhythms are correlated with the objective aspects of the stimuli structure, participants' pleasantness ratings were compared to four objective features of the rhythmic stimuli. This includes the average and standard deviation of inter-onset-interval duration measured over one complete rhythmic cycle, the average number of events per second in each cycle, and cycle duration. Correlations were computed across the all of the stimuli (see Table 3 and Table 4 and Appendix G for further numerical data).

120 BPM

Correlation of mean pleasantness rating with a rhythm's:	**r**	**R^2**	**p**
Average Inter-onset interval	0.163874878	0.02685	0.5927
Standard Deviation of inter-onset intervals	-0.302973162	0.09179	0.3143
CV of Inter-onset interval	-0.339898676	0.115531	0.2558
CV of intensity	0.375623889	0.141093	0.2059
Cycle Duration	-0.473740643	0.22443	0.1198
Average Number of events per second	-0.2714438	0.0736817	0.3697

Table 3. Correlations between pleasantness and objective properties of the polyrhythms in which the faster tempo is set to 120 BPM

2-Second Cycles

Correlation of mean pleasantness rating with a rhythm's:	**r**	**R^2**	**p**
Average Inter-onset interval	0.55263008	0.3054	0.0502
Standard Deviation of inter-onset intervals	0.66820655	0.4465	**0.0125**
CV of Inter-onset interval	-0.36959437	0.1366	0.2139
CV of intensity	0.69856997	0.4880	**0.0079**
Tempo of Faster Metronome	.746967201	0.55796	**0.0033**
Average Number of Events per Second	-.711709210	0.50653	**0.0064**

Table 4. Correlations between pleasantness and objective properties of the polyrhythms set to 2-second cycles

Discussion

The pleasantness ratings for polyrhythms generated by translating the frequency ratios of common pitch intervals into metronomic pulse trains with corresponding tempo ratios, are extremely similar to the pleasantness ratings previously reported for the corresponding pitch intervals (McDermott et al., 2010) (see Figure 9 and Figure 10). This is especially true with respect to the polyrhythms condensed into 2-second cycles (see Figure 9), suggesting that condensing the polyrhythms into a cycle duration that fits within our echoic memory capabilities leads to more accurate and appropriate pleasantness ratings for the polyrhythms.

In addition, the data indicates that beat induction, or the ability to perceive an underlying beat from a rhythm, is strongly correlated to the rhythms' perceived pleasantness. In addition to having numerical data to support this claim, via the questionnaire, when participants were asked what their personal criterion was for pleasantness, the majority of participants articulated, either explicitly or indirectly (i.e. "I can tap my foot along to it”), that their ability to perceive an underlying beat guided their pleasantness ratings.

However, if beat induction is the sole driver of the pleasantness ratings, it should be expected that the average pleasantness rating for the ‘rhythmic’ octave (2:1) would be greater than the pleasantness ratings for all other polyrhythms. Interestingly, when participants explained their criteria for pleasantness, they often stated that they enjoyed the rhythms that they could tap their foot to - with the exception of the ‘boring’ or ‘non-complicated’ rhythm, which is assumed to be the ‘rhythmic’ octave. The brain is often considered a pattern-recognition machine. Thus, it’s reasonable to argue that there is no reward or pleasant experience when listening to the ‘rhythmic’ octave since it is not a pattern that needs to be decoded. It’s too simple.

With respect to participants’ previous musical experience and how this influences pleasantness ratings, while it was hypothesized that greater musical experience would correlate with greater strength for consonance preferences for the polyrhythms, the data suggests that musical experience does not significantly influence the perceived pleasantness of the polyrhythms (see Figure 13 and Figure 14). In addition, the numerical data and the answers from the questionnaire also support the notion that both musicians and non-musicians rely on their ability to locate the underlying beat of a polyrhythm in order to guide pleasantness ratings (see Figure 15 and Figure 16).

A structural feature of the stimuli that has a significant positive correlation with pleasantness ratings for the polyrhythms condensed into 2-second cycles is the *CV of intensity*. At the beginning of each polyrhythm’s cycle, the two pulse-trains that generate the polyrhythm align and play simultaneously. As a consequence, the amplitude is doubled. We hypothesize that the significant correlation between the *CV of intensity* and the pleasantness ratings for the polyrhythms condensed into 2-second cycle durations is a result of the participants relying on the click with the larger amplitude as an anchor or a 'down beat' of the rhythm, which is an indicator of where the rhythm presumably begins. The sound of the summed amplitudes is distinct from the other elements of the rhythm and it occurs every 2 seconds. Perhaps participants internalize and memorize when this distinct click will occur. For the polyrhythms with greater varied intensity between clicks, we suggest that this variation makes it easier for participants to 'latch on' to this anchor and conceivably, this then assists in identifying an underlying beat of the polyrhythm, which is the reasoning for the higher pleasantness ratings. In order for future work to address this, these polyrhythms should be created such that the amplitudes at the beginning of each cycle are not summed rendering the sound of each click consistent throughout the entire cycle.

Despite the strengths of the study design, it has several limitations. One in particular is with regard to our definition of a 'musician' and a 'non-musician'. While we relied on years of musical experience in the past 10 years as the determining factor to separate individuals with significant musical experience from those without significant musical experience, 'musical experience' is vague and should be defined more clearly. A participant's musical experience may only involve strumming a few chords on the guitar once a week. However, if this is the extent of this individual's musical experience, but the individual has been doing this for the past 6 years, this subject would be considered a musician under our criteria. In contrast, a participant who has only been playing an instrument for 4 years but with high practice intensity would still be considered a non-musician. Future work should use more stringent criteria, which can include having at least 10 years of constant training in Western music, having begun music training before the age of eight, and receiving musical training within the last 3 years on a regular basis (Liang, Earl, Thompson, Whitaker, Cahn, Xiang Fu & Zhang, 2016).

Future Research Directions

Subsequent studies should investigate the ambiguous area between rhythm and pitch perception by creating polyrhythms occurring at a tempo such that the distance between frequency periods of the polyrhythms become so short that it begins to reach the threshold in which we no longer perceive the elements of a rhythm as separate events, but rather, we perceive them as a single pitch (Epstein, 1995). This can provide an opportunity to investigate whether pleasantness ratings are consistent between these timescales, which could offer further support of nonlinear oscillator models of pitch and rhythm perception, like the model described by Large and Snyder (2009) (Razdan & Patel, 2016).

Events per second is an objective structure of the stimuli that was found to be significantly correlated with the pleasantness ratings for the polyrhythms condensed into 2-second cycle durations (see Appendix J). This is not the case for the polyrhythms in which the faster metronome is set to 120 BPM (see Appendix K). However, events per second are unlikely to be the driving force behind the pleasantness ratings of these polyrhythms. When being compared to the polyrhythms condensed into 2-second cycle durations, there is relatively little variation in events per second for the polyrhythms in which the faster metronome is set to 120 BPM. If a trivial explanation like events per second happened to drive pleasantness ratings, the pleasantness ratings for the polyrhythms in which the faster metronome is set to 120 BPM would be unlike the pleasantness ratings for the polyrhythms condensed into 2-second cycles. However, this is not the case (see Figure 8). Regardless, future studies should investigate and compare the pleasantness ratings of one polyrhythm across a range of tempi (i.e. 4:3 polyrhythm with the faster click train occurring at 60 BPM, 120 BPM, 240 BPM, etc.). By doing this, it can bring more insight into this negative correlation that exists between number of events per second and pleasantness ratings (see Table 4, Column 6).

Moreover, while the tapping data that was collected was not analyzed for the purposes of this thesis, future research should seek to uncover if there is a general consensus among participants with respects to where the underlying beat of the polyrhythms exist. To provide an example, for a 3:2 polyrhythm with the fastest click train occurring at 120 BPM, the perceived underlying beat could presumably exist at 120 BPM or any multiple of 120 *or* the perceived underlying beat could occur at 80 BPM or any multiple of 80.

