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Understanding the Relationship between Perception and Production of the Beat

Taylor W. Parrott, *The University of Western Ontario*

Supervisor: Dr. Jessica Grahn, *The University of Western Ontario*

A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Neuroscience

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UNDERSTANDING THE RELATIONSHIP BETWEEN PERCEPTION AND
PRODUCTION OF THE BEAT

(Thesis format: Monograph)

by

Taylor Parrott

Graduate Program in Neuroscience

A thesis submitted in partial fulfilment
of the requirements for the degree of
Master of Science

The School of Graduate and Postdoctoral Studies
The University of Western University
London, Ontario, Canada

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Abstract

Impaired discrimination of sequences with a ‘beat’ in patients with Parkinson’s disease (PD) suggests the basal ganglia are responsible for the perception, or ‘internal generation’ of the beat in addition to motor timing. As a first step, we examined how young healthy participants performed on tests assessing perception, internal generation, and motor production of the beat to determine if a common mechanism guides all three processes and how this mechanism affects timing. The results suggest that perception, internal generation and production are controlled by a common timing mechanism. In general, a strong perception of the beat was associated with good synchronization accuracy (tapping and walking) and timing accuracy. Thus, previous findings of impaired beat processing in PD patients may result from deficient beat perception, in addition to or in lieu of deficient motor timing. Future studies with PD patients are needed to better understand the role of the basal ganglia in beat processing.

Keywords: Music, rhythm, beat perception, internal generation, beat production, timing mechanisms, gait, synchronization

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Chapter 1: General Introduction

Introduction

Across individuals, rhythmic ability is thought to vary widely. An important element to one's rhythmic ability is the sense of a periodic pulse or 'beat'. Perception of the beat often causes spontaneous synchronized movement, such as toe tapping, finger snapping, or body swaying, implying that humans are sensitive to the beat. Previous research has shown that the beat is important for perception and accurate mental representation of a rhythmic sequence. Perception of rhythmic sequences with a regular beat has been shown to be impaired in patients with Parkinson's disease (PD; Grahn & Brett, 2009). However, it is still unknown if this deficit is due to impairments in perceiving the beat, in producing the beat, or both.

Knowing if PD patients show deficits in the stages of rhythm perception and not just the production of movements may aid in the development of appropriate musical stimuli for rehabilitation. Many rehabilitation studies with PD patients require synchronization of body movements with a metronome (Lim et al., 2005; Spaulding et al., 2013; Thaut et al., 1996), a process that has been studied extensively in tapping and walking experiments (Repp & Su, 2013; Repp, 2005; Thaut, 2005). For example, Rhythmic Auditory Cueing is used to facilitate coordinated actions in patients with movement disorders, such as stroke, or Parkinson's disease (McIntosh & Brown, 1997; Thaut et al., 1996). In addition, synchronization can also occur when listening to music (Styns, van Noorden, Moelants, & Leman, 2007). Currently little work has been done to show how the stages of rhythm processing affects synchronization movements (e.g., tapping, walking).

The research I have undertaken seeks to develop the necessary tasks to study whether the deficits seen in PD patients arise from difficulty in perceiving or producing the beat. Production of the beat is divided into two categories: ‘internal’ generation and motor production. Internal generation of the beat occurs once the beat has been found and refers to the process of predicting the next beat location. Prediction of future beat locations allows for timing of future events, specifically motor responses or motor production (e.g. tapping). The main question becomes whether the mechanism used for perceptual timing (perception and internal generation of the beat) has any commonality with the mechanism used for motor production and how perception and production correspond to rhythm perception.

Rhythm perception and the role of timing mechanisms

Broadly defined, rhythm is a pattern of temporal intervals in a stimulus sequence. The rhythm pattern is indicated by the sequential onsets of a sound (tone, click) and the time between onsets defines the length of the time intervals that comprise the sequence. Rhythms can have different levels of regularity and structure. For example, in Western music, rhythms are often regular and induce a beat; however, rhythms can also be irregular and may not have a regular beat.

To perceive the intervals within a rhythm we require an internal ‘clock’ to measure time. In the field of timing, the nature of this clock is still under debate. ‘Absolute’ timing theories view the clock as a stopwatch that can be started at the beginning of an interval, stopped at the end of an interval, and reset for the next interval. Alternatively, ‘relative’ timing theories view the clock as an oscillator that entrains to the

regularities (the beat) in a rhythm and generates expectancies about the occurrence of future events in time (Large & Jones, 1999).

Use of absolute timing versus relative timing

Using the clock, an absolute, duration-based timing mechanism measures the absolute duration of each time interval within a rhythm, then stores interval durations into a reference memory (Church & Broadbent, 1990; Gibbon, Malapani, Dale, & Gallistel, 1997). Previous neuropsychological studies of patients with cerebellar damage established the role of the cerebellum in absolute timing (Grube, Cooper, Chinnery, & Griffiths, 2010; Grube, Lee, Griffiths, Barker, & Woodruff, 2010). Cerebellar degeneration patients showed a specific impairment on the duration-based timing tasks (e.g., comparing single intervals that do not establish a beat); however, they showed no deficits on relative timing tasks (e.g., discriminating a more regular target sequence against a less regular reference sequence). This dissociation specifically implicated the cerebellum in the explicit encoding of the absolute duration of time intervals.

The clock in relative, beat-based timing entrains to the beat to which durations are then measured (Teki, Grube, Kumar, & Griffiths, 2011). This mechanism may be analogous to “chunking”, a way of reducing complex patterns to simpler components (Graybiel, 1998). Representing intervals as multiples and subdivisions of a single beat duration may be more efficient than representing each interval separately as seen in an absolute timer. For example, a performance benefit might be seen when sequences containing intervals of different durations are timed.

Neuroimaging studies have shown that a relative timing mechanism recruits a striato-thalamo-cortical system involving basal ganglia (BG), thalamus, premotor cortex

(PMC), supplementary motor area (SMA), and DLPFC (dorsolateral prefrontal cortex; Grahn and Brett, 2007; Teki et al., 2011). Further confirmation of the role of the BG in relative timing comes from neuropsychological studies showing impaired beat-based timing in PD (Artieda, Pastor, Lacruz, & Obeso, 1992; Grahn & Brett, 2009; Pastor, Artieda, Jahanshahi, & Obeso, 1992). Grahn & Brett (2009) compared patients with PD and older adults on a perceptual discrimination task in which participants listened to two types of rhythms. The first rhythm, called a metric simple rhythm gave a clear sense of the beat, while the second, called metric complex, was designed so participants could not easily extract a beat (for a schematic drawing see Figure 1). Subjects heard two presentations of a rhythm, then a comparison rhythm that was the same or different (contained a transposition of intervals). In the metric simple condition, where intervals can be timed with a relative mechanism, lower discrimination performance was observed in patients with PD compared to aged control participants. However, performance in the metric complex condition, where intervals are timed with an absolute mechanism, was similar between the two groups. Impairment in the use of a relative timing mechanism supports the role of the BG in processing the beat. It is noteworthy that the authors found no difference between individuals with PD and aged adults in the metric complex rhythms. This suggests that the deficit seen in relative timing is selective and not due to general deficits in timing or difficulty with the task.

The exact role of BG in mediating beat perception is still unknown. There are two possibilities that will be tested: 1) BG are engaged in the search to find (or perceive) the beat; and 2) BG might make predictions and produce (i.e., internally generate) the beat to use as a guide during the discrimination phase in the above task. Internal generation of

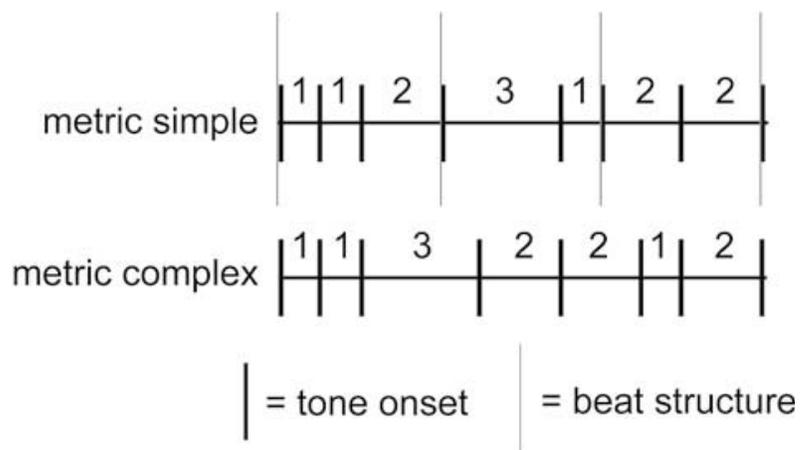


Figure 1. A schematic of example rhythms used in the reproduction experiment (Grahn & Brett, 2009). Grey bars represent the location of the beat, while the numbers denote relative length of intervals in each sequence.

the beat allows for the organization of onsets in the different rhythmic intervals with reference to the regular beat. To elucidate the role of the BG in beat perception and internal generation, we will develop tests to determine if perception and internal generation of the beat are dissociable in a healthy population. If the tasks are dissociable, performance on the beat perception tests will not correlate with performance on the internal generation tests. If a dissociation is present in some participants, the relative contributions of perception and internal generation of the beat in discriminating metric simple rhythms can be determined. If participants with a dissociation are able to discriminate changes in metric simple rhythms then impaired discrimination accuracy in PD patients might be due to impaired perception of the beat. Conversely, if there is no dissociation, it would be expected that people with a stronger representation of the beat are also better able to internally generate the beat.

Beat perception

The core difference between absolute and relative timing is the presence of a beat. However, not all sequences induce a sense of the beat and therefore these sequences are likely to be timed using an absolute mechanism. In music, the beat is emphasized by non-temporal cues such as pitch, volume, and timbre, yet even rhythms without these cues can induce listeners to “feel” a beat. Current studies investigating perception of the beat in the general population use the perceptual subtest of the Beat Alignment Test (BAT; Iversen & Patel, 2008). In the BAT, participants hear musical clips from various genres with a series of regular beeps superimposed. Participants judge whether the superimposed beeps are on or off the beat. One limitation with the BAT is the use of real music with non-temporal cues (e.g., pitch, volume, timbre), which provide additional information for

beat locations. For example, the bass drum may be consistently heard on the beat, and/or notes may be louder on the beat. Therefore, performance may be indicative of a participant's ability to use non-temporal factors to find the beat, hence the need to develop a beat perception test using rhythmic sequences where non-temporal factors are not present.

Essens and Povel (1985) developed a theory to describe how the beat is induced by a rhythmic pattern containing only temporal grouping accents created by the durations of intervals between events. This theory classifies temporal patterns into two types: those that contain a metrical (i.e. measured by the beat) framework and those that do not contain a metrical framework (i.e. do not contain a beat). Within a rhythm, multiple beat rates can be perceived at different rates, with the fastest rate at the level of the smallest duration of an interval. The perceived beat is induced by the distribution of 'accents' in the sequence.

An accent is an emphasis on an interval onset making it sound louder than the surrounding intervals. In music, accents that cue the beat, called non-temporal factors, are provided by pitch, volume, and timbre, in addition to rhythm. However, in sequences where the tones are identical in all physical aspects except for duration, auditory events occurring on the beat sound more prominent or louder than events that occur off the beat (Large & Palmer, 2002; Large & Snyder, 2009). Accents placed on the beat by the listener are called subjective accents and can be explained by the dynamic attending theory (DAT). According to the DAT, perception of the beat corresponds to entrained internal neural oscillators, and subjective accents represent the point in time when the oscillators align with each other (Large & Palmer, 2002). The oscillators are thought to control

attention; once a beat is expected our attention is at its peak. This increased attention might heighten sensitivity to changes in the physical properties of an interval in a rhythm. Moreover, heightened sensitivity might increase the salience of the attended event leading to a perceived increase in loudness relative to neighbouring intervals with identical physical properties.

If a subjective accent occurs on a tone that falls on the beat, it should be possible to demonstrate this in psychophysical tasks requiring judgments of the perceived relative loudness of tones. The presence of a subjective accent has been tested in a study by Povel and Okkerman (1981) who had participants listen to two tones and adjust the volume of the tones to be equal. Participants increased the second of two tones in a row by about four decibels compared to the first tone for both tones to be perceived as equal volume. The authors speculate that participants heard an accent on the second tone because the processing of the first tone was interrupted by the second, and a more complete processing of the second tone caused it to be perceived as accented. This subjective accent has been studied using single intervals by using metronomic tones. However, it is still unknown if subjective accents can occur in rhythms with various interval length.

Tones in a rhythmic sequence that are perceived to be louder because of subjective accenting may cause masking of real intensity changes placed on that tone. Therefore, a note with an external intensity change on a beat location would be masked, hindering detection, when placed on the beat. Alternatively, a note that occurs off the beat does not contain an attention shift and may not mask an external intensity change. Using a rhythmic sequence with the physical characteristics of the tones being identical provides a purely perceptual task that can be used to deduce deficits in beat perception.

This test can not only be used in PD patients to determine whether their difficulties lie in perception of the beat, but it could tell us about whether perception and production are dissociable in the general population. By looking at individual differences in perception and production, we can assess whether individuals show preserved perception, as measured by failed detection of intensity changes on the beat, but impaired production of the beat.

Tapping to the beat: Sensorimotor synchronization

The perception of a beat and the accurate motor production of a beat may be dissociable processes, or may reflect a single mechanism. There is some support for the idea of reliance on a single mechanism (Schubotz, Friederici, & von Cramon, 2000). However, it is possible that someone could exhibit accurate beat perception but poor synchronization. Synchronization to the beat may be explained by the activities in motor areas associated with beat perception and generation. The ability to detect the beat requires intact BG. Specifically, BG have been implicated in generating and predicting the location of the beat in an auditory rhythm (Grahn & Rowe, 2012). However, activation is dependent on beat salience; the more salient the beat, the more activation seen in motor areas (e.g., PMC, BG; Chen, Zatorre, & Penhune, 2006). The coupling between beat salience and motor areas has been implicated in the precision of sensorimotor synchronization (Repp, 2010).