Research that provides electrophysiological information on rhythm and pitch processing will also provide further insight into the link between pitch and rhythm processing. In a study conducted by Nozaradan (2014), the research describes an electrophysiological approach by means of EEG, which successfully captures the processing of beat perception. It was found that when a rhythmic stimulus is repeated periodically, it generates a periodic change in voltage amplitude in the brain's electrical activity. Presumably, similar neuropsychological approaches can help better understand the parallel between pitch and meter periodicity (Nozaradan, 2014).

Obtaining pleasantness ratings from individuals with non-Western musical backgrounds would be an additional important future step. Pitch intervals that are considered highly dissonant by Western listeners, including the minor second and tritone, are considered consonant in some cultures (i.e. Bulgarian folk-music) (Rice, 1980). If ratings of pleasantness for pitch and 'rhythmic' intervals differed from the ratings given by Western listeners but were found to be correlated, it then raises the question as to how external factors can manipulate and influence neural oscillator models, such as the one described by Large et al. (2010).

For future research, it is also worth creating polyrhythms in which the individual elements of the two click trains consists of different pitches. For example, observing how the pleasantness ratings of a 3:2 polyrhythm, in which one pulse stream consists of periods of 440hz and the other pulse stream consists of periods of 660hz (creating a 3:2 pitch frequency ratio), may differ from the pleasantness ratings of a 3:2 polyrhythm in which one pulse stream consists of periods of 440hz and the other pulse stream consists of periods of 466hz (creating a 16:15 pitch frequency ratio). It is important to note, however, that when generating these stimuli, in instances where the pitch intervals are large distances apart (i.e. major sevenths), the polyrhythms must be played at a relatively slower tempo. Otherwise, the rhythm sequence breaks down and it will be perceived as two distinct streams (known as the Galloping Rhythm Paradigm). Conversely, humans have difficulty discriminating between pitches if the tone is less than 12.5 ms in duration. Thus, when creating these polyrhythms, the rhythms cannot exceed a tempo in which the distance between each rhythmic element is less than 12.5 ms (Moore, 1973).

In addition to generating polyrhythms formed by expressing the frequency ratios of pitch intervals, Razdan and Patel (2016) also generated ‘rhythmic’ triads (see Appendix H). However, timing errors were discovered in the stimuli[3], thus the perceptual ratings for these triads cannot be relied on. Follow up studies should look to obtain perceptual ratings for rhythmic triads along with obtaining perceptual ratings on more complex chords with upper extensions (i.e. Maj7, min9, etc.).

Carl Stumpf’s fusion principle of tonal consonance argues that we perceive the composite sound of pitch intervals as opposed to perceiving the individual tones that construct a pitch interval (Stumpf, 2012). The same appears to hold true with respect to the perception of polyrhythms. For example, rather than interpreting a 3:2 polyrhythm as two pulse trains occurring at 120 BPM and 80 BPM, we perceive it as a composite rhythm. Presumably, when hearing pitch intervals or polyrhythms, humans attempt to identify a unitary percept from the polyrhythm (underlying beat) or pitch interval (single complex harmonic tone). If extracting this percept is either too difficult or too boring, this likely leads to a lower pleasantness rating. Further development should continue to explore this parallel that exists between the process in which the brain identifies how nicely the composite set of frequencies in a pitch interval resembles the spectrum of a single complex harmonic tone, and the process in which the brain can identify the underlying beat in the complex structure of a polyrhythm, and how both of these influence the perceived pleasantness of pitch intervals and their corresponding polyrhythms.

[3] Timing errors were thought to arise due to a lack of temporal precision capabilities in the visual programming language, MAXMSP

References

Benward, B., & Saker, M.N. (2003). Music: In Theory and Practice, Vol. 1, seventh edition. Boston: McGraw-Hill. *ISBN 0-07-294262-2*.

Bowling, D. L., & Purves, D. (2015). A biological rationale for musical consonance. *Proceedings of the National Academy of Sciences*, *112*(36), 11155-11160.

Brown, S., & Weishaar, K. (2010). Speech is" Heterometric": The Changing Rhythms of Speech. In *Speech Prosody 2010-Fifth International Conference*.

Crocker, R. L. (1963). Pythagorean mathematics and music. *The Journal of Aesthetics and Art Criticism*, *22*(2), 189-198.

Cowan, N., Lichty, W., & Grove, T. R. (1990). Properties of memory for unattended spoken syllables. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16(2), 258.

Epstein, D. (1995). *Shaping time: Music, the brain, and performance*. Wadsworth Publishing Company.

Fowler, C. A., Smith, M. R., & Tassinary, L. G. (1986). Perception of syllable timing by prebabbling infants. *The Journal of the Acoustical Society of America*, *79*(3), 814-825.

Itoh, K., Suwazono, S., & Nakada, T. (2003). Cortical processing of musical consonance: an evoked potential study. *Neuroreport*, *14*(18), 2303-2306.

Lots, I.S., & Stone, L. (2008). Perception of musical consonance and dissonance: an outcome of neural synchronization. *Journal of the Royal Society Interface*, *5,* 1429-1434.

Large, E. W. & Kim, J.C., Flaig, N.K., Bharucha, J.J., & Krumhansl, C.L. (2016). A neurodynamic account of musical tonality. *Music Perception, 33*, 319-331.

Large, E. W. & Snyder, J.S. (2009). Pulse and meter as neural resonance. *Annals of the New York Academy of Sciences, 1169*, 46-57.

Large, E.W., Herrera, J.A., & Velasco, M.J. (2015). Neural networks for beat perception in musical rhythm. *Frontiers in Neuroscience*, *9:*159. doi: 10.3389/fnsys.2015.00159

Liang, C., Earl, B., Thompson, I., Whitaker, K., Cahn, S., Xiang, J., ... & Zhang, F. (2016). Musicians are better than non-musicians in frequency change detection: behavioral and electrophysiological evidence. *Frontiers in neuroscience*, *10*, 464.

McDermott, J., & Hauser, M. (2004). Are consonant intervals music to their ears? Spontaneous acoustic preferences in a nonhuman primate. *Cognition*, *94*(2), B11-B21.

McDermott, J. H., Lehr, A. J., & Oxenham, A. J. (2010). Individual differences reveal the basis of consonance. *Current Biology*, *20*(11), 1035-1041.

McDermott, J. H., Schultz, A. F., Undurraga, E. A., & Godoy, R. A. (2016). Indifference to dissonance in native Amazonians reveals cultural variation in music perception. *Nature*, *535*(7613), 547.

Moore, B. C. (1973). Frequency difference limens for short-duration tones. *The Journal of the Acoustical Society of America*, *54*(3), 610-619.

Nozaradan, S. (2014). Exploring how musical rhythm entrains brain activity with electroencephalogram frequency-tagging. *Phil. Trans. R. Soc. B*, *369*(1658), 20130393.

Patel, A.D. (2008). Music, Language, and the Brain. NY: Oxford Univ. Press.

Patel, A. D., & Iversen, J. R. (2014). The evolutionary neuroscience of musical beat perception: the Action Simulation for Auditory Prediction (ASAP) hypothesis. *Frontiers in systems neuroscience*, *8*, 57.

Ramus, F., & Mehler, J. (1999). Language identification based on suprasegmental cues: A study based on resynthesis. *Journal of the Acoustical Society of America*, 105(1), 512-521.

Razdan, A.S. & Patel, A.D. (2016). Rhythmic consonance and dissonance: perceptual ratings of rhythmic analogs of musical pitch intervals and chords. In: *Proceedings of the 14th International Conference on Music Perception & Cognition (ICMPC14), July 2016, San Francisco.* T. Zanto (Ed.), Adelaide: Causal Productions, pp. 807–812.

Rice, T. (1980). Aspects of Bulgarian musical thought. *Yearbook of the International Fold Music Council, 12*, 43-66.

Savage, P. E., Brown, S., Sakai, E., & Currie, T. E. (2015). Statistical universals reveal the structures and functions of human music. *Proceedings of the National Academy of Sciences*, *112*(29), 8987-8992.

Soley, G., & Hannon, E. E. (2010). Infants prefer the musical meter of their own culture: A cross-cultural comparison. *Developmental psychology*, *46*(1), 286.

Stumpf, C. (2012). *The origins of music*. OUP Oxford.

Stupacher, J., Wood, G., & Witte, M. (2017). Neural entrainment to polyrhythms: a comparison of musicians and non-musicians. *Frontiers in neuroscience*, *11*, 208.

Schwartz, D.A., Howe, C.Q., & Purves, D. (2003) The statistical structure of human speech sounds predicts musical universals. *Journal of Neuroscience, 23,7160-7168.*

Tenney, J. (1988). A History of 'Consonance' and 'Dissonance.' New York: Excelsior Music Publishing.

Tramo, M. J., Cariani, P. A., Delgutte, B., & Braida, L. D. (2001). Neurobiological foundations for the theory of harmony in western tonal music. *Annals of the New York Academy of Sciences*, *930*(1), 92-116.

Trehub, S. E., Plantinga, J., Brcic, J., & Nowicki, M. (2013). Cross-modal signatures in maternal speech and singing. *Frontiers in psychology*, *4*, 811.

Winkler, I., Háden, G. P., Ladinig, O., Sziller, I., & Honing, H. (2009). Newborn infants detect the beat in music. *Proceedings of the National Academy of Sciences*, *106*(7), 2468-2471.

Winold, A. (1975). Rhythm in twentieth-century music. *Aspects of twentieth-century music*, 208-69.

Zentner, M. R., & Kagan, J. (1996). Perception of music by infants. *Nature*, *383*(6595), 29.

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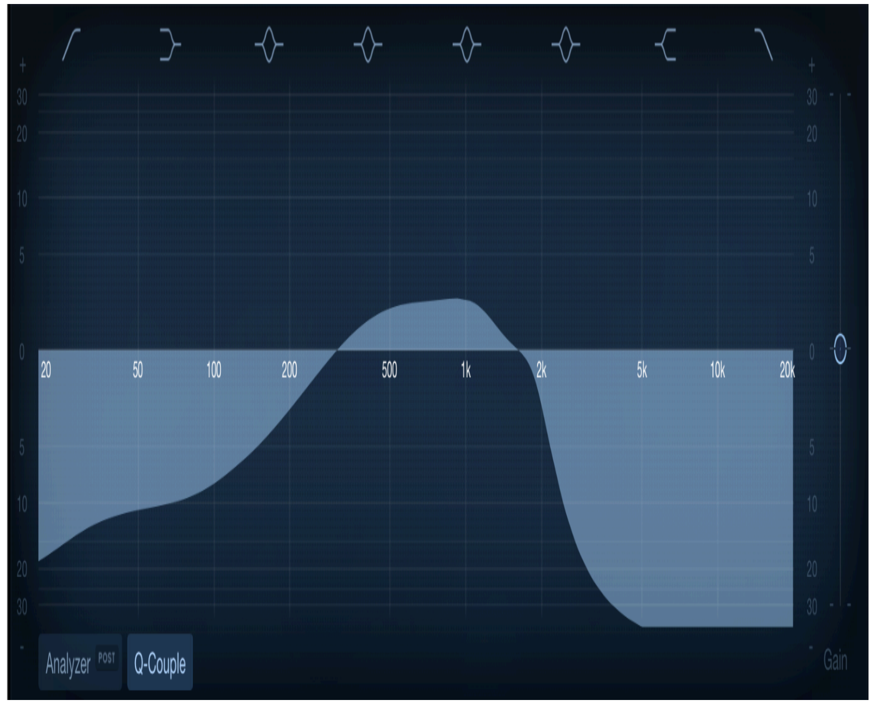
APPENDIX A

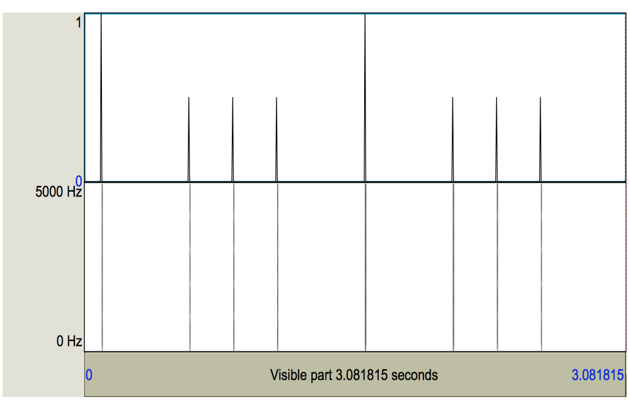
Filter settings and visual mapping of filters, which was applied to the timbre of the stimuli after the initial 28 participants. The software used for manipulating the timbre of the stimuli was Logic Pro X Version 10.1.1 Workstation

	Frequency (Hz)	Gain/Slope	Q Factor
Band1: High-pass filter	230	24 dB/Oct	0.1
Band 2: Low-shelving filter	52	+17 dB	1
Band 3: Parametric bell filters	1940	+10.5 dB	60
Band 4: Parametric bell filters	7000	+16.5 dB	30
Band 5: Parametric bell filters	11800	+11.5 dB	30
Band 6: Parametric bell filters	2350	+17 dB	20
Band 7: High-shelving filter	810	-14 dB	1
Band 8: Low-Pass filter	1120	24 dB/Oct	71

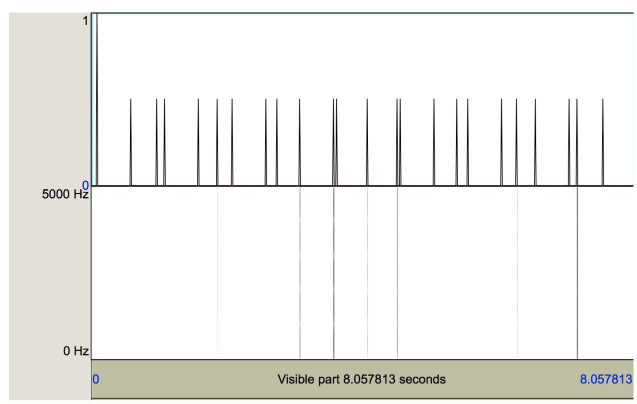


Waveforms of the 3:2 polyrhythm for the original and updated stimuli (a; original, b; updated) and waveforms for the 16:9 polyrhythm (c; original, d; updated) The image of the waveform for the 3:2 polyrhythm displays two cycle durations. The image of the waveform the 16:9 polyrhythm displays one cycle duration

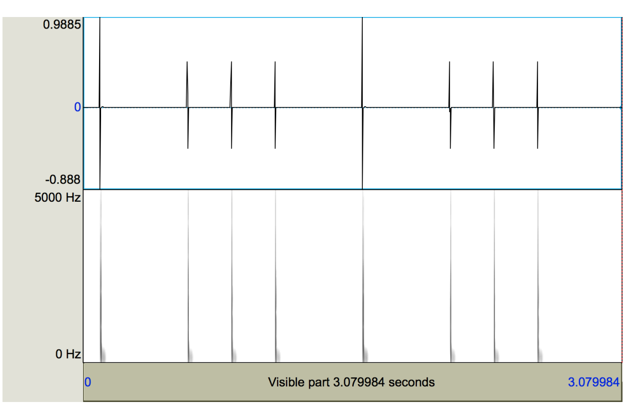
a)



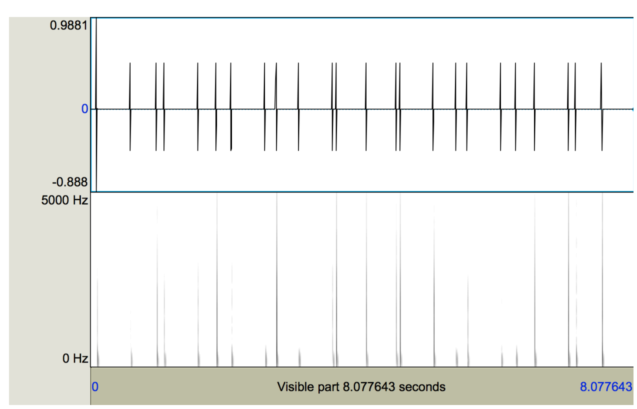
c)



b)



d)



APPENDIX B

Questionnaire distributed to the first 28 participants of the study

Study Title: Human preferences for different types of rhythms

Questionnaire: Music training

Participant ID:

Age:

Gender: *M* *F*

1) Do you have any hearing problems that you know of? If yes, please specify.