When asked to synchronize tapping to the beat, participants tap at a rate that is synchronized with an internal periodic process that marks the beat. As a result, synchronization is most accurate at beat rates matched to the frequency of internal period processes, known as a preferred rate. The rate at which we tap can be predicted by the

resonance model (van Noorden & Moelants, 1999). The resonance model can be used to explain the distribution of movement rates when relative timing can be used (Van Noorden & Moelants, 1999). Based on an overview of different experiments, Moelants (2002) concluded that there is a clear correspondence between the rate of spontaneous movements, as observed in walking, clapping and finger tapping, and the beat rate perceived in music. Among adults, tapping variability of rhythms slower and faster than their preferred rate is generally lower for highly trained musicians than for non-musicians (Repp & Su, 2013; Repp, 2007, 2010). Accurate synchronization across a range of rates in musicians has been attributed to better perception of the beat. How beat perception relates to motor synchronization to the beat is still unclear.

Walking to the beat

While many studies have focused on the synchronization of tapping (Repp & Su, 2013; Repp, 2005), fewer have focused on the synchronization of gait. Gait is a broad term and for this thesis it will be defined as the pattern of movement of the lower limbs. We are interested in studying gait because of its clinical application in movement disorders such as PD (Lim et al., 2005; Spaulding et al., 2013; Thaut et al., 1996). Acoustic cues may alter gait in the same way it alters tapping synchronization: creating a stable coupling between footfalls and the beat. By using acoustic cues, a number of temporal parameters can be altered (e.g., cadence) by changing the rate of acoustic stimuli. For example, rhythmic auditory stimulation, where participants listen to isochronous tones, has proved to be useful in gradually increasing the number of steps by synchronizing to each tone (Roerdink, Bank, Peper, & Beek, 2011).

Recently, research has expanded the type of auditory stimulation to include music and not just a metronome (as seen in RAS) to determine what the optimal stimuli are for synchronization. However, the use of music implies participants are able to perceive and synchronize their gait to the beat. In a study by Styns, Van Noorden, Moelants, and Leman (2007), participants tried to synchronize their steps with the beat of musical stimuli while walking on a treadmill. Synchronization was most accurate when the beat frequency was around 120 beats per minute (BPM). The authors suggest that walking speed can be modeled using a resonance curve. Synchronization is optimal at their preferred rate (120BPM) and becomes more variable as the rate deviates from their preferred rate. In light of this discovery it is still unknown whether perception of the beat may lead to improved synchronization of a greater range of beat rates. Most protocols require participants to synchronize steps to the beat, but never measure their perceptual capability (Hove, Suzuki, Uchitomi, Orimo, & Miyake, 2012; Nessler, Kephart, Cowell, & De Leone, 2011; Styns et al., 2007). If production and perception of the beat share a common timing mechanism, then participants with poor beat perception will likely show a deficit in synchronizing their footfalls to the beat of music. Knowing if better perception of the beat predicts synchronization performances may be useful when creating the optimal stimuli for gait rehabilitation.

The relationship between “groove” and movement

There is an additional quality in music that makes people want to move and should be controlled for when selecting musical stimuli. This quality is called groove, and is defined as “wanting to move some part of the body in relation to some aspect of the sound pattern” (Madison, 2006 p. 201). Groove has been studied in tapping

experiments; however, no studies have examined the effect of groove on walking synchronization.

After examining the acoustic features of music, Madison (2011) found the number of cues around the beat (beat density) and beat salience to be strong predictors of groove across genres. In addition, groove ratings were higher for fast than for slow music, and were highly correlated with enjoyment ratings. Of particular importance is beat density and beat salience. High beat density and beat salience can increase engagement and attention (Pressing, 2002) and improve the ability to predict and synchronize with a beat (Janata et al., 2012; Madison et al., 2011). When participants were asked to tap the beat to music that elicited a strong sense to move, they reported feeling more “in the groove” compared to low-groove excerpts and found tapping was easier in high groove music than low groove music (Janata et al., 2012). The resonator model of Tomic and Janata (2008), which generates a spectrum of the periodicities present in an input signal, indicated that sensorimotor coupling strength was higher in high groove music than it was for mid groove and low groove music.

Although research demonstrates that groove induces movement and improves tapping synchronization, it is still unknown whether groove has an effect on walking synchronization. Therefore, I aim to measure walking synchronization to determine if groove has the same effects on walking as it does on tapping synchronization.

Overview of thesis

Beat perception is integral to temporal reproduction and discrimination of rhythms. Previous literature has shown impaired discrimination of beat-based rhythms in PD patients (Grahn & Brett, 2009). A deficit in discrimination of beat-based rhythms

might be attributed to the role of the BG in normal beat perception or in internal generation of the beat. Moreover, synchronization of motor responses with a beat involves both the perception of a beat as well as the motor expression of this internally perceived beat. Little work has investigated whether beat perception and production (internal generation and motor production) share a common relative timing mechanism. That is, can some people perceive the beat, but not internally generate or synchronize to the beat, or are all three processes required to be successful in each task? The findings will set the stage for future work that dissociates whether the PD deficit results from a perceptual or productive deficit, which further tells us about the role of the BG in rhythm processing.

The first study consists of 7 experiments, collectively designed for two reasons: 1) to develop tasks to measure beat perception, internal generation of the beat, and motor production of the beat 2) to determine if there is dissociation between perception and production in a young population (that might explain the relative timing deficits seen in PD patients).

To test beat perception, we employed the perception beat alignment test (BAT) and an intensity threshold test. The perception BAT was used to test beat perception in the absence of internal generation or motor production using music stimuli. In the perception BAT participants determined if the superimposed tones were on or off the beat. Since this test uses real music containing non-temporal factors that aid in the perception of the beat, we developed a second task using rhythmic sequences. The second task, called the intensity threshold test, uses rhythmic sequences containing intensity changes on or off the beat. Tones in a rhythmic sequence that are perceived to be louder because of

subjective accenting may mask an external intensity change. Whereas a note that occurs off the beat does not contain an attention shift and may not mask an external intensity change. The intensity threshold test does not contain additional, non-temporal factors that aid perception of the beat, and thus is a pure representation of beat perception.

To measure internal generation of the beat we employed the metronome tempo discrimination test and the rhythm tempo discrimination test. In the metronome tempo discrimination test participants must listen to the beat that is given by the first metronomic sequence, then internally generate during the second metronomic sequence. Using two metronomic sequences minimizes perceptual demand. The only requirement is to internally generate a given beat. In the second task, we assess internal generation of the beat in the context of rhythm. Participants are asked to compare the beat of the rhythm to the beat given by the metronomic sequence. This task increases perceptual demands, as it requires participants to internally generate the beat while they perceive the beat of the rhythm. Using a rhythm provides a more accurate representation of internal generation seen in the task used in Grahn and Brett (2009).

To determine motor production of the beat, participants tapped to the beat of the stimuli from the BAT. Synchronization accuracy was determined while participants tapped their perceived beat rate. By developing tests for perception and production (internal generation and motor production), we are able to correlate each task to investigate if dissociation occurs in the general population and determine what effects it has on relative timing.

To test if a dissociation between perception and production have an effect on relative representations, we developed a more sensitive rhythm discrimination test as seen

in Grahn and Brett (2009). Participants listened to two identical standard rhythms, to which they compared a third rhythm that was either the same as or different from the standard rhythms. The rhythm discrimination test requires both perception and internal generation of the beat. Subjects must first find or perceive the beat, then internally generate the beat from the standard rhythms onto the comparison rhythm. If the intervals in standard and comparison rhythms match, they are the ‘same’, if not, they are ‘different’. The discrimination test requires larger perceptual demands, in that the beat of the standard rhythm must be perceived and internally generated.

The follow-up study was designed to investigate the relationship between perception and production of the beat using a walking paradigm, rather than a tapping paradigm. The second study measured whether beat perception explains not only tapping synchronization but also walking synchronization. Different types of stimuli (metric simple rhythms, metronomes, music) were presented to subjects, who were asked to synchronize their footfalls to the beat (metric simple rhythms, music) or tones (metronome). The purpose of this experiment was to investigate the difference in synchronization accuracy across different levels of beat perception ability (using perception BAT), in addition to finding the optimal stimuli for accurate synchronization to the beat.

The final chapter summarises the findings of the thesis, and discusses the implications of the results for theories of beat-based timing. Limitations of the current work and possible future lines of research are outlined.

Chapter 2

Introduction

As mentioned above, the BG could either engage in the search for the beat, internally generating the beat to predict its next occurrence, or to control synchronization of movements to the beat. The experiments in this chapter were developed to measure beat perception, internal generation, and motor production. We were concerned whether these stages of beat processing are controlled by a common mechanism.

One approach to the question of a common timing mechanism controlling perception, internal generation and production of the beat, involves the exploitation of individual differences. Individuals have been shown to vary in their ability to perceive (Iversen, 2008), internally generate (Grahn & Rowe, 2012), and produce the beat (Iversen, 2008; Repp, 2007). This raises the question of whether performance correlates across these processes, indicating whether the mechanism used for perception has any commonality with that used for production. If each process has a different mechanism, it may be that performance in one area of beat processing shows no correspondence to the performance of another. However, if a common mechanism controls all processes, then individuals who are good at one area would be expected to be good at another.

To study beat perception we used two tests: the perception BAT and intensity threshold test. In the perception BAT, participants listened to music from various genres and determined if the superimposed tones were on or off the beat. The task used real music, which contains non-temporal factors that aid in the perception of the beat, making it necessary to develop an additional beat perception test without non-temporal factors. Thus, we developed a second task called the intensity threshold test that uses rhythmic

sequences [i.e., metric simple (MS) or metric complex (MC)] containing intensity changes on or off the beat. Tones in a rhythmic sequence that are on the beat are subjectively accented, therefore perceived as louder than surrounding tones (Large & Jones, 1999). This perception may subsequently mask a true external intensity change. A note that occurs off the beat is not subjectively accented and, therefore, there is nothing to mask an external intensity change. As the rhythms do not contain any non-temporal changes (such as pitch, timbre, harmony, etc.) this test is a purer measurement of temporally-induced beat perception than the perception BAT.

Internal generation was measured using two tests: the metronome tempo discrimination test and the rhythm tempo discrimination test. In the metronome tempo discrimination test participants compared the beat rate between two metronomic stimuli (i.e., sequences of evenly spaced tones). Participants listened to the beat that is given by the first metronomic sequence, then internally generate during the second metronomic sequence. Using only two metronomic sequences minimizes perceptual demand. The only requirement is to internally generate a given beat. In the second task, we assess how well internal generation works in a rhythmic context. The first stimulus is a metronomic sequence, but now the comparison sequence is a MS or MC rhythm. Participants were asked to compare the beat of the rhythm to the beat given by the metronomic sequence. This task increases perceptual demands relative to the metronome tempo discrimination test, as it requires participants to perceive the beat in the rhythm then internally generate the beat given by the metronomic sequence. Thus, this task looks at internal generation of the beat in the context of a rhythm, similar to the requirements seen in the task used by Grahn and Brett (2009).

To measure motor production of the beat, participants tapped to the beat of music stimuli from the BAT in a task called the production BAT. However, in this task there were no superimposed tones on or off the beat. Participants tapped as they perceived it, and their synchronization accuracy was measured. It is still unknown whether a common mechanism is responsible for accurate perception, internal generation and motor production of the beat. By correlating tests investigating beat perception and production with (synchronization) and without (internal generation) a motor response, we are able to investigate if a single or multiple mechanism(s) control performance across tests.

The final aim of this experiment was to determine whether perception and internal generation explains performance on tasks requiring relative timing. The current study used the MS and MC rhythmic stimuli from Grahn and Brett (2009). MS rhythms induce a clear sense of the beat; while MC rhythms do not. Thus half the sequences give rise to perception of a regular beat, such that relative timing can occur, while the other half do not give rise to a regular beat, requiring an absolute timing mechanism to encode. A dissociation between perception and internal generation of the beat might indicate that perception and internal generation of the beat might not be governed by the same mechanism, and that participants might show a deficit in perception or a deficit in internal generation. Therefore, it is possible that some participant's show preserved beat perception, but their deficit lies in internal generation of the beat. Thus, A dissociation would indicate that a deficit in forming a relative representation of a rhythm might arise from a selective impairment in internal generation of the beat. On the contrary, if no dissociation is observed, it could mean that perception and internal generation of the beat rely on a single relative mechanism that begins with perception.

Method

Metric simple and metric complex rhythm generation

The MS and MC rhythms in this experiment were created using integer-ratio related sets of intervals. Integer-ratio sequences contain durations that are related only by small integers. For example, a sequence containing intervals of 250, 500, and 1000 ms has a 1:2:4 relationship between its intervals. The integer-ratio intervals in both metric simple and metric complex rhythms were related by ratios of 1:2:3:4. In the metric simple condition, the intervals were also arranged in groups of four units (e.g., in the sequence 4-31-1111, every four units an interval signaled by a tone begins), thereby creating a beat every four units (Povel, 1981). The relation of intervals conformed to previous guidelines (Essens & Povel, 1985) to induce a perceptual accent every four units. In addition, perceptual accents will occur every four units, cueing the subjects to hear a beat. In the metric complex condition, intervals were arranged so that, unlike the metric simple condition, the intervals could not be reliably classified into repeating two, three, or four unit groups (e.g., 2132141). Since there were no regularly occurring perceptual accents, no beat should be induced. For a schematic drawing of MS and MC rhythms, please refer to Figure 1. The length of the ‘1’ interval was varied depending on the experiment. The rest of the intervals in each sequence were multiples of the ‘1’ interval.

Participants

Forty-four (23 male and 21 female) introductory psychology students at the University of Western Ontario participated in all experiments in return for a course credit ($M_{age} = 19.32$ $SD = 2.29$). All participants completed all tests, which were presented in a fixed order: the metronome tempo discrimination test, the rhythm discrimination test, the rhythm tempo discrimination test, the production BAT, the perception BAT, and lastly

the intensity threshold test. The presentation of the auditory stimuli and visual instructions was controlled by a paradigm created in the E-Prime (2.0) program (Psychology Software Tools, 2002). There were no inclusion criteria other than normal hearing, which was based on antidotal reports. The participants gave informed consent as approved by the University of Western Ontario Ethics Board and completed a music experience questionnaire.