2) Do you have any musical training? *Yes* *No*

3) Please list what instruments, including voice, you have studied and for how long.

4) Are you still playing an instrument?

No → How long ago did you stop?

5) Do you think you have a good sense of rhythm? *Yes* *No* *Don't know*

6) How often do you listen to music (in hours/week)? *0-1* *2-4* *4-6* *6-8* *8+*

7) What genres do you primarily listen to?

APPENDIX C

Questionnaire distributed to last 49 participants of the study

Study Title: Human preferences for different types of rhythms

Questionnaire: Music training

Participant ID:

Age:

Gender:

1) With respects to rating the rhythmic patterns on their 'pleasantness', please briefly explain what your rating criteria was (i.e. you had an easy/difficult time tapping your foot to it)

2) Do you have any hearing problems that you know of? If yes, please specify.

3) Do you have any musical training? *Yes* *No*

4) Please list what instruments, including voice, you have studied and for how long.

5) Are you still playing an instrument?

No → How long ago did you stop?

6) Do you think you have a good sense of rhythm? *Yes* *No* *Don't know*

7) How often do you listen to music (in hours/week)? *0-1* *2-4* *4-6* *6-8* *8+*

8) What genres do you primarily listen to?

APPENDIX D

The order in which the stimuli was presented to participants in the third block of the study

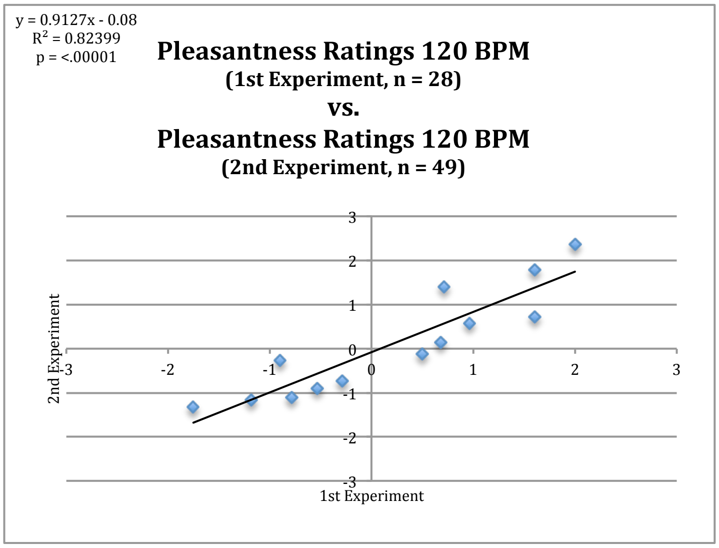
Interval	Ratio Between Fundamental Frequencies	Tempo of Faster Metronome (BPM)	Number Order
M2	9:8	270	1
m2	16:15	120	2
m6	8:5	240	3
TT	45:32	120	4
M6	5:3	150	5
NA	Random	Avg = 120	6
M3	5:4	150	7
P5	3:2	120	8
m3	6:5	180	9
m3	6:5	120	10
M7	15:8	450	11
m6	8:5	120	12
m7	16:9	480	13

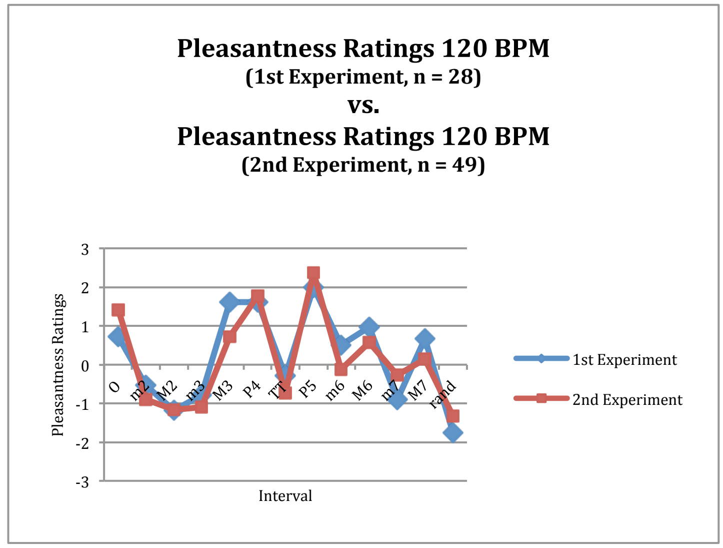
The order in which the stimuli was presented to participants in the fourth block of the study

Interval	Ratio Between Fundamental Frequencies	Tempo of Faster Metronome (BPM)	Number Order
m7	16:9	120	1
P5	3:2	90	2
M3	5:4	120	3
NA	Random	Avg = 335	4
M7	15:8	120	5
O	2:1	60	6
P4	4:3	120	7
TT	45:32	1350	8
M2	9:8	120	9
m2	16:15	480	10
M6	5:3	120	11
O	2:1	120	12

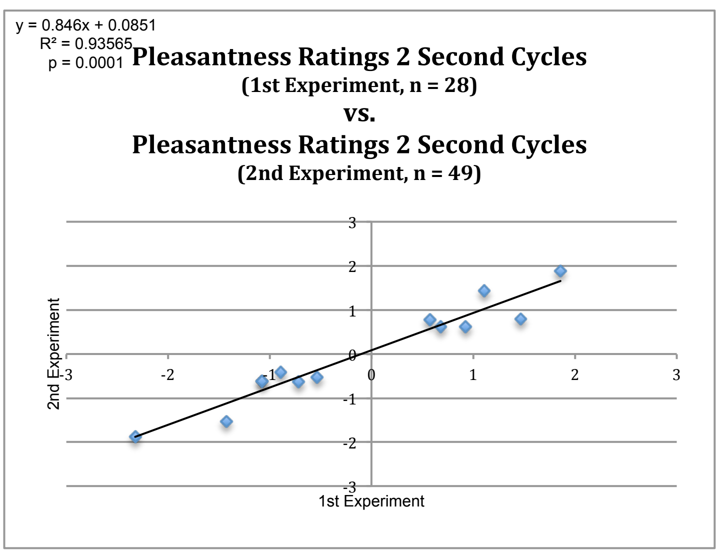
APPENDIX E

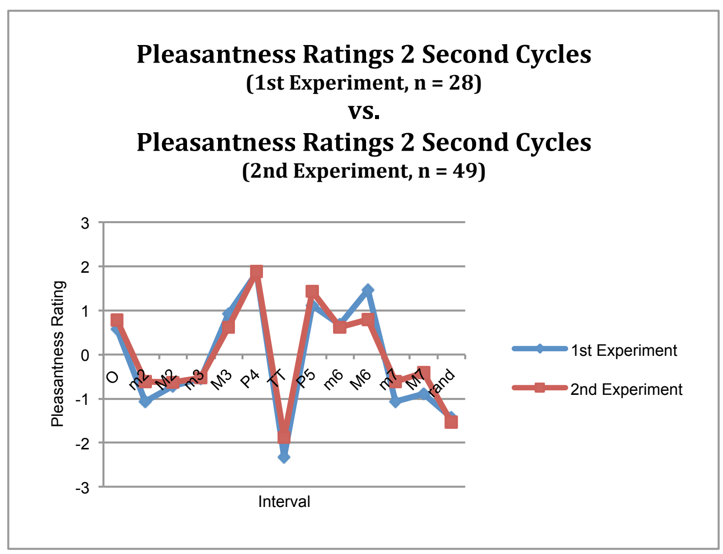
Comparison of mean pleasantness ratings for the stimuli in which the faster metronome is set to 120 BPM between the first 28 participants (1st Experiment) and the following 49 participants (2nd Experiment). These two groups of participants listened to stimuli in which the rhythmic elements of the polyrhythms differed in timbre