Beat perception tests

Task 1: Perception Beat Alignment Test (BAT)

The perceptual subtest of the BAT (Müllensiefen et al., 2011) was used to assess participants' abilities to perceive the beat in music. In the BAT, participants hear various genres of music with a series of regular beeps superimposed on the music clip. The beeps may coincide with the beat or they may fall off the beat. Participants judge whether the superimposed beeps are on or off the beat.

Materials

Seventeen Western musical clips from a variety of different musical genres (pop, orchestral, jazz, and rock) with a series of regular beeps superimposed were used for this test. The beeps occurred either on the beat or off the beat. The beeps in the on beat locations were aligned in time with the beat of the music, while the off-beat condition had either a tempo error (beeps were 10% faster or slower than the true beat rate) or phase error (consistently early or late by 25%). There were a total of 17 trials, 4 had beeps aligned to the beat, 8 had a tempo error, and 5 had a phase error.

Procedure

Participants listened to the 17 excerpts in a random order. Participants judged whether the superimposed beeps were “on the beat” or not. When listening to an excerpt, participants pressed the spacebar when they had made their judgment, to provide a reaction time measurement. After they pressed the spacebar, the stimulus ended and subjects pressed “y” if the beeps were on the beat or “n” if the beeps were off the beat. Listeners were also asked to rate the confidence of their judgment: 1 = guessing, 2 = somewhat sure, 3 = completely certain. Before starting the experiment, participants practiced three trials to familiarize themselves with all the conditions. The experimental session lasted approximately 20 min. Percent correct was calculated on each trial for each participant.

Task 2: Intensity threshold test

The intensity threshold test investigated beat perception using stimuli without the influence of non-temporal factors. Specifically, metric simple and metric complex sequences were used. The use of rhythmic sequences eliminates the influence of non-temporal factors that exist in music and allows for a pure temporally-induced measurement of beat perception. Tones in a rhythmic sequence that are on the beat are subjectively accented, therefore perceived as louder than surrounding tones. This subjective accent may subsequently mask a true external intensity change. A note that occurs off the beat is not subjectively accented and, therefore, there is nothing to mask an external intensity change. Thus, larger external intensity changes on notes that are on the beat are needed to compensate for the subjective accents. A staircase threshold procedure was used to obtain levels of external intensity changes needed to perceive a difference in loudness on notes that fall on and off the beat.

Materials

Thirty MS and MC rhythms were created. Each sequence was composed of 10, 12, or 14 intervals. The length of the shortest interval was 250 ms and each tone in the sequence was 50 ms in duration. The remainder of the intervals in the sequence were multiples of the smallest interval length (i.e., 500, 750, or 1000 ms). A single intensity change was placed on one tone in each rhythm. Within the MS rhythm, two conditions were created: MS-on and MS-off. In the MS-on condition, a tone that coincides with the perceived beat was made louder. In the MS-off condition, a tone that begins off the perceived beat was made louder. Because the MC condition does not have a regular beat, any note with an intensity change is necessarily off the beat, MC-off. Thus, the third condition, MC-off, contained intensity changes only off the beat. Within the MS condition 15 rhythms had intensity changes coinciding on the beat, while 15 rhythms had intensity changes off the beat. Up to seven intervals surrounding the intensity change were matched in both MS-on and MS-off conditions, the only difference being where the intensity change occurred relative to the beat (i.e., on or off the beat).

For every intensity change location and surrounding intervals in the MS-on and MS-off condition, matching intensity locations and surrounding intervals were created for the MC-off condition. Therefore, 30 rhythms were created in the MC-off to balance MS and MC rhythms. See Figure 2 for an example of an intensity change location in a rhythm and the surrounding intervals. In all conditions the intensity change occurred in the second half of the rhythm, so that the participant had established a perception of the beat before the intensity change occurred. To create the intensity changes the amplitude of the

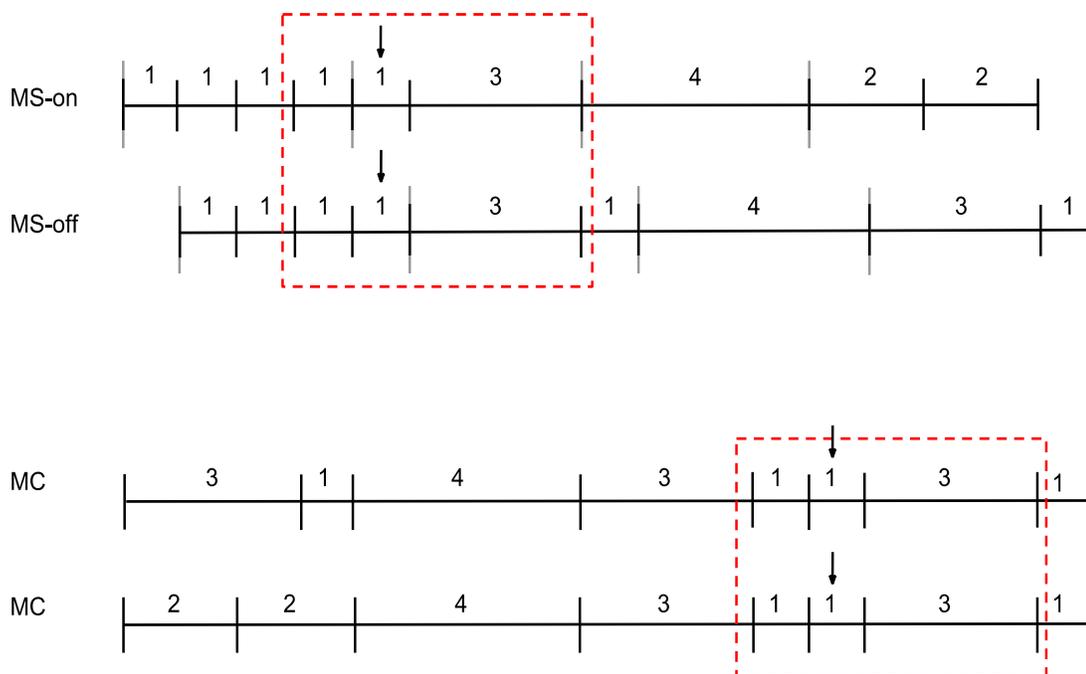


Figure 2. A schematic of MS-on, MS-off, and MC rhythms from the intensity threshold test. The arrows represent what interval contains an intensity change. In each sequence the intensity change occurs on a '1' interval with surrounding intervals of '1' and '3' (i.e., those in the red box). The grey bars in the MS-on and MS-off conditions represent the beat structure. The black bars represent a tone onset.

tone was modulated from 0.2 Pascal (Pa) to 0.9 Pa in seventy equal increments of 0.01 Pa for each condition (MS-on, MS-off, MC-off).

Procedure

Participants heard MS and MC rhythms that contained one note with an intensity change. A staircase procedure was employed for each condition (MS-on, MS-off, and MC-off) to determine the thresholds needed to perceive intensity changes ‘on beat’ and ‘off the beat’. Each staircase was interleaved, so that participants could not predict whether any given sequence would have a beat or not. The amount of amplitude change (intensity) was adjusted between trials based on participants’ responses to the previous trial in that particular staircase. Amplitude was varied adaptively according to a “two-down, one-up” staircase schedule. In a given staircase, a reversal was coded each time the participant recorded an incorrect answer following two previous correct answers. In addition, a reversal was recorded when the amplitude of the test tone was reduced after two subsequent correct answers. Initial amplitude of tones in the test trial was set to 0.9 Pa. The step size was initially set at a 0.25 Pa amplitude change. After the second reversal, the amplitude step size was reduced to 0.05 Pa. After five reversals the amplitude step was reduced to 0.01 Pa. The experiment was completed when the participant achieved 14 reversals in each staircase procedure. Amplitude thresholds were calculated by averaging the amplitudes of the final 6 reversals. The experimental session lasted approximately 20 min.

Average amplitude threshold values were converted to a decibel (dB) level using equation 1.

$$20 \log_{10} \left(\frac{A_{\text{rms}}}{A_{\text{ref}}} \right) \text{ dB} \quad (1)$$

where A_{ref} is the root mean squared of the reference or baseline amplitude and A_{rms} is the root mean squared of the amplitude being measured.

Internal generation tests

Task 3: Metronome tempo discrimination test

The metronome tempo discrimination test was designed to study internal generation of the beat in the absence of the rhythm by comparing the rate of two metronomic sequences. Using two metronomic sequences minimizes perceptual demand—participants only compare two clearly given beat rates. The standard metronome sequences provided an example beat that needed to be generated during the comparison stage. Participants judged whether the rate of the comparison metronomic sequence was ‘faster’, ‘same’, or ‘slower’ as the standard metronomic sequence. Metronome sequences are the most rudimentary way to present the beat, as only the beat itself is played – the beat does not have to be perceived in the context of a rhythm with temporally varying intervals, or complex music. With minimal perceptual demands, this test looks purely at how well an individual can internally generate a given beat.

Materials

Metronome sequences of four tones with intervals of 250, 500, or 1000 ms were created. These specific intervals were used because they were within the range of regular periodicities seen in most Western music and in the sequences used in all other tests. Filled tones (tones last the entire duration of the interval) were used to remain consistent between tests. To create comparison metronome sequences that were faster and slower than the metronome rate, each interval was decreased or increased by 10%. For each interval (250, 500, and 1000 ms), two base metronome sequences were created, for a total

of six metronome sequences. From these base intervals a 10% faster and 10% slower version of the rhythm was created, for a total of 18 rhythms.

Procedure

On each trial, participants heard two metronomic sequences, with each sequence separated by 1100 ms of silence. After the second sequence, participants indicated whether the rate of the second sequence was the same, faster, or slower than the first sequence. Participants pressed “1” for slower, “2” for same, and “3” for faster on a computer keyboard. Subjects practiced four trials, and then completed one block of 18 randomly ordered trials. The experimental session lasted approximately 10 min.

Task 4: Rhythm tempo discrimination test

The rhythm tempo discrimination test was designed to test internal generation of the beat in a rhythmic context. Participants heard a sequence of metronomic tones followed by a MS or MC rhythm. Participants had to determine if the beat rate of the rhythm was either the same, faster, or slower than the rate of the metronome sequence. The metronome sequence acted as an example beat, to which the participants compared the beat of the rhythms too. As MS rhythms contain a definitive beat, while MC rhythms do not, it was expected that performance in the MS condition would be greater than the MC condition.

The difference between the metronome tempo discrimination test and the rhythm tempo discrimination test is that the metronome tempo discrimination test explicitly gave participants the beat (in the form of the metronome sequence), placing minimal demand on beat perception, whereas, the rhythm tempo discrimination test requires participants to perceive and extract the beat when listening to the rhythm. Thus, this task requires participants to internally generate the beat (given as a metronome sequence) and compare

it to the perceived beat rate of the comparison rhythm. Using internal generation in the context of a rhythm is more applicable to the internal generation seen in the rhythm discrimination test found in Grahn and Brett (2009). In the rhythm discrimination task, participants must first perceive a beat and then internally generate that beat during the discrimination phase to organize the onsets of the different rhythmic intervals.

Materials

Metronome sequences of eight tones with intervals of 900, 1000, or 1100 ms were created as a standard sequence. Each tone was 50 ms of the interval. Eighteen MS and 18 MC rhythms were created with 10, 12, or 14 intervals (for MS and MC sequences see Table 1) as comparison rhythms. The length of the base interval ('1' interval) in the MS and the MC rhythms were selected from 225, 250, or 275 ms to create rhythms with perceived beat rates of 900, 1000, and 1100 ms, respectively. Therefore, the beat rates of the rhythms with base intervals of 225, 250, and 275 ms were matched to the rate of the metronome sequences. To create rhythms with beat rates that were faster and slower than the metronome rate, the base intervals were decreased or increased by 25%. For each base interval length (225, 250, and 275 ms), two rhythms were created, for a total of six base rhythms. From these base rhythms a 25% faster and 25% slower version of the rhythm was created, for a total of 18 rhythms. A 25% deviation from the base interval length was used as piloting indicated participants responded at chance level when the rate was adjusted by less than 25%.

Procedure

Each trial consisted of two phases: a standard phase and a comparison phase. In the standard phase, participants listened to a metronome sequence with intervals of 900,

Table 1.

MS and MC sequences used in the rhythm tempo discrimination test

Intervals	Metric Simple	Metric Complex
10	4312222413	3314141331
	2241313112	3314141331
	4311343122	2342143113
12	421142221131	121233122142
	411231422112	221224131321
	211134222114	122142124113
	112314112422	221224131321
	211134222114	132321214221
	112422211134	124113221241
14	11231221212231	11221221421113
	11114311122114	31131211314111
	11114311122114	11321311132212
	22111131421113	11221221421113
	42211111111431	31131211314111
	31221121123122	21232114113111

Note: 1 = 200, 250, or 300. All other intervals were multiples of the '1' interval

1000, or 1100 ms. During the comparison phase, participants listened to a rhythm in which the beat rate was 25% slower, 25% faster, or the same as the sequence in the standard phase. The metronome and rhythm pairing were pseudo-randomly selected such that the perceived beat rate was matched to the rate of the metronome sequence. For example, the shortest metronome sequence with intervals of 900 ms was only paired with a rhythm with the shortest intervals of $225 \text{ ms} \pm 25\%$. Similarly, metronome sequences of 1000 and 1100 ms were coupled with rhythms of base intervals of $250 \text{ ms} \pm 25\%$ and $275 \text{ ms} \pm 25\%$, respectively. Participants were asked if the beat rate of the comparison rhythm was slower, faster, or the same as the rate of metronome sequence. They then indicated their response by pressing “1” for slower, “2” for same, and “3” for faster on the computer keyboard. The onset of the comparison rhythm relative to the last tone of the standard sequence was equal to one interval length such that the comparison rhythm began on the next predicted beat. For example, if the standard sequence base interval was 900 ms the first tone of the comparison rhythm began 900 ms after the last tone of the standard sequence. The next trial began after a response was entered and the spacebar key pressed. The block of trials consisted of 36 rhythms including 18 MS and 18 MC and took approximately 20 minutes to complete. Percent correct score for each trial was calculated for each participant.

Beat production test

Task 5: production BAT

This test used the production subtest of the BAT (Müllensiefen et al., 2011) to assess participants’ ability to produce the beat via tapping. Participants heard musical

clips from the perception BAT and tapped to the beat. Using the same musical clips as the perception BAT enables a direct comparison between perception and production.

Material

The BAT production task was designed to test the ability to tap with the beat of music. Seventeen western musical clips from a variety of different musical genres (pop, orchestral, jazz, and rock songs) were used. The 17 music clips used in the production BAT were also used in the perception BAT.

Procedure

Participants heard a musical excerpt once and were instructed to tap the spacebar to the beat. Tap times were collected and the accuracy and variability of synchronization were measured. The order of the stimuli was randomized for each participant. Before starting the experiment, participants practiced one trial to familiarize them with the procedure. The experimental session lasted approximately 10 min.

For each trial, time indices of beep or beat onsets and time indices for each tap were registered to determine the coefficient of deviation (CDEV). The CDEV is the absolute time between each tap (inter-tap-interval) minus the time between each beat in the musical stimulus (inter-beat-interval, IBI) and divided by the mean inter-tap-interval (ITI; see equation 2). We normalized the CDEV using the subjects' mean ITI to control for tapping rate. Lower CDEV indicates more accurate synchronization compared to higher CDEV values.

$$\text{CDEV} = \frac{|\text{ITI} - \text{IBI}|}{\text{mean ITI}} \quad (2)$$

Rhythm discrimination

Task 6: Rhythm discrimination test

To measure relative timing, we used a similar rhythm discrimination task to that described in Grahn and Brett (2009). Participants listened to two identical standard rhythms, to which they compared a third rhythm that was either the same as or different from the standard rhythms. MS rhythms are expected to show higher discrimination accuracy, as shown in the past, because a relative timing mechanism will be used. The difference between this rhythm discrimination test and the one used in Grahn and Brett (2009) was that the third presentation sometimes contained a change in the overall rate. Participants were instructed to ignore any change in rate, and to make the same/different judgement only on the basis of the relative pattern of time intervals. Thus, participants had to change the rate of their representation of the standard rhythm to match the rate of the comparison rhythm; a process known as rescaling. For example the rhythm of happy birthday is recognized when sung quickly or slowly, as the relative relationships between each note are the same, even though the overall rate has changed. Participants are able to rescale MS rhythms, but are unable to rescale MC rhythms (Collier & Wright, 1995). With a rate change, the absolute mechanism used to encode MC rhythms should struggle, because all the absolute interval lengths will differ when there is a rate change. However, relative relationships will be maintained, therefore we can be more confident that performance on this task should index relative mechanisms.

Materials

There were 30 trials (15 MS and 15 MC) with each trial containing rhythms that were composed of 5, 6, or 7 intervals of 225, 250, or 275 ms base interval durations (Table 2). In half of the trials, the third sequence was different from the previous two

Table 2.

MS and MC sequences used in the rhythm discrimination test

Intervals	Metric Simple		Metric complex	
	Standard	Deviant	Standard	Deviant
5	22413	22431	41232	14232
	31413	31431	13242	31242
	43113	41313	23241	23214
6	112314	112134	121233	121323
	112422	211422	122142	122412
	211134	211314	124113	124131
	222114	221124	221241	221214
	211224	112224	231123	213123
	312213	312231	412212	142212
7	2113113	2113131	1132131	1132311
	1111431	1111413	2141211	2411211
	1122114	1121124	2331111	2313111
	2211114	2112114	1411311	1141311
	3121113	3121131	2123211	2132211
	3122112	1322112	3114111	1314111

Note: 1 = 250 ms for the standard rhythms. 1 = 225, 250, or 275 ms, chosen at random for each trial. All other intervals were multiples of the '1' interval

presentations (standards rhythm). The standard rhythms were created with interval lengths that were integer multiples of 250 ms, while the rhythms were created with interval lengths of 225, 250, or 275 ms. The change in rate between the standards and deviants ensured the use of a relative timing mechanism in MS rhythms. Deviant sequences contained a transposition of two time intervals in the sequence. For example, the standard metric simple rhythm 314211 might have a deviant sequence 134211, in which the 3 and the 1 interval have been transposed. To ensure the preservation of the metrical structure in each rhythm, only deviant sequences that were in the same category as the standard sequences were allowed (e.g., MS trials could not have a MC deviant and vice versa). The sequences employed filled intervals as they have been used in previous studies (Grahn & Brett, 2007).

Procedure

On each trial participants heard three rhythms: two standard rhythms and one comparison rhythm. The task was to indicate if the standard rhythms were the same as or different from the comparison rhythm. Participants were told to ignore rate changes between the standard rhythms and comparison rhythms. Participants pressed “1” if the third rhythm was the same, and “0” if the third rhythm was different on a computer keyboard. Participants practiced four trials and then completed one block of 15 randomly ordered MS and MC rhythms (total of 30 rhythms). The experimental session lasted approximately 20 min.

To assess discrimination accuracy d' scores were calculated for the MS and MC conditions for each subject. It has been noted that d' scores are a more sensitive measure for same/different discrimination tasks than percent correct, as they are less affected by response bias than other measures.

Task 7: Questionnaire

Upon the completion of all the tests participants completed a standardized examining musical experience and problems encountered within the experiment. If any major issues (e.g., major reported hearing loss) subjects were excluded from analysis.

Data analysis

For the intensity threshold test and perception BAT a one-way repeated measures ANOVA was used to test difference between means. A Mauchly's Test of Sphericity was used to determine violations of sphericity. If Mauchly's test was significant then the Greenhouse-Geisser correction was applied. For all other comparisons (the rhythm tempo discrimination test, the rhythm discrimination test) a paired sample t-test was used to test differences between means.

Results

Task 1: Perception BAT

Using the perception BAT, we measured participant's ability to perceive the beat in music. Participants judged whether the superimposed tones on the musical excerpts were on the beat or not. Figure 3 shows overall population performance for the three conditions: on beat ($M = 86.36\%$, $SD = 25.23\%$), phase error ($M = 50.45\%$, $SD = 25.33\%$), tempo error ($M = 79.55\%$, $SD = 16.07\%$). A one-way ANOVA was used to compare the effect of stimulus condition on performance accuracy (Figure 3). There was a significant effect of condition on performance accuracy ($F(2,129) = 31.25$, $p < 0.001$). Paired samples post hoc t-tests indicated that performance on the phase condition was significantly worse than the on-beat condition ($t(43) = 6.96$, $p < .001$) and tempo condition ($t(43) = 7.19$, $p < .001$). No significant difference was found between on-beat and tempo error ($t(43) = 1.77$, $p = .080$). Thus, participants were more likely to

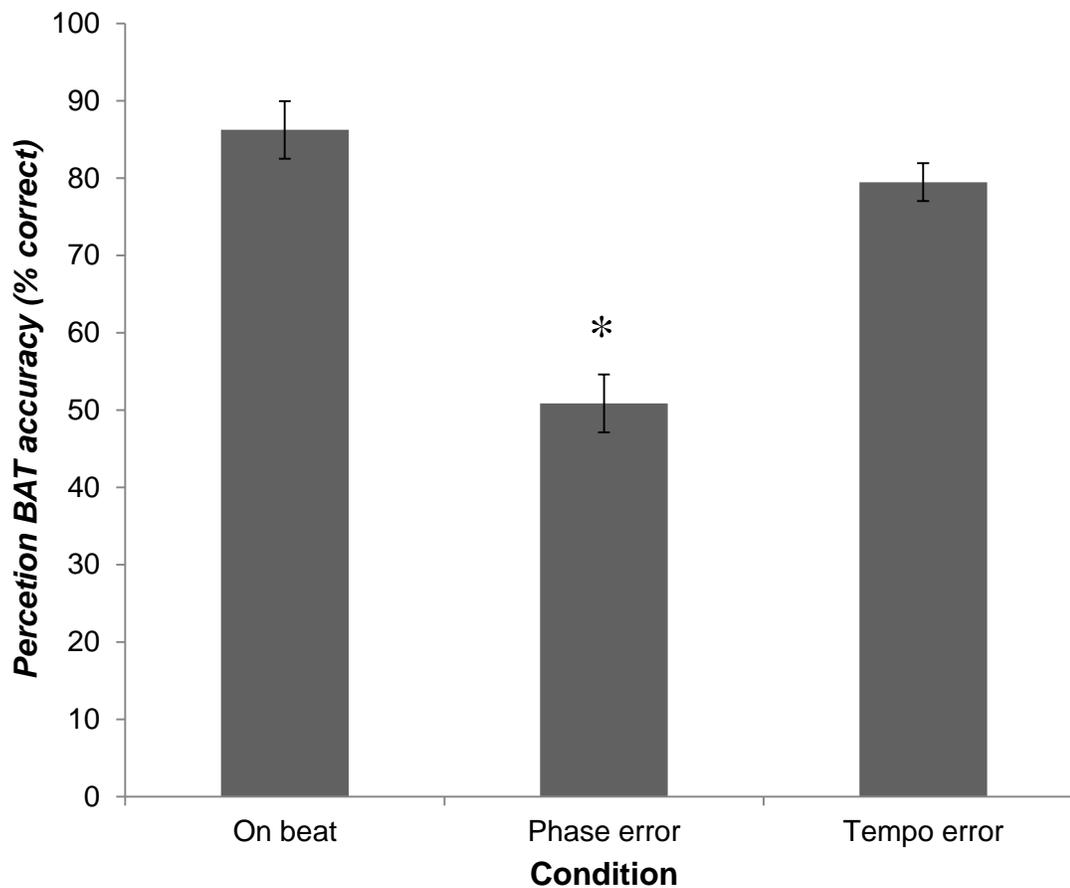


Figure 3. Beat perception performance across all 45 participants for three beat alignment conditions: on beat, tempo error, and phase error. Performance in the phase error condition was significantly less than performance on the on beat and tempo error conditions. Error bars indicate standard error of the mean. * $p < .05$.

incorrectly judge an off-beat phase error tone sequence as being on the beat than they were to judge on-beat tones as off-beat and tempo tone sequence to be on the beat. Overall the BAT test showed a wide distribution of performance across individuals.

Task 2: Intensity threshold test

Using the intensity threshold test, we measured participant's ability to perceive the beat in a rhythmic context (without non-temporal factors). The thresholds for detecting intensity changes were compared for on the beat (MS-on) and off the beat (MS-off and MC) conditions (Figure 4). It was predicted that thresholds would be higher for intensity changes on beat (MS-on) compared to off the beat (MS-off and MC), to compensate for participants' internal emphasis on on-beat tones. A one-way repeated measures ANOVA revealed a main effect of condition ($F(2, 43) = 3.75, p = .027$). Pairwise comparisons using paired t-tests showed that threshold significantly differed between MS-on ($M = 6.11$ dB , $SE = 2.55$ dB) and MS-off ($M = 5.76$ dB , $SE = 2.69$ dB , $t(43) = 2.66, p = .011$). No significant differences were found between MS-on and MC ($M = 5.88$ dB , $SE = 2.68$ dB , $t(43) = 1.728, p = .091$) and MS-off and MC ($M = 4.85$ dB , $SE = 1.62$ dB , $t(43) = -1.09, p = .283$). Therefore, larger intensity changes were needed to perceive a change on the beat compared to off the beat in the metric simple condition.

Task 3: Metronome tempo discrimination test

The metronome tempo discrimination test uses metronomic sequences to investigate internal generation of the beat with minimal demands on beat perception. The mean percent correct value of $79.8\% \pm 14.6\%$ and a range of 50% to 100% correct. Therefore, no ceiling effects or floor effects were found and participants were able to accurately discriminate rate changes between two metronomic sequences.

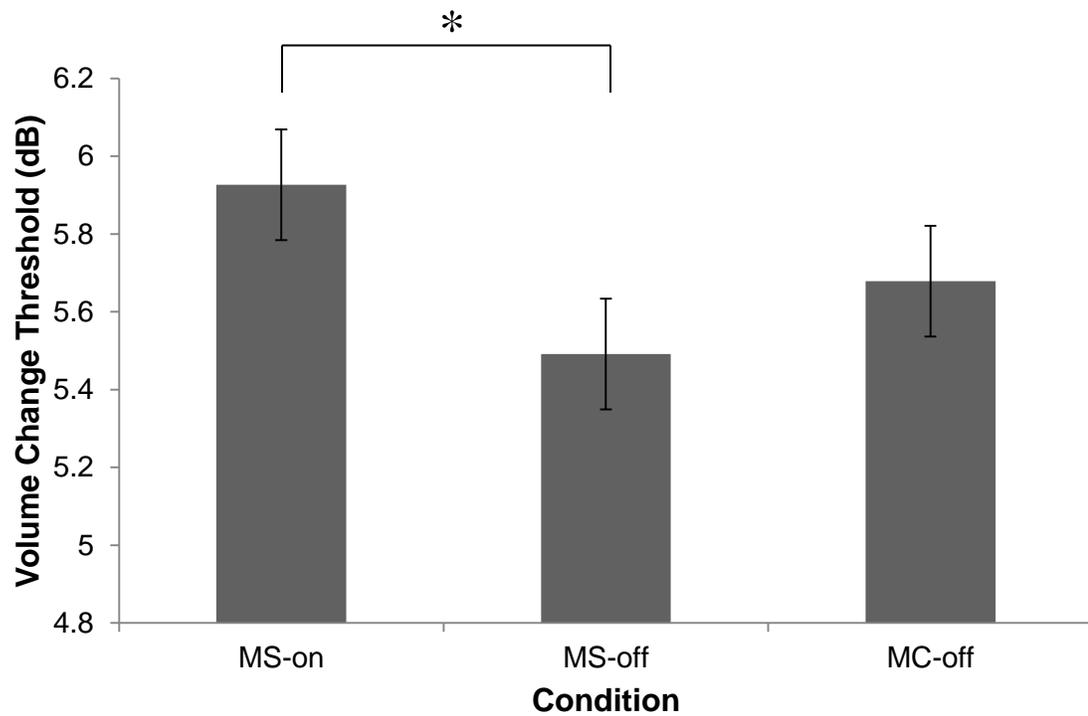


Figure 4. Mean dB thresholds for healthy young subjects on MS and MC rhythms with intensity changes on or off the beat. Greater intensity change threshold values represent poorer performance. Error bars indicate standard error of the mean. * $p < 0.05$

Task 4: Rhythm tempo discrimination test

The rhythm tempo discrimination test uses metronomic sequences and rhythms (MS and MC) to investigate internal generation of the beat in a rhythmic context. Participants showed numerically higher accuracy in the MS condition ($M = 54.09\%$, $SD = 16.66\%$) than the MC condition ($M = 52.58\%$, $SD = 15.63\%$). However, this difference was not statistically significant ($t(43) = 0.57$, $p = .571$; see Figure 5). MS rhythms did not elicit better performance over MC rhythms when comparing the rate of a beat given in a metronomic sequence to the beat of a rhythmic sequence.