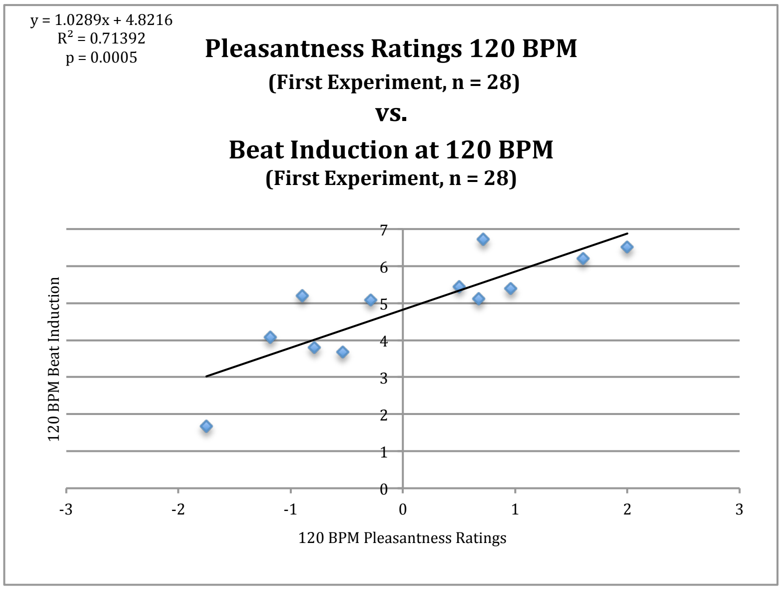


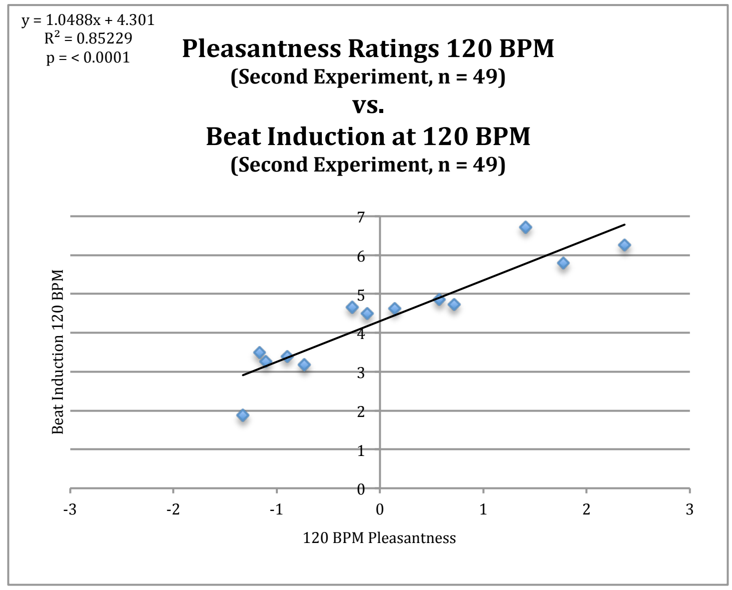
Comparison of mean pleasantness ratings for stimuli condensed into 2-second cycle durations between the first 28 participants (1st Experiment) and the following 49 participants (2nd Experiment). These two groups of participants listened to stimuli in which the rhythmic elements of the polyrhythms differed in timbre



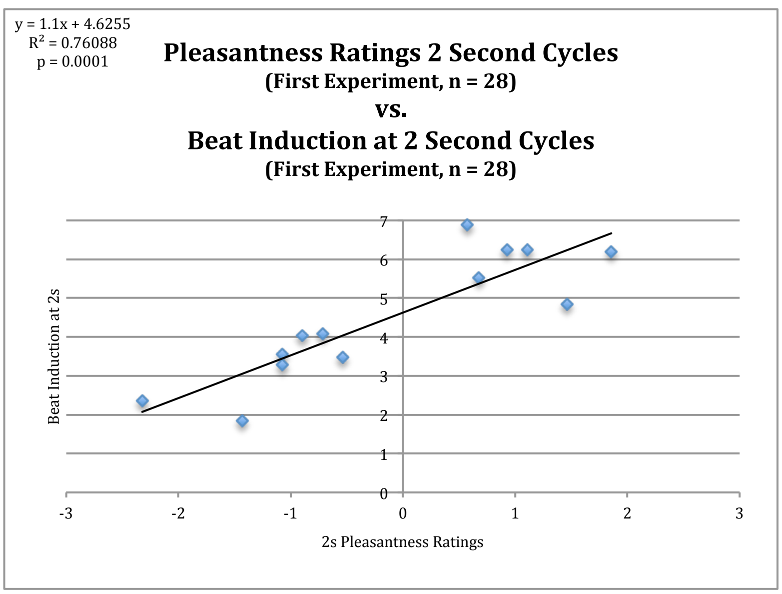


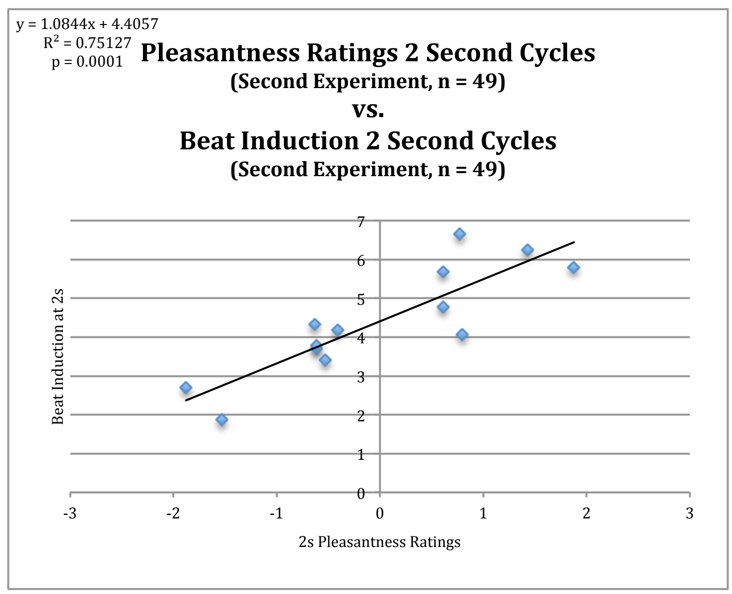
Comparison of mean pleasantness ratings and ratings for beat induction among first 28 participants (1st Experiment) and among the following 49 participants (2nd Experiment) for polyrhythms in which the faster metronome is set to 120 BPM. These two groups of participants listened to stimuli in which the rhythmic elements of the polyrhythms differed in timbre