Task 5: Production BAT

The rationale behind using the BAT was to measure beat production performance and relate performance on the production task to perception and internal generation tasks. The mean co-efficient of deviation value was 0.052 ± 0.033 with a range of 0.026 to 0.14.

Task 6: Rhythm discrimination test

The rationale behind using the rhythm discrimination test was to measure performance using a relative timing mechanism, and to relate performance on using a relative timing mechanism (MS condition) to perception and internal generation of the beat. Performance in the MS condition ($M = 2.09$, $SD = 0.94$) was significantly better than in the MC condition ($M = 1.40$, $SD = 0.83$; $t(43) = 5.268$, $p < 0.001$; Figure 6).

Correlations across tests

This section selectively describes correlations among variables which address the research questions. A more complete correlation matrix among the remaining variables in

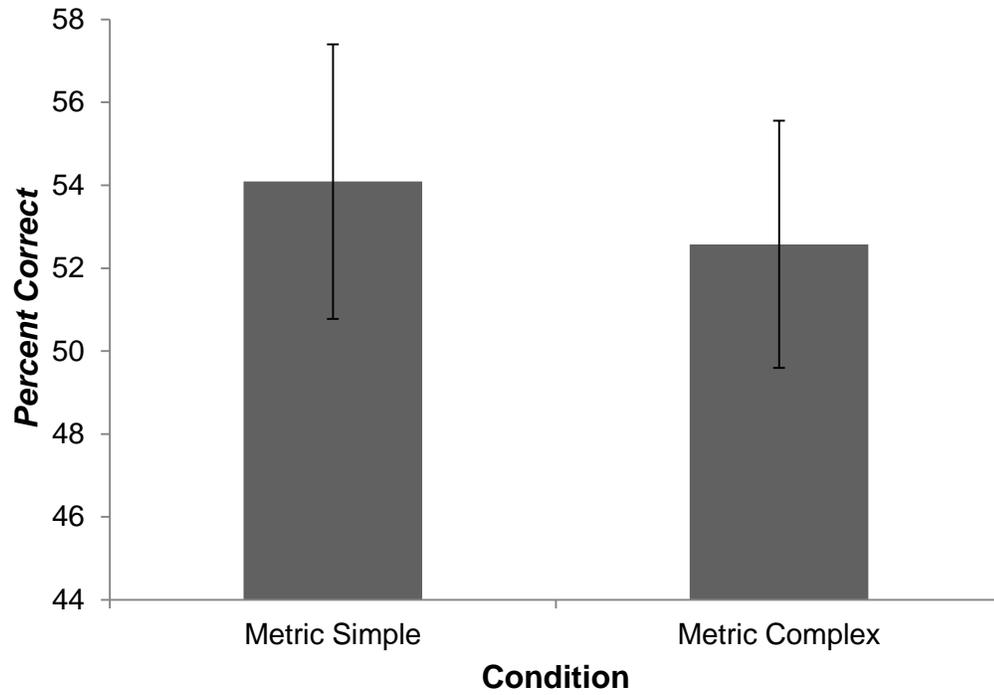


Figure 5. Percent correct scores for healthy young subjects on MS and MC rhythms in the rhythmic tempo discrimination task. Error bars indicate standard error of the mean.

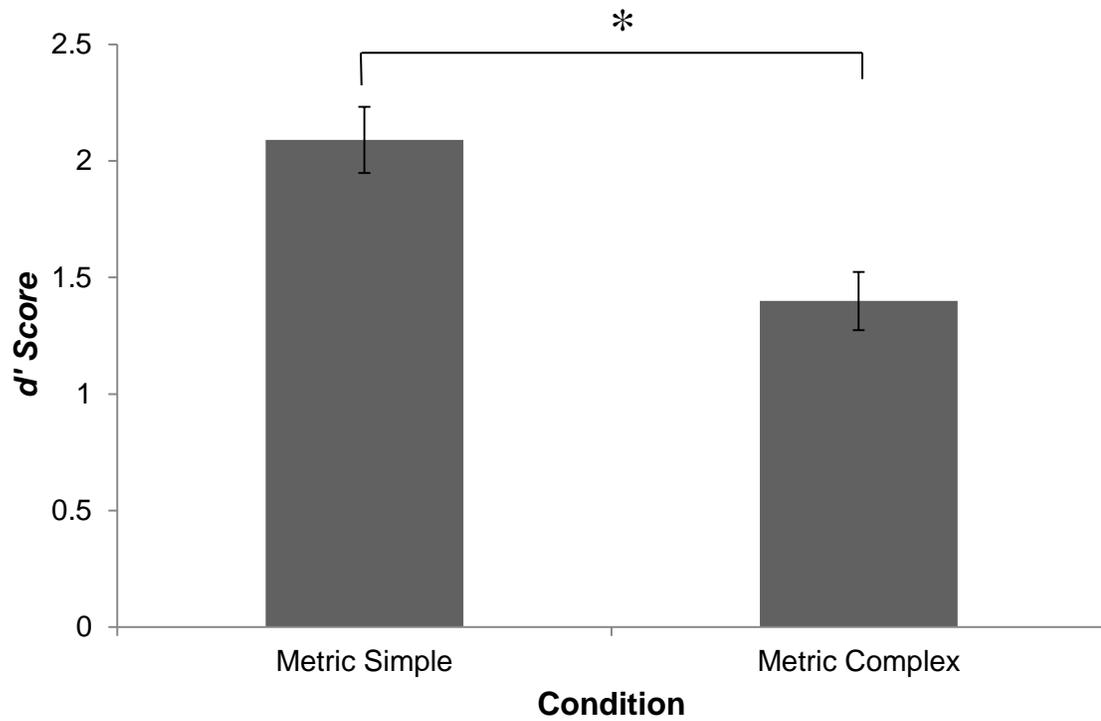


Figure 6. Mean d' scores for healthy young subjects on MS and MC rhythms in the discrimination task. Errors bars indicate standard error of the mean. * $p < .05$.

these experiments is shown in Appendix A. The overall aim of this section is to determine any dissociation between perception, internal generation, or production of the beat, and to determine if any dissociation explains a deficit in using a relative timing mechanism.

To assess whether a dissociation occurred between perception and internal generation of the beat, a correlation was performed between percent correct scores from the perception BAT (beat perception ability) and percent correct scores from the metronome tempo discrimination test (internal generation ability; Figure 7a). No dissociation, or a common mechanism controlling both perception and internal generation of the beat, would result in significant positive correlations between perception BAT scores and metronome tempo discrimination scores. Specifically, a participant's performance on either test should enable one to predict that participant's performance on the other test. A significant positive correlation was found, indicating that the ability to perceive the beat is related to the ability to internally generate the beat with minimal perceptual demands. This suggests a relationship between perception and internal generation of the beat.

To determine if the same mechanism controls motor production of the beat, we correlated both perception BAT and the metronome tempo discrimination test with the production BAT. Perception BAT performance was significantly and positively correlated with production BAT performance (Figure 7b) and the metronome tempo discrimination test significantly correlated with the production BAT (Figure 7c), indicating commonality between perception, internal generation, and production of the beat. However, 4 participants had synchronization accuracies beyond four standard

deviations of the mean in the production BAT. Upon visual inspection of the scatterplots correlating perception BAT and metronome tempo discrimination with the production BAT test, these participants appear to be outliers. These four outliers indicate that participants were able to accurately perceive and internally generate the beat, but unable to accurately synchronize to the beat, suggesting that in these individuals, beat production may be a dissociable part of beat processing. Upon removal of these four outliers, all correlations remained significant.

To determine how the mechanism controlling both perception and internal generation of the beat contribute to the formation a relative timing representation, we correlated perception BAT and metronome tempo discrimination with the MS condition in the rhythm discrimination test. The perception BAT alignment task was correlated with MS and found to be significant (Figure 7d). This result hints at the importance of the mechanism controlling beat perception in forming a relative representation.

Discussion

There were two aims to the present set of experiments. The first aim was to develop paradigms to test perception, internal generation, and production of the beat. The second aim was to determine if perceptual or production stages could be dissociated from each other. One further application of these tasks would then be to assess whether perceptual or production deficits explain the differences seen in relative timing in PD patients. The results show that the majority of our tasks succeed in testing their respective goals.

Both perception BAT and intensity threshold tasks were used to test perception of the beat. The perceptual BAT was judged successful because perception ability showed a

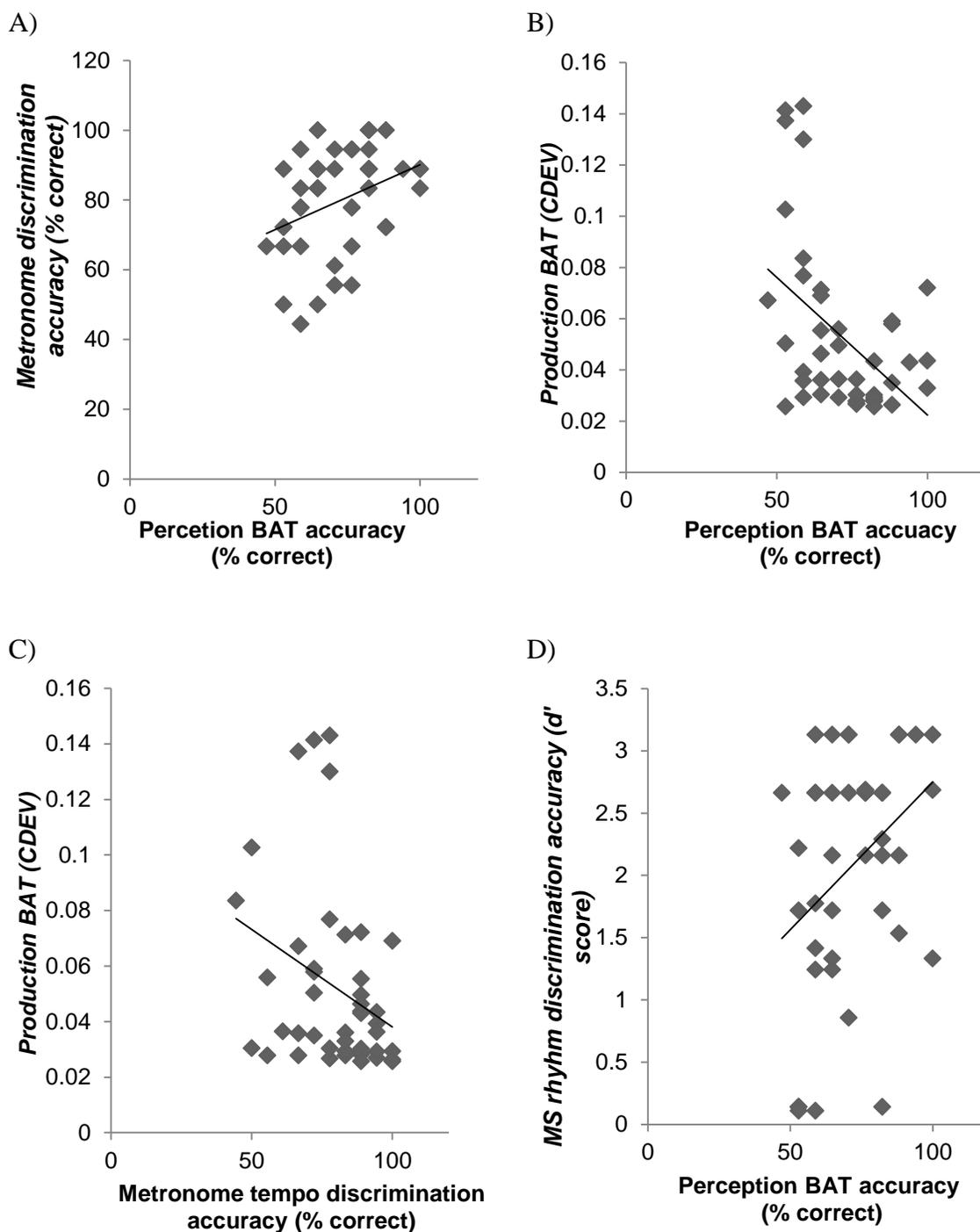


Figure 7. Significant correlations between perception, internal generation, and production of the beat tests. (A) Correlation between perception BAT and production BAT scores. (B) Correlation between metronome tempo discrimination test and production BAT scores. (C) Correlation between perception BAT and metronome tempo discrimination test scores. (D) Correlation between perception BAT and the MS rhythm condition in the rhythm discrimination test scores.

wide distribution of performance when using music stimuli. The finding that beat perception ability varies in a population is consistent with previous literature using the same test (Grahn & Schuit, 2012; Iversen, 2008). To determine beat perception ability in rhythms without non-temporal factors, the intensity threshold test was developed. The intensity threshold test showed that detection of on-beat intensity changes was masked by subjective accents located on notes that coincide with the beat. Specifically, intensity thresholds for MS on-beat were significantly greater than MS off-beat, however, MS on-beat was only marginally greater than MC off-beat conditions and did not significantly differ.

According to the dynamic attending theory, in rhythms without beat (MC rhythms) there are no peaks of attention, therefore, attention remains steady throughout the rhythm. In contrast, the MS-on/off conditions may be indexing increases and decreases in attention (the latter on the off-beat notes). Thus, comparing places where attention is maximal and minimal (comparing MS-on to MS-off), may give a stronger effect than comparing places where attention is maximal and attention is consistent throughout the rhythm (comparing MS-on to MC off).

Previous work has examined subjective accents on notes that coincide with the beat (Repp, 2010). Musicians detected loudness changes more accurately when the tone was subjectively accented. Repp attributed his findings to an increase in attention on subjective accents. However, an enhancement of the sensitivity to physical changes regardless of increase or decrease in the loudness was found, which suggest that attention leads to a heightened sensitivity rather than producing subjective accents in listeners' minds. One major difference between my intensity threshold test and Repp's study was

his employed metronomic stimuli rather than rhythmic stimuli. Rhythmic stimuli induce regular subjective accents, whereas, metronome sequences have not been shown to have this critical accent distribution. Thus, subjective accents in rhythmic stimuli might mask on-beat intensity changes.

A dissociation between the intensity threshold test and the other tests in this experiment was found. The intensity threshold test requires participants to actively group the intervals in a rhythm to produce subjective accents or perceive the beat. However, it is possible that participants were focused on the detection of an intensity change rather than perceiving and forming an internal representation of the beat. Without an internal representation of the beat, participants will not create subjective accents that coincide with on-beat locations. As a result no masking effect will be observed in participants who ignore the beat in a rhythm. Additional studies should emphasize creating a representation of the beat while searching for a intensity change rather than just searching for a intensity change.

Both the metronome tempo discrimination test and rhythm tempo discrimination test measured internal generation of the beat. The metronome tempo discrimination test required participants to compare the rate of two metronomic sequences. The standard metronomic sequences provided an example beat that needed to be internally generated during the comparison stage. Using two metronomic sequences that require minimal perceptual demand (participants only compare two clearly given beat rates), internal generation ability varied within the population. This experiment provides evidence that internal generation can occur when participants compare two given beat rates. However, internal generation of the beat during the comparison stage of the rhythm discrimination

test is more perceptually demanding, hence the development of the rhythm tempo discrimination test.

The rhythm tempo discrimination test is more perceptually demanding than the metronome tempo discrimination test as it requires participants to perceive and extract the beat when listening to the rhythm. Thus, this task requires participants to internally generate the metronome beat and compare it to the beat rate of the comparison rhythm. In the rhythm tempo discrimination test, MS rhythms contain a definitive beat, while MC rhythms do not. Thus, participant's performance was expected to be greater in the MS condition compared to the MC condition as the MS has a beat to extract and compare to the metronome sequence. However, our results show no significant difference between the scores in the MS condition compared to the MC condition. These results suggest that participants were unable to internally generate the beat (given as a metronome sequence) and compare it to their perceived beat in the rhythm. The negative results may be explained by variability in the beat rate perceived by the participants. The rhythms we created were expected to induce a beat rate of 900, 1000, or 1100 ms. However, the beat could have been induced at half or double the expected rate, that is 450, 500, 550 ms, or 1800, 2000, or 2200 ms respectively. The differences between the expected beat rate and perceived beat rate may be reflected in speed ratings between a given beat structure and a perceived beat in a rhythm. For example, if a participant perceived the beat at half of the expected beat rate (450, 500, or 550 ms) then a 25% increase in the rhythm beat rate will still not approach their perceived beat rate, potentially causing participants to respond 'slower' when the correct response was in fact 'faster'. Difficulty in perceiving the expected beat rate may have led to lower performance scores in the MS condition of the

rhythm tempo discrimination test. Lower accuracy scores may be reflected in the non-significant correlations between the rhythm tempo discrimination test and the perception/production BATs. The rhythm tempo discrimination test might not be accurately measuring internal generation of the beat in a rhythmic context. Future studies should include beat rates at half the expected beat rate, the expected beat rate and double the expected beat rate to remove ambiguity when comparing participants perceived beat rate with the given beat rate.

The rhythm discrimination task was designed to investigate how beat perception and internal generation explain discrimination of rhythms encoded using a relative timing mechanism. Consistent with literature (Grahn & Brett, 2009) changes in MS rhythms were easier to discriminate than changes in MC rhythms. Importantly, greater discrimination accuracy occurred in the MS condition compared to the MC condition when a rate change between the standard and comparison stages was introduced. This is consistent with previous work using two-tone simple and complex integer ratio rhythms (Collier & Wright, 1995). In that study the simple ratios were 2:1, 3:1, 4:1, or 3:2, and the complex ratios were 2.72:1, 3.33:1, or 1.82:1. It was found that temporal patterns with two intervals related by a simple ratio can be rescaled, but two intervals related by complex ratios cannot be. It is possible that the metric simple condition in the current study was discriminated with greater accuracy than complex rhythms because a relative representation could be formed, and a relative representation can be rescaled. If a MC condition engaged a relative timing mechanism, then a similar ability to scale the rhythms should have been seen.

Few studies have directly compared timing performance across perceptual and motor tasks (Bangert, Reuter-Lorenz, & Seidler, 2011; Ivry & Hazeltine, 1995; Keele, Pokorny, Corcos, & Ivry, 1985). These studies compared the perception of single time intervals with the production of single time intervals. These studies have found conflicting results with few supporting the idea of a common mechanism driving both perception and production of time intervals (Keele et al., 1985; Schubotz et al., 2000), while some arguing against a common timing mechanism (Bangert et al., 2011). The current study was designed to test whether a common timing mechanism exists between perception, internal generation and production of the beat in music and rhythmic sequences. A significant correlation between beat perception (perception BAT) and the motor production of the beat (production BAT) was found. In addition, it was found that perception BAT significantly correlated with internal generation ability, and internal generation significantly correlates with the production BAT accuracy. Thus, people who exhibit relatively low variability in synchronization performance also tend to have relatively good perception of the beat and a strong ability to internally generate the beat. In turn these results suggest a common timing mechanism controlling perception, internal generation and motor production of the beat.

Within the correlations between beat perception (perception BAT) and beat production (production BAT), and internal generation of the beat (metronome tempo discrimination test) and beat production (production BAT), four outliers were found in the correlation between internal generation (metronome task) and beat production (production BAT), and between beat perception (perception BAT) and beat production (production BAT). At least in these four subjects, a dissociation is found between internal

processes (perception and internal generation of the beat) and production of the beat. It appears that perception and internal generation of the beat might be governed by one mechanism as no dissociation between these stages was seen, whereas, beat production might require an extra stage that perception does not use. Given previous findings of involvement of the BG in internal generation of the beat, future studies might examine the possibility of dissociation between internal beat processes and beat production in PD patients.

Whereas the outliers can be interpreted as dissociation between each process, there are caveats. It is possible the participant misinterpreted the instructions and was tapping to the rhythm (every note in the song), not the beat. However, if these subjects understood the other tasks and show relatively normal results, it seems unlikely that they would misinterpret the instructions on the production test.

The current task was also set up to determine if some participants with a dissociation between perception and internal generation of the beat show a preserved or impaired representation of a rhythm (impaired relative timing mechanism). That is, an impaired representation of a rhythm might be a result of a selective impairment in internal generation, or both perception and internal generation. No dissociation was found between beat perception and internal generation tests. However, the results showed a significant correlation between performance on the perception BAT and accuracy on the MS condition in the rhythm discrimination task. This result indicates that a more accurate perception of the beat leads to a stronger representation of the rhythm, thereby producing greater discrimination scores. Similar findings have been found in work on individual differences using a rhythm reproduction task. Grahn and Schuit (2012)

correlated BAT scores and reproduction accuracy in MS rhythms and found that perception of the beat predicted unique variance in rhythm reproduction performance across MS rhythms. This finding implies that a strong perception of the beat may lead to a better representation of the rhythm.

Previous research has shown that PD patients have lower discrimination accuracy in MS rhythms compared to healthy controls (Grahn & Brett, 2009). The results of this correlation suggest that PD patients may in fact have a weak perception of the beat leading to a deficit in forming relative representations of MS rhythms in the rhythm discrimination test. However, without any participants showing a dissociation between perception and internal generation of the beat, the importance of internal generation of the beat in creating a relative representation of a rhythm is still unknown. A dissociation in some participants would indicate that preservation of beat perception, but impairment in internal generation can still enable participants to use a relative representation of a rhythm.

A common mechanism was shown to guide perception and motor production of the beat; however, it remains unknown whether the same mechanism controls perception and motor production of the beat in different movements. The next chapter is designed to investigate the relationship between perception and production of the beat using a walking paradigm, rather than a tapping paradigm.

Chapter 3

Introduction

As discussed in Chapter 1, when people listen to music, they readily clap, tap their feet, or generally synchronize their body movements in time with the beat of music. Synchronization occurs when body movement moves to an event (e.g., the beat) in an auditory stimulus (Thaut, Miller, & Schauer, 1998; Thaut, 2003). When moving to a rhythmic auditory stimulus, synchronization becomes increasingly complex; the movement of limbs must be period-locked (i.e. steps matched to the rate of music) to the frequency of the auditory signal as well as phase-locked (i.e. when steps occur near the musical beat) to temporally coincide with the auditory beat.

Synchronization to the beat of auditory stimuli has been studied extensively using simple rhythmic auditory cues such as metronomes and MS rhythms (Repp, 2007; Snyder, Hannon, Large, & Christiansen, 2006; Thaut, Rathbun, & Miller, 1997). However, how movement synchronization is affected by non-temporal factors (e.g., harmony, timbre, intensity changes) found in music remains less clear. Indeed, studies have compared music and metronome stimuli where they had participants tap to the beat of music and to the tone of a metronomic sequence (Thaut et al., 1997). Synchronization accuracy improved significantly when subjects tapped to the beat of music. The authors attributed an improvement in synchronization accuracy to the non-temporal factors in music that coincide with beat locations, providing additional timing information to better anticipate and synchronize a rhythmic response. However, there is no empirical evidence to suggest what specific qualities of music improve synchronization.

One particular characteristic of music that has been shown to improve synchronization is ‘groove’. Groove is defined as the degree to which the music makes us want to move with the rhythm or beat (Janata et al., 2012; Madison, 2006). After examining the acoustic features of music, Madison (2011) found high groove music to have a greater number of non-temporal cues around the beat compared to low groove music. Groove may influence the way in which movements are synchronized to the beat, as high groove songs have been shown to yield accurate movement synchrony in a tapping task (Madison et al., 2011). This suggests that non-temporal factors around the beat play a role in sensorimotor coupling and that the number of non-temporal factors may predict how well we synchronize to the beat (Madison et al., 2011). The extent that walking synchronization is impacted by groove music has received little attention. Our understanding of its contribution in synchronization may lead to more comprehensive applications of acoustic cues in rehabilitation practice.

Experiment 1 found that tapping synchronization was influenced by beat perception ability. Thus, the ways that groove influences walking synchronization may also be influenced by individual differences in beat perception ability. The ability for participants to benefit from non-temporal factors may depend upon their adeptness in perceiving a beat. The synchronization accuracy of an individual who has a strong perception of the beat may not be improved by non-temporal cues. Conversely, individuals who are relatively poor at perceiving the beat may capitalize on non-temporal factors, thereby, improving their synchronization accuracy. Specifically, high groove music – where there is a high density of non-temporal factors around the beat – should

lead to a greater improvement in synchronization accuracy in weak beat perceivers compared to strong beat perceivers.

The goal of the current study is two-fold 1) to investigate synchronization accuracy in acoustically-paced walking, and 2) to determine how beat perception ability affects synchronization to different acoustic stimuli. To examine synchronization accuracy in acoustically-paced walking, participants walked to an auditory stimulus at either their preferred rate (preferred cadence), 22.5% faster, or 22.5% slower. Previous studies have shown that synchronization accuracy decreases when the rate of an auditory stimulus deviates from a participant's preferred cadence (Roerdink et al., 2011; Styns et al., 2007). Thus, by adjusting the rate of the stimuli we are able to create variability in synchronization to the beat, thereby, allowing us to examine how different auditory stimuli and beat perception ability affect synchronization accuracy. Historically, previous studies have only used metronomes to adjust the rate of walking. Here, I compared synchronization accuracies of acoustically-paced walking in time with metronome, MS stimuli, low groove music, and high groove music to determine if non-temporal factors promote accurate synchronization. Using a metronomic sequence, it can be determined if participants can synchronize to a given beat. To determine the effect of non-temporal factors on synchronization to the beat a MS rhythm was created. Like music, MS rhythms require perception of a beat, but like the metronome sequence, consists only of pure tones (devoid of non-temporal factors). High and low groove music were selected to investigate how a large amount of non-temporal factors (high groove music) and a minimal amount of non-temporal factors (low groove) influence synchronization accuracy. Therefore, the

only major difference between the music and a MS rhythm condition is the presence of non-temporal factors.

In addition to measuring synchronization accuracy in acoustically-paced walking, I also evaluated whether strong beat perceivers show more accurate synchronization than weak beat perceivers. Moreover, I looked at how non-temporal factors around the beat (using high and low groove music) are used differentially in strong and weak beat perceivers. If strong beat perceivers rely on their perception of the beat, rather than their use of non-temporal factors, synchronization would be expected across all stimuli type. Conversely, weak beat perceivers may not rely on their perception of the beat, but rather the location of non-temporal factors. Thus, weak beat perceivers were expected to show more accurate synchronization in high groove music followed by low groove music, metronome (no beat perception required), and MS rhythms.

It is hypothesized that individuals with a weak perception of the beat will benefit from non-temporal factors in music more than individuals with a strong perception of the beat. Specifically, I predict that weak beat-perceivers will show similar synchronization accuracy as strong beat-perceivers in the high groove music condition, but not the low groove music and MS rhythm condition.