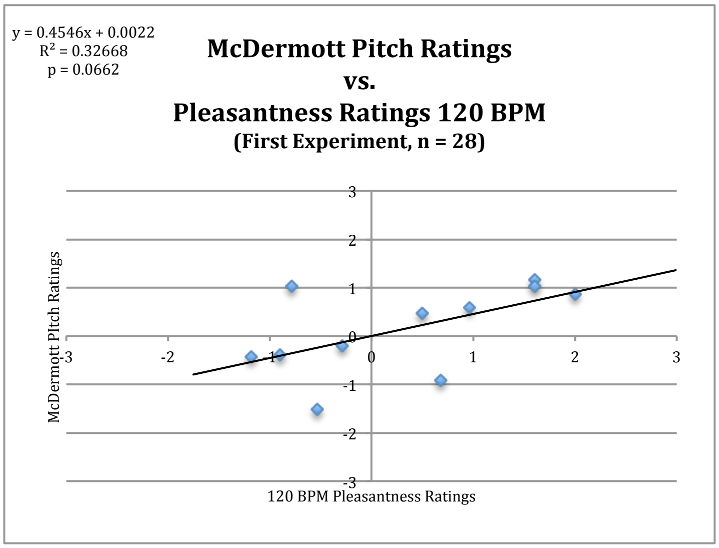


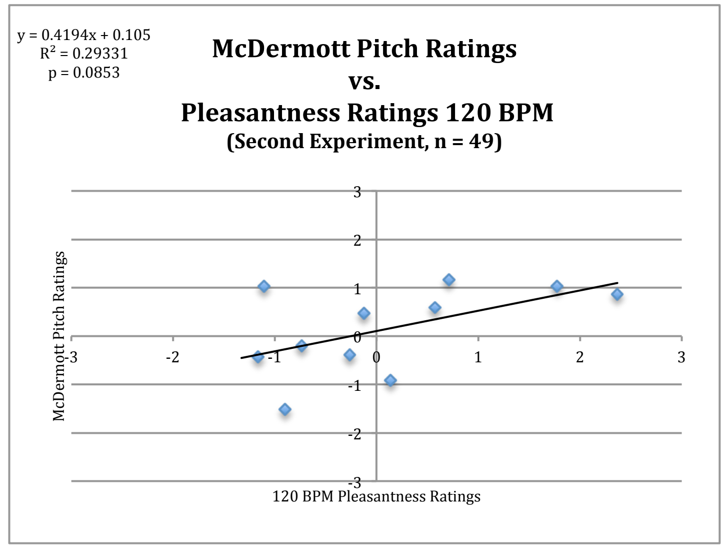
Comparison of mean pleasantness ratings and ratings for beat induction among first 28 participants (1st Experiment) and among the following 49 participants (2nd Experiment) for polyrhythms condensed into 2-second cycles. These two groups of participants listened to stimuli in which the rhythmic elements of the polyrhythms differed in timbre



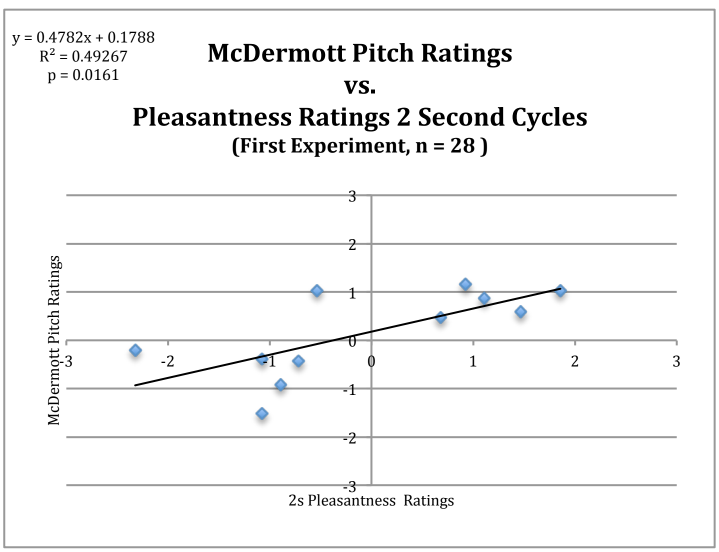


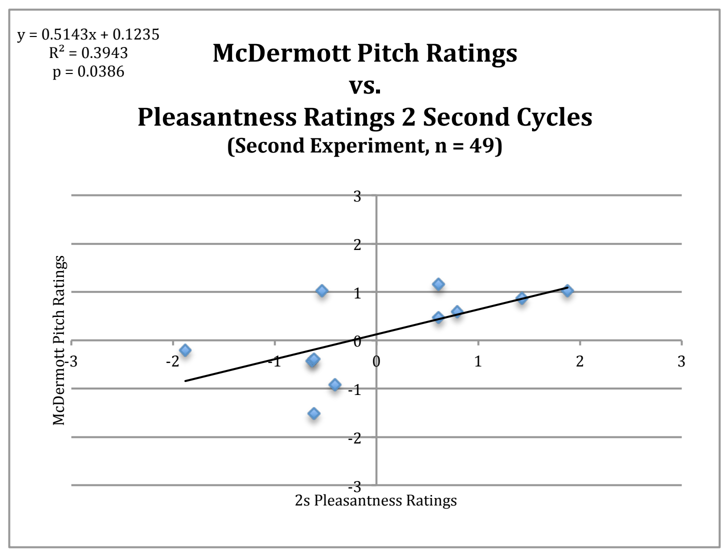
Comparison between McDermott et al's (2010) pitch interval pleasantness ratings and mean pleasantness ratings for the first 28 participants (1st Experiment) and the following 49 participants (2nd Experiment) for polyrhythms in which the faster metronome is set to 120 BPM. These two groups of participants listened to stimuli in which the rhythmic elements of the polyrhythms differed in timbre





Comparison between McDermott's (2010) pitch interval pleasantness ratings and mean pleasantness ratings for the first 28 participants (1st Experiment) and the following 49 participants (2nd Experiment) for polyrhythms condensed into 2-second cycles. These two groups of participants listened to stimuli in which the rhythmic elements of the polyrhythms differed in timbre





APPENDIX F

Total rating data (mean and standard errors) for pleasantness (P) and beat induction (B) ratings for polyrhythms in which the faster metronome is set to 120 BPM (120) and 2-second cycles (2s) in addition to pleasantness ratings for corresponding pitch intervals from McDermott et al. (2010) (McDermott). See Table 1 for definition of symbols in column 1. Pleasantness ratings are obtained from 77 participants and ratings for beat induction are obtained from 74 participants. It should be noted that the mean rating of beat induction for the 5:4 polyrhythm for the condition in which the faster metronome is set to 120 BPM was obtained from n = 49. SE = standard error.

Interval	120 P	120 P SE	2s P	2s SE	120 B	120 B SE	2s B	2s B SE	McDermott P
O	1.155844156	0.184928479	0.701298701	0.191287446	6.71621626	0.097203151	6.72972973	0.090858135	NA
m2	-0.766233766	0.204942437	-0.779220779	0.229879591	3.48648646	0.191685023	3.648648649	0.207622632	-1.516
M2	-1.168831169	0.164732843	-0.662337662	0.178864794	3.68918919	0.178360707	4.243243243	0.176152061	-0.434
m3	-0.987012987	0.177794557	-0.532467532	0.176918655	3.44594596	0.1689985	3.432432432	0.164490261	1.031
M3	1.038961039	0.188022735	0.727272727	0.153158101	4.73469388	0.203656019	5.081081081	0.198808704	1.166
P4	1.714285714	0.141828146	1.87012987	0.135030754	5.93243242	0.163644037	5.932432432	0.163644037	1.022
TT	-0.571428571	0.195146659	-2.038961039	0.184351553	3.82432434	0.196562563	2.581081081	0.219391941	-0.201
P5	2.233766234	0.115296438	1.311688312	0.152737316	6.35135131	0.123853397	6.243243243	0.128803928	0.872
m6	0.103896104	0.197025398	0.636363636	0.200741185	4.81081081	0.178101049	5.621621622	0.152363464	0.471
M6	0.714285714	0.178143712	1.038961039	0.185276168	5.04054051	0.17470469	4.324324324	0.210874405	0.596
m7	-0.142857143	0.197138003	-0.779220779	0.219225768	4.83783788	0.168872633	3.608108108	0.205277976	-0.391
M7	0.337662338	0.182646293	-0.584415584	0.203649755	4.79729727	0.167720667	4.135135135	0.203926946	-0.922
rand	-1.480519481	0.163909005	-1.493506494	0.175014282	1.810810811	0.131456787	1.864864865	0.100580184	NA