Method

Participants

Sixteen participants (9 males, 7 females) from Experiment 1 were recruited for the second experiment ($M_{age} = 19$ yrs $SD = 1.41$). Their beat perception ability was defined by their scores on the perception BAT. Two groups were created using the median split of the perception scores. Nine participants were parsed into the strong beat-

perceiver group, while the remaining seven were assigned to the weak beat-perceiver group. The presentation of auditory stimuli was controlled by a paradigm created in the E-Prime (2.0) program (Psychology Software Tools, 2002).

Materials

All participants performed walking trials across a Zeno walkway system under the following cuing conditions: music, metronome sequences, and metric simple rhythms. In the music condition, 10 high groove, low familiarity songs were selected from a set of 40 songs that were previously rated by 25 separate participants for their degree of groove and familiarity. Additionally, 10 low groove, low familiarity songs were selected from a list of 150 songs that were recently rated on groove in a previous study (Janata et al., 2012). Low familiarity songs were chosen to reduce the evoked emotional response associated with familiar musical clips. The high and low groove songs were selected as pairs matched as closely as possible for their beat rate. Before the rate of the musical clips were adjusted to match participants preferred walking rate, the rate of the musical pieces were measured using an online source beat tracking program (Ellis, 2007). As determining the beat rate in music is highly subjective (cf. Mc Kinney & Moelants, 2007), three individuals with musical training tapped to the beat of each musical clip to determine the beat rate. Only those musical clips that the trained musicians and the software agreed upon the beat rate were used in this study. The loudness of the clips were equalized using Audacity; an open source software program (<http://audacity.sourceforge.net>). Audacity was also used to trim the beginning of each musical clip to start on a beat.

MS stimuli were created with the '1' interval of 250 ms (all other intervals were multiples of the 1 interval length) as seen in Experiment 1. The metronomic sequences

and MS stimuli were created using 50 ms tones. Metronomic sequences were initially created with IOIs of 500 ms. Both stimuli were created at a beat rate of 120 beats per minute, which is approximately the preferred cadence in a young adult population (Styns et al., 2007).

The rate of the stimuli used was adjusted to match the participants' preferred cadence, sped up 22.5% faster than their preferred cadence and 22.5% slower than their preferred cadence. Rate changes were performed using a phase vocoder (<http://www.ee.columbia.edu/ln/rosa/matlab/pvoc/>), which is a system that can scale both the frequency and time domains of audio signals while preserving the sound quality of the auditory signal.

Procedure

Before the experimental walking protocol, each participant's preferred cadence was determined by instructing the participants to walk eight times on a 16 ft Zeno walkway (1 walk is 1 length of the walkway). Walks started and finished two metres beyond the end of the walkway to reduce the effects of acceleration and deceleration on overall walking speed. The number of steps collected from 8 walks is considered sufficient for determining a participant's preferred cadence (Wittwer, Webster, & Hill, 2012). Participants also rated 20 musical pieces for their degree of groove and familiarity on a 10-point scale. For groove ratings we asked participants "how much did the music make you want to move" (1 = *did not want to move* to 10 = *very much wanted to move*). For familiarity ratings we asked participants "how familiar are you with what was just played" (1 = *not at all familiar* to 10 = *very familiar*). Six music clips among the original 20 pieces were used: 3 rated as high groove, low familiarity and 3 rated as low groove, low familiarity. The respective rates of the music, MS, and metronomic stimuli were then

adjusted to match participants' preferred cadence, as well as 22.5% below and above their preferred cadence.

Participants were also familiarized with each stimulus type prior to the experiment. Before each trial, participants indicated their perceived beat rate for that trial's stimulus by walking on the spot or clapping in time to the beat. This was done to ensure that participants were walking at the appropriate beat rate (as decided by the experimenter), not walking at half the beat rate, or not walking to double the beat rate. Once the participants indicated the appropriate beat rate, the experimenter instructed the participants to walk up and down the Zeno mat with each step in time to the beat (music and MS rhythm conditions) or to the tone in the metronome condition. If the participant indicated the incorrect beat rate, the experimenter instructed the participant to walk at double or half the indicated beat rate. Similar to the trials to determine a participant's cadence, walks started and finished two metres beyond the end of the walkway. When the participant turned around at the end of the mat to continue their walk in the opposite direction, they were instructed to continue to step to the beat, so that their perception of the beat was not lost. Participants performed three trials (eight walks per trial) of each condition for a total of 24 trials. The 24 experimental trials were presented in random order. To prevent fatigue, participants were given as much time as they needed to rest between trials.

At the end of the experimental session, participants completed an open-ended questionnaire, inquiring about the logistics of walking while listening to music and any problems they may have encountered throughout the experiment. The duration of the entire experiment was approximately one hour.

Data analysis

For each trial, time indices of beep or beat onsets (determined by the rate of the music) and time indices of foot contact were compared to determine the coefficient of deviation (CDEV). Similar to the production BAT, synchronization was calculated based on the deviation of the time between each step (inter-step-interval) and IBI. Synchronization performance was quantified using the CDEV as described in Experiment 1. Greater CDEV values indicated poor synchronization accuracy. To determine if beat perception had an effect on synchronization accuracy across each stimuli type and beat rate, a 2x3x4 between-subjects repeated measures ANOVA was conducted, with beat perception ability (weak, strong) as the between-subjects factor, beat rate (slower, preferred, faster) as within-subjects factors, and stimulus type (low groove music, high groove music, simple rhythm, and metronome). Pairwise comparisons identified significant differences between conditions, and Dunn-Sidak corrections were carried out for all analyses to adjust for multiple comparisons. Moreover, Mauchly's Test of Sphericity was used to determine violations of sphericity. If Mauchly's test was significant then the Greenhouse-Geisser correction was applied. All analyses were run in SPSS version 21.

Results

A 2x3x4 between-subjects repeated measures ANOVA was conducted. There was a significant main effect of beat rate ($F(2,28) = 1.407, p = 0.042$, see Figure 8). Pairwise comparisons showed a significant difference between the slower and preferred condition ($t(15) = 2.77, p = .014$), and faster and preferred conditions ($t(15) = -2.692, p = .017$), but not the slower and faster condition ($t(15) = -.30, p = .769$). This result suggests that

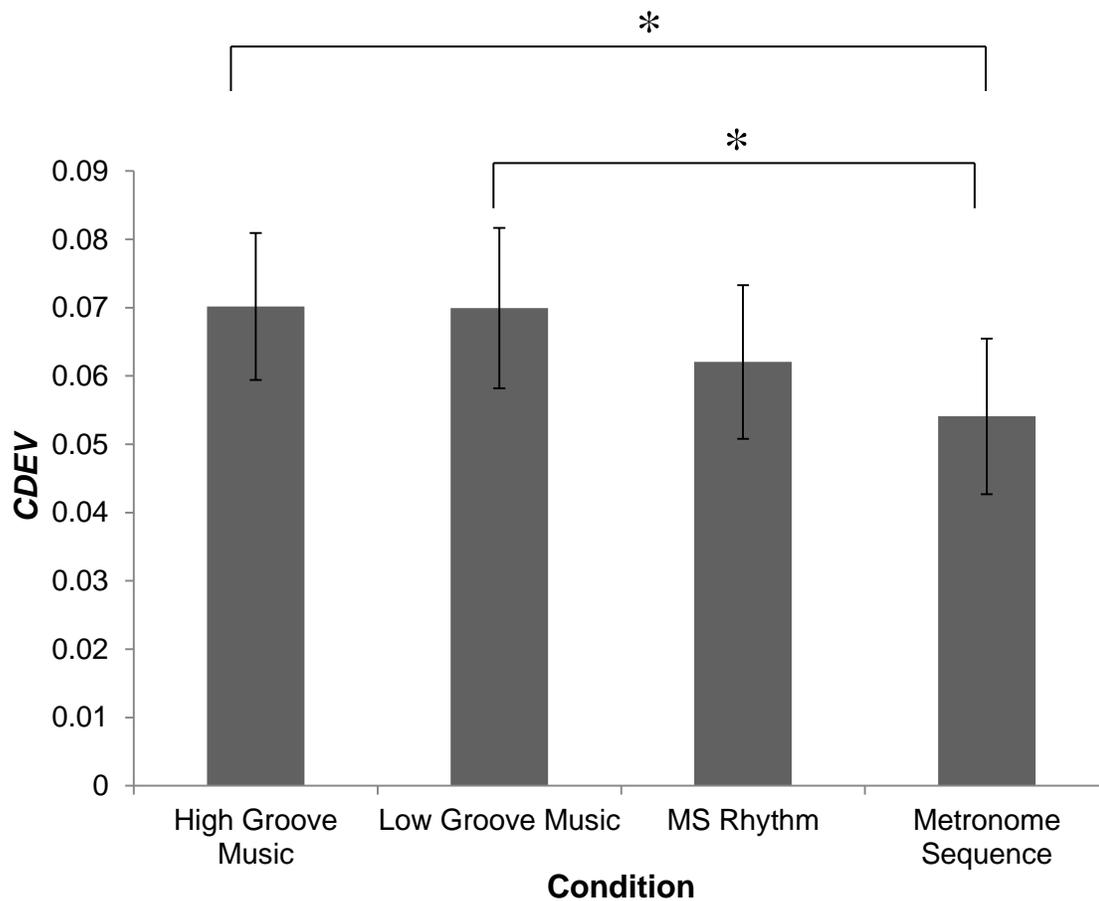


Figure 8. Mean CDEV for high groove, low groove, MS, and metronome stimuli. CDEV was calculated based on the deviation of the time between the ISI and IBI. Lower values indicate accurate synchronization. Each condition is collapsed across beat rate and beat perception group. Error bars indicate standard error of the mean. * $p < .05$.

synchronization accuracy declines when the rate diverges from the preferred walking cadence.

A significant effect of beat perception ability was also observed ($F(1,14) = 9.23, p = 0.009$). An independent t-test indicated accuracy was significantly greater in strong beat-perceivers ($M = 0.044, SD = 0.023$) compared to weak beat-perceivers ($M = 0.097, SD = 0.047, t(14) = 2.97, p = 0.01$). A significant main effect of stimulus type was also found ($F(2,28) = 5.08, p = 0.013$, see Figure 9). Pairwise comparisons revealed that the CDEV values for high groove music and low groove music ($t(15) = 0.22, p = .83$), high groove and MS rhythm ($t(15) = 1.50, p = .16$), low groove and MS rhythm ($t(15) = 1.31, p = .21$), and MS rhythm and metronome ($t(15) = 1.43, p = .17$) did not significantly differ. However, both high and low groove music showed significantly greater CDEV values relative to the metronome (high: $t(15) = 3.55, p = .003$; low: $t(15) = 3.32, p = .005$). Music in general (both high and low groove music) showed greater CDEV values compared to the metronome sequence, but not compared to simple rhythms. Moreover, there was no difference in CDEV values between metronome and simple rhythm.

The main effects were qualified by a significant two-way interaction between stimuli type and beat rate (Figure 10). Pairwise comparisons showed no significant difference between the stimulus type in the slower and preferred condition ($p > .14$). However, high and low groove music showed significantly greater CDEV values in the faster condition compared to the MS rhythm and metronome ($p < .033$). In the faster condition, the metronome sequence and the MS rhythm had the lowest CDEV (most accurate synchronization). Additionally, the two-way interactions between beat perception ability and beat rate ($F(3,84) = 2.05, p = .16$) and beat perception ability and

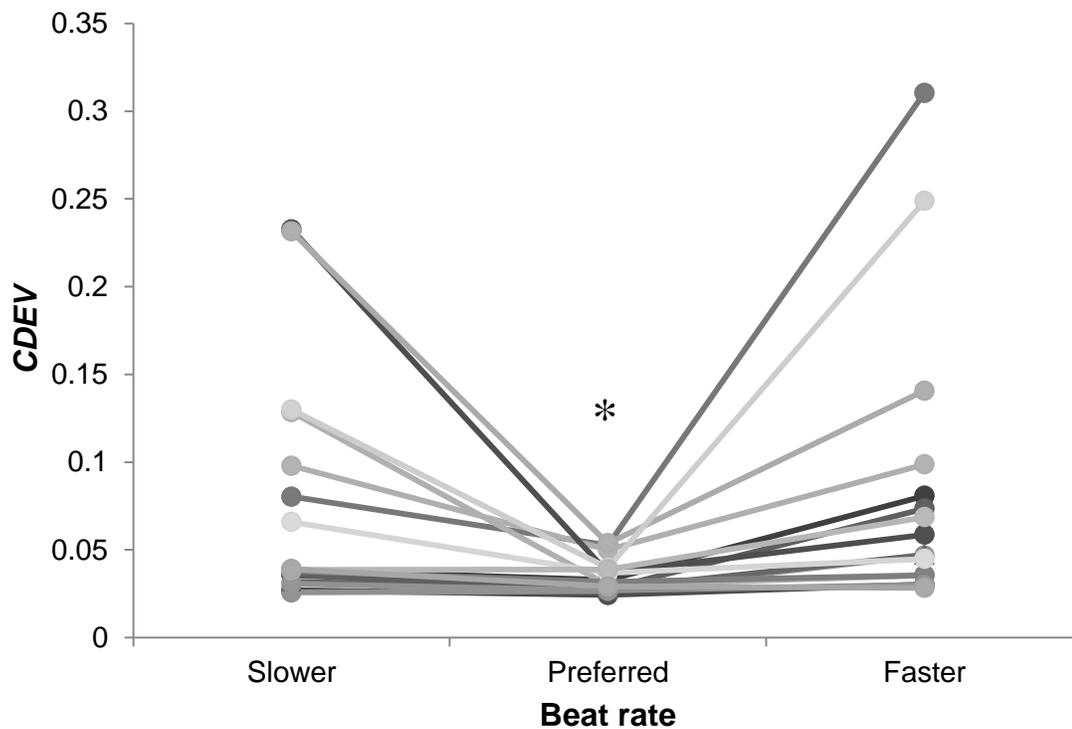


Figure 9. Mean CDEV of individuals at slower, preferred, faster beat rates. Each point is collapsed across stimuli type and beat perception ability. Lines represent participants' performance across beat rates. Performance in the preferred beat rate was significantly less than performance on slower and faster beat rates. * $p < .05$.