Musicians' rating data (mean and standard errors) for pleasantness (P) and beat induction (B) ratings for polyrhythms in which the faster metronome is set to 120 BPM (120) and 2 second cycles (2s) in addition to pleasantness ratings for corresponding pitch intervals from McDermott et al. (2010) (McDermott). See Table 1 for definition of symbols in column 1. Pleasantness ratings are obtained from 31 participants and ratings for beat induction are obtained from 30 participants. It should be noted that the mean rating of beat induction for the 5:4 polyrhythm for the condition in which the faster tempo is set to 120 BPM was obtained from n = 16. SE = standard error.

Interval	120 P	120 P SE	2s P	2s SE	120 B	120 B SE	2s B	2s B SE	McDermott P
O	1.709677419	0.250563015	1.35483871	0.252081174	6.8	0.100573071	6.833333333	0.108100989	NA
m2	-0.548387097	0.340267794	-0.193548387	0.372204577	3.733333333	0.295301651	3.966666667	0.357138478	-1.516
M2	-1.290322581	0.254818292	-0.129032258	0.288645094	4.2	0.289271777	4.566666667	0.228354098	-0.434
m3	-0.419354839	0.285017236	-0.387096774	0.280849018	3.566666667	0.269880064	3.933333333	0.224547224	1.031
M3	1.419354839	0.2572568	0.774193548	0.195154625	5.0625	0.322344924	5.3	0.303807259	1.166
P4	2	0.196747751	2.225806452	0.183804931	5.866666667	0.261443092	5.866666667	0.261443092	1.022
TT	-0.129032258	0.330336861	-1.709677419	0.353761807	4.333333333	0.346852293	2.8	0.38774325	-0.201
P5	2.161290323	0.180183743	1.548387097	0.235726786	6.566666667	0.149199653	6.366666667	0.200478355	0.872
m6	0.451612903	0.296353137	1.161290323	0.262726704	4.9	0.276887462	5.866666667	0.223521108	0.471
M6	0.935483871	0.296704059	1.741935484	0.258064516	5.366666667	0.289602714	4.666666667	0.315621384	0.596
m7	-0.096774194	0.290919339	-0.806451613	0.354447487	5.133333333	0.257009027	3.733333333	0.317798944	-0.391
M7	0.387096774	0.280849018	-0.258064516	0.307496803	4.933333333	0.239411795	4.1	0.322882136	-0.922
rand	-1.322580645	0.275864611	-1.193548387	0.309071989	1.666666667	0.175075244	1.966666667	0.162476052	NA

Non-Musicians' rating data (mean and standard errors) for pleasantness (P) and beat induction (B) ratings for polyrhythms in which the faster metronome is set to 120 BPM (120) and 2 second cycles (2s) in addition to pleasantness ratings for corresponding pitch intervals from McDermott et al. (2010) (McDermott). See Table 1 for definition of symbols in column 1. Pleasantness ratings are obtained from 46 participants and ratings for beat induction are obtained from 44 participants. It should be noted that the mean rating of beat induction for the 5:4 polyrhythm for the condition in which the tempo of the faster metronome is set to 120 BPM, was obtained from n = 33. SE = standard error.

Interval	120 P	120 P SE	2s P	2s SE	120 B	120 B SE	2s B	2s B SE	McDermott P
O	0.782608696	0.246547256	0.260869565	0.253353894	6.659090909	0.089261454	6.659090909	0.120950606	NA
m2	-0.913043478	0.255993069	-1.173913043	0.280276516	3.318181818	0.252521247	3.431818182	0.258401161	-1.516
M2	-1.086956522	0.217197982	-1.02173913	0.214203683	3.340909091	0.187166632	4.022727273	0.253295933	-0.434
m3	-1.369565217	0.211638868	-0.630434783	0.229173469	3.363636364	0.210983664	3.090909091	0.237817049	1.031
M3	0.782608696	0.258036142	0.695652174	0.221696501	4.575757576	0.249346062	4.931818182	0.274718437	1.166
P4	1.52173913	0.193466047	1.630434783	0.182199911	5.977272727	0.218585268	5.977272727	0.218585268	1.022
TT	-0.869565217	0.231793461	-2.260869565	0.192704581	3.477272727	0.164907117	2.431818182	0.26306012	-0.201
P5	2.282608696	0.151204643	1.152173913	0.198952307	6.204545455	0.169823807	6.159090909	0.172948492	0.872
m6	-0.130434783	0.259335263	0.282608696	0.275686308	4.75	0.217386875	5.454545455	0.212218219	0.471
M6	0.565217391	0.221222283	0.565217391	0.233958116	4.818181818	0.214483414	4.090909091	0.256829394	0.596
m7	-0.173913043	0.267939621	-0.760869565	0.28178997	4.636363636	0.19985627	3.522727273	0.284619675	-0.391
M7	0.304347826	0.242510153	-0.804347826	0.268507352	4.704545455	0.231228783	4.159090909	0.266015907	-0.922
rand	-1.586956522	0.202820896	-1.695652174	0.203518721	1.909090909	0.195895714	1.795454545	0.143201928	NA

APPENDIX G

Objective measures of stimuli structure (faster metronome set to 120 BPM)

Symbol	Frequency Ratio	STD of IOI	Mean IOI	CV of IOI	Avg. # Events/Second	CV of Intensity	Cycle Duration (s)
O	2:1	0	0.500	0	2.133	23.549	1
m2	16:15	0.142	0.259	0.550	4.000	16.544	8
M2	9:8	0.138	0.281	0.490	3.683	17.040	4.5
m3	6:5	0.141	0.300	0.471	3.462	17.861	3
M3	5:4	0.143	0.313	0.457	3.333	18.734	2.5
P4	4:3	0.137	0.326	0.421	3.200	19.140	2
TT	45:32	0.163	0.298	0.548	3.491	17.468	22.5
P5	3:2	0.128	0.375	0.342	2.800	20.664	1.5
m6	8:5	0.151	0.326	0.464	3.200	18.816	4
M6	5:3	0.142	0.357	0.398	2.933	20.034	2.5
m7	16:9	0.160	0.326	0.491	3.200	18.563	8
M7	15:8	0.160	0.341	0.469	3.067	19.241	7.5
rand_120	NA	0.134	0.499	0.269	2.111	22.338	NA

Objective measures of stimuli structure (2-second cycles)

Symbol	Frequency Ratio	STD of IOI	Mean IOI	CV of IOI	Avg. # Events/Second	CV of Intensity	Cycle Duration (s)	Tempo of Faster Metronome (BPM)
O	2:1	0	1	0	1.143	33.318	2	60
m2	16:15	0.036	0.066	0.543	15.238	8.227	2	480
M2	9:8	0.064	0.124	0.514	8.229	11.423	2	270
m3	6 :5	0.104	0.183	0.571	5.609	14.625	2	180
M3	5:4	0.112	0.245	0.457	4.211	16.450	2	150
P4	4:3	0.137	0.326	0.421	3.200	19.140	2	120
TT	45:32	0.014	0.026	0.541	38.222	5.091	2	1350
P5	3:2	0.172	0.489	0.352	2.182	23.643	2	90
m6	8:5	0.075	0.165	0.456	6.194	13.286	2	240
M6	5:3	0.123	0.271	0.453	3.816	17.639	2	150
m7	16:9	0.040	0.083	0.476	12.191	9.241	2	480
M7	15:8	0.042	0.090	0.463	11.186	9.671	2	450
rand_335	NA	0.064	0.179	0.358	5.630	13.447	NA	NA

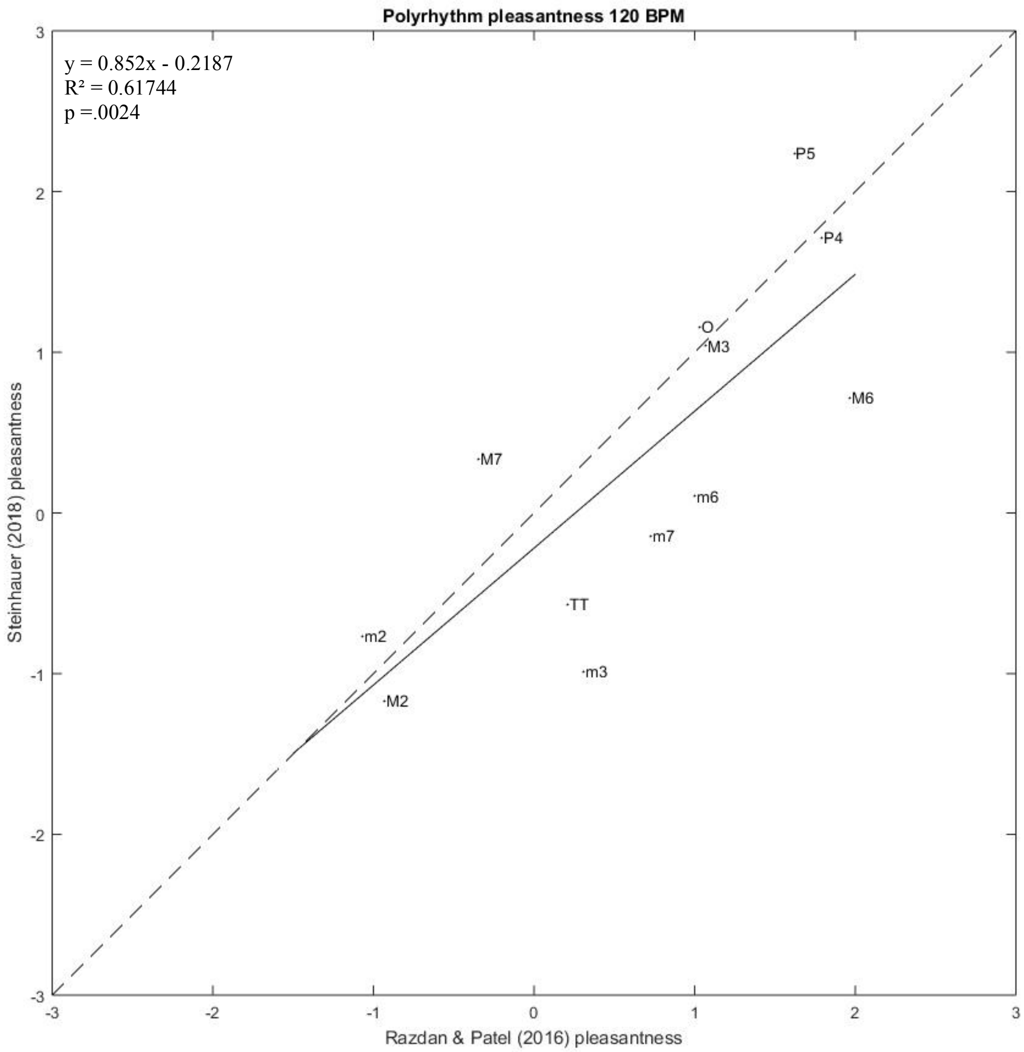
APPENDIX H

Information regarding the rhythmic triads used in Razdan and Patel (2016)

Triad	Frequency Ratio	Cycle Duration (s)
Major	6:5:4	3
Minor	15:12:10	7.5
Augmented	25:20:16	12.5
Diminished	64:54:45	32

APPENDIX I

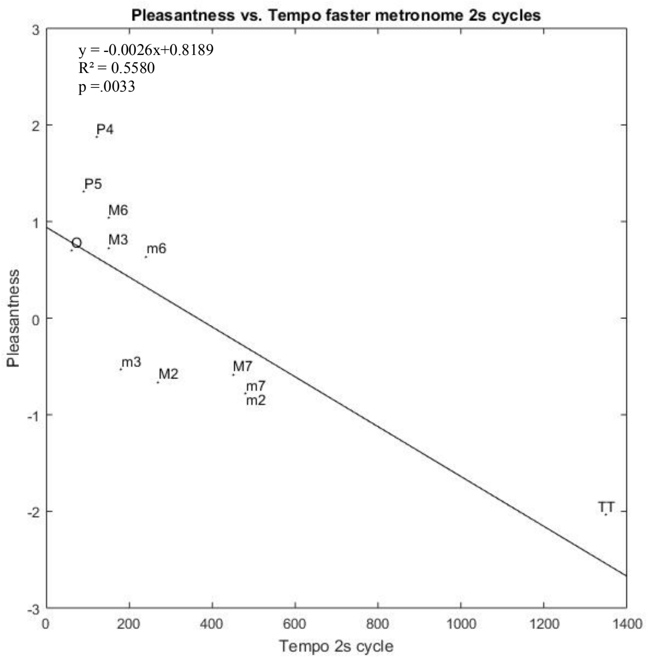
Relationship between Razdan and Patel (2016) pleasantness ratings for polyrhythms in which the faster metronome is set to 120 BPM and the current study's pleasantness ratings for polyrhythms in which the faster metronome is set to 120 BPM. The dashed line shows the identity line, and the solid line shows the best-fitting regression line (equation shown in upper left of graph).



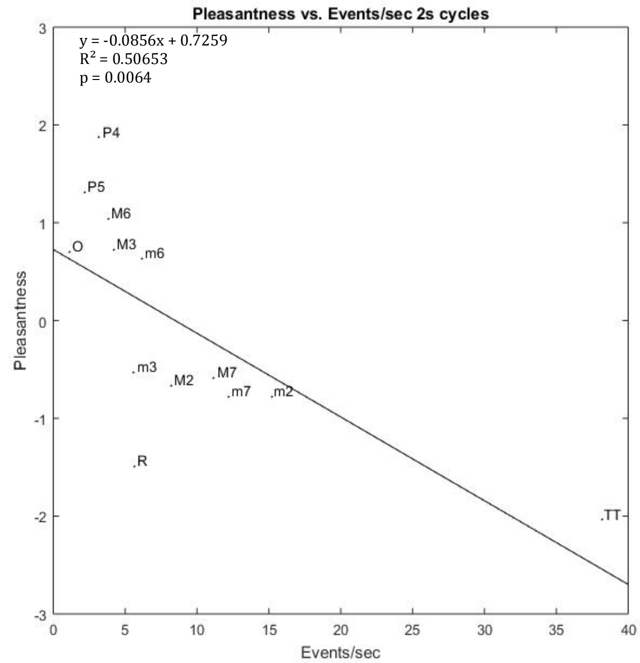
APPENDIX J

Relationship between pleasantness ratings for polyrhythms condensed into 2-second cycle durations and a) tempo of the faster metronome for polyrhythms condensed into 2-second cycles. b) events/second for the polyrhythms condensed into 2-second cycle durations. It should be noted that in Figure (a) the data point for the m2 and m7 are the same, since they share the same value for pleasantness and for tempo of the faster metronome.

a



b



APPENDIX K

Relationship between pleasantness ratings for polyrhythms in which the faster click train is set to 120 BPM vs. events/second for these polyrhythms.