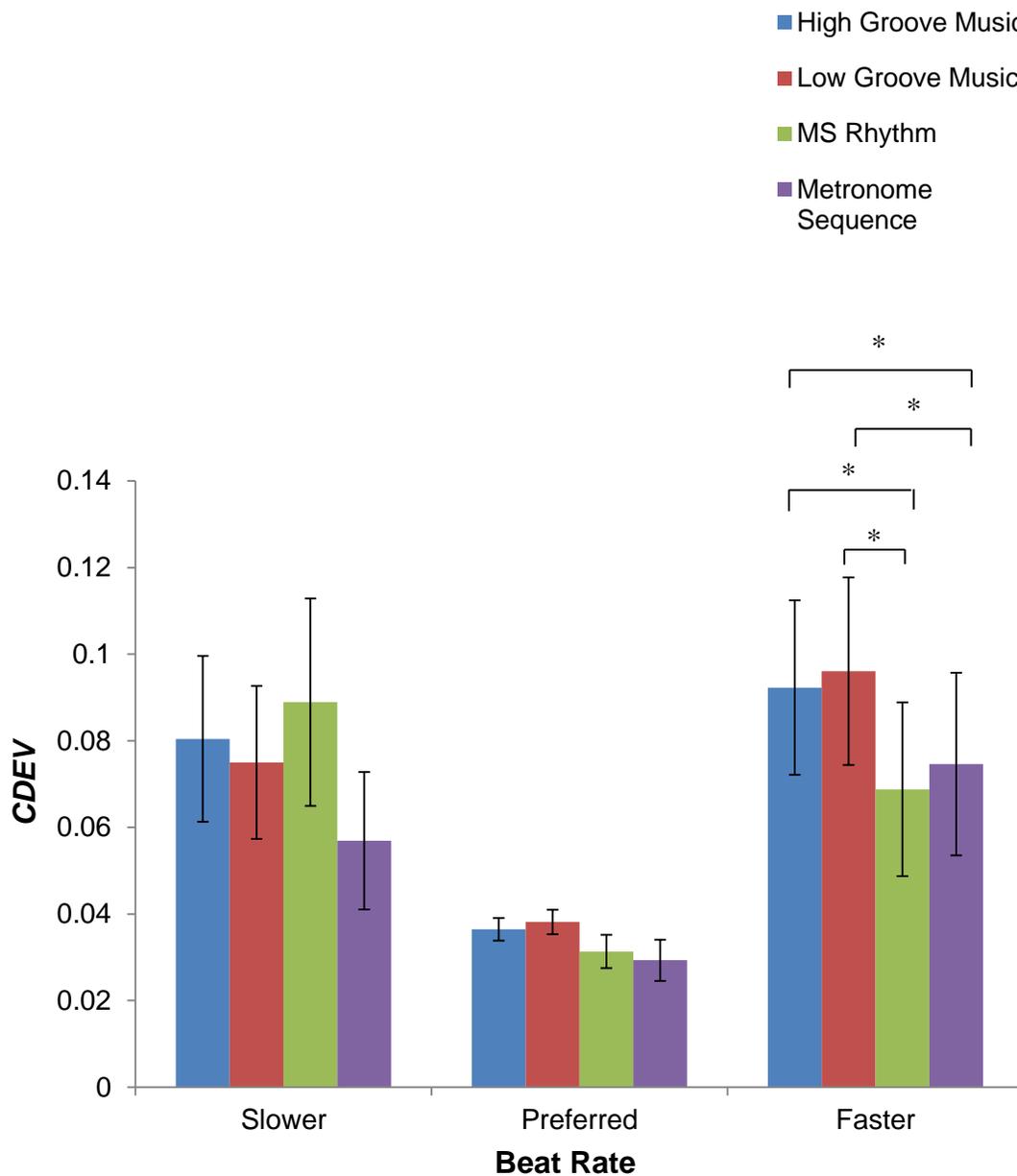


Figure 10. Mean CDEV of high groove, low groove, MS, and metronome stimuli at slower, preferred, and faster beat rates. The graph depicts the two-way interaction between stimulus type and beat rate on CDEV. Error bars indicate standard error of the mean. * $p < 0.05$.

stimulus type did not reach significance ($F(3,84) = 1.55, p = .23$). The main effects of stimuli and tempo do not differ between strong and weak beat perceivers. Non-significant interactions must be interpreted with caution because they are found within a higher-order interaction. The three-way interaction was not significant ($F(6,84) = 2.75, p = .073$; Figure 11). Therefore, performance on each stimulus type across each rate is not distinctly different between each beat perception group.

Discussion

By altering the beat rate of an auditory stimulus, we were able to determine the effects of different stimuli and beat perception ability on synchronization accuracy. A 22.5% increase and decrease from participants preferred cadence was shown to induce synchronization variability within our sample. Strong beat-perceivers showed lower synchronization variability than weak beat-perceivers. In addition, music stimuli were shown to produce the highest CDEV values, particularly in the faster beat rate condition.

The purpose of changing the beat rate (pacing frequencies) in the stimuli was to induce variability in synchronization accuracy to determine if beat perception ability or stimuli type improved synchronization around one's preferred cadence. Pacing frequencies beyond participants preferred cadence (22.5% slower and faster) induced larger CDEV values in slower and faster conditions compared to participant's preferred cadence. The finding that synchronization accuracy declines as the beat rate of the auditory stimuli deviates from a participants preferred cadence is consistent with the resonance curve for locomotion (Styns et al., 2007). Thus, acoustically paced gait training aimed at improving auditory-motor coordination (synchronization accuracy) probably fares best if the auditory stimuli is set near one's preferred cadence.

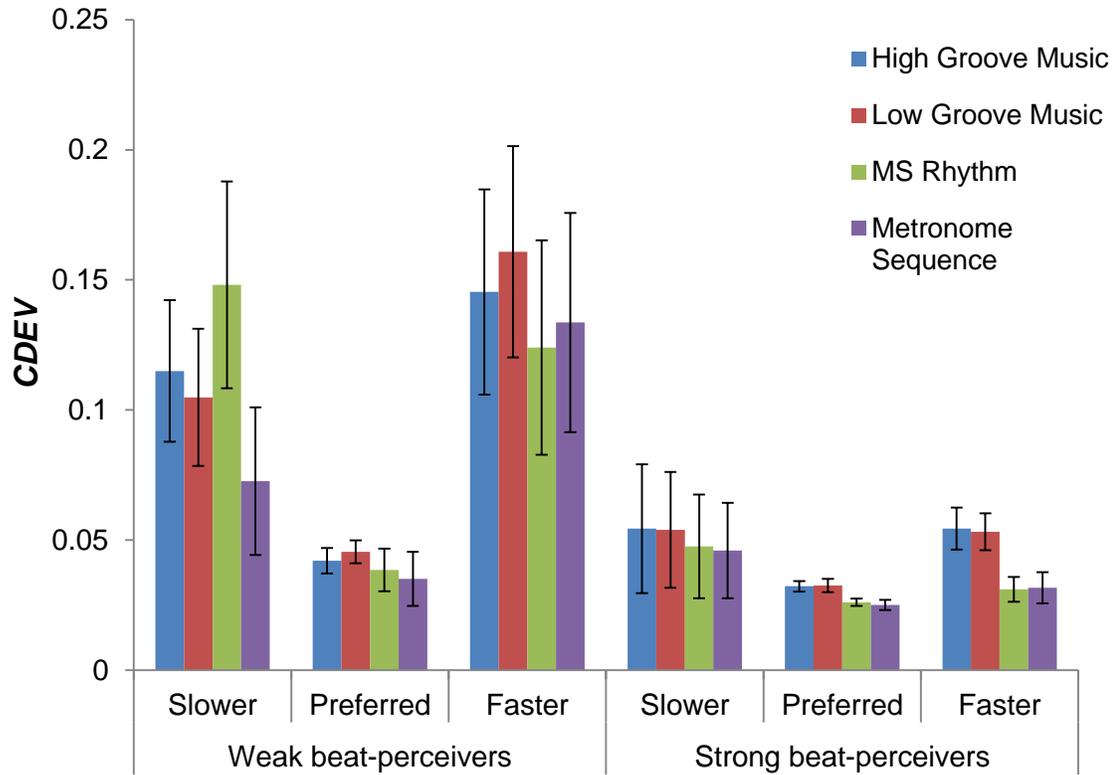


Figure 11. Mean CDEV of high groove, low groove, MS, and metronome stimuli at slower, preferred, and faster beat rates in strong and weak beat-perceivers. The figure depicts the reduced CDEV values in the high and low groove music condition within the weak beat perceivers at the slower beat rate compared to the MS rhythm condition. Error bars indicate standard error of the mean.

Strong beat-perceivers were found to have significantly lower CDEV values than weak beat-perceivers. Beat perception had similar effects on walking and tapping synchronization. Previous literature has shown correlations with beat perception ability in left angular gyrus, left supplementary motor area, left dorsal and ventral premotor cortex, and inferior frontal operculum (Grahn & Schuit, 2012). This network is implicated in auditory to motor transformation in speech (Hickok, Buchsbaum, Humphries, & Muftuler, 2003) and may be responsible for auditory to motor transformation when listening to rhythms (Chen, Penhune, & Zatorre, 2008; Grahn & Brett, 2007). It may be that participants with a strong perception of the beat in the current experiment have stronger auditory motor connections allowing subjects to alter their movement to match an external auditory stimulus.

In addition to the difference in the CDEV values between strong and weak beat-perceivers, synchronization accuracies under different auditory stimuli were examined. The CDEV values in the high and low groove music conditions did not significantly differ. Therefore, music that elicits a strong tendency to want to move shows no benefit for improving synchronization accuracy compared to music that does not elicit a tendency to want to move. Thus, the quality of the sensorimotor coupling is not reflected in the subjective experience of being in the groove. This observation is in contrast to the tapping data showing high groove music improves synchronization accuracy (Tomic & Janata, 2008). No difference between high and low groove music may have been driven by the high CDEV values in the faster beat rate conditions. At the faster beat rates, instead of enhancing motor timing, the non-temporal cues in high groove music may have led to a perceptual overload due to insufficient processing time for the additional

information (Thaut, McIntosh, & Rice, 1997). If the pacing frequencies were reduced to slower beat rates, the additional non-temporal factors in high groove music may have been sufficiently processed leading to better synchronization accuracies than low groove music. Moreover, music had significantly greater CDEV values than the MS rhythm and metronome sequence conditions. These data suggest that the non-temporal factors present in music may create a dual task condition, thereby exerting a distracting effect (de Bruin et al., 2010).

For gait training it is optimal to know which stimuli is best to synchronizing to faster and slower pacing frequencies. Low and high groove music showed significantly greater CDEV values than metronome and MS rhythm conditions in the faster condition, but not the preferred and slower condition. These data suggest that metronome and MS rhythms are optimal stimuli to improve synchronization accuracy in the faster condition. High CDEV values in the music and MS rhythm conditions compared to the metronome condition might be attributed to greater difficulty in perceiving the beat in music and MS stimuli. Perceiving the beat within a stimulus might place additional cognitive demands on the participant and acts as a distractor (de Bruin et al., 2010).

Beat perception ability did not have distinct effects across beat rates, and stimulus type, suggesting that weak beat perceivers do not benefit more from any stimulus type in the slower or faster conditions. However, in the slower condition, weak beat perceivers showed lower CDEV values in low and high groove music compared to MS rhythm, suggesting that music may improve synchronization accuracy in the slower beat rate condition. These data, suggest weak beat perceivers are able to use non-temporal factors in music to find and synchronize their footfalls to the beat. The difference between the

low/high groove music and the MS rhythm condition was not seen in the strong beat-perceiver group. Thus, the data suggest that weak beat-perceivers may be better able to use non-temporal factors around the beat to improve synchronization accuracy compared to strong beat-perceivers.

These data show strong beat perceivers were better able to adjust their gait compared to weak beat perceivers. The within subjects analysis suggests that participants showed greater variability in synchronizing footfalls at beat rates slower and faster than their preferred cadence. The stimulus type comparison showed that the music conditions (low and high groove) had significantly higher CDEV values compared to MS rhythm and metronome conditions. Moreover, synchronization accuracies in the music conditions were significant worse than the metronome and MS rhythm conditions in the faster beat rate. Thus, metronome or MS rhythm may be more beneficial for auditory-pacing in patients with movement disorders (e.g., PD patients).

Chapter 4: General Discussion

Summary and implications of results

There were two aims in Experiment 1. The first aim was to develop paradigms to test beat perception, internal generation, and production of the beat. The importance of each stage can be illustrated when tapping to music. Tapping begins when the beat has been perceived or found. Beat perception requires detection of salient or accented events. This may be through detection of non-temporal factors or subjective accents in rhythmic sequences. After tapping begins, the beat must be internally generated to time future taps or to time intervals around the beat. If a deficit occurs in any of these stages in rhythm processing, production or timing of a rhythm (relative timing) may be affected. Thus, the second aim was to determine if perceptual or production stages could be dissociated from each other. These paradigms can be used in the future to assess whether PD patients' deficits in relative timing result from perception and/or production deficits (Grahn & Brett, 2009).

We used two tests to explore beat perception: the perception BAT and the intensity threshold test. The perception BAT used music clips with superimposed tones placed on or off the beat. The results of the perception BAT replicated the original behavioural findings that beat perception ability varies within a sample population. In addition, the same musical stimuli used in the perception BAT were also used in the production BAT to assess beat production. Thus, a direct comparison between perception and production can be made. If PD patients show poor performance on the perception BAT relative to age matched controls, beat perception may be impaired in the context of music. In contrast, if PD patients show similar accuracies to age matched controls; it may

indicate that PD patients are able to perceive the beat in the context of music, when non-temporal factors can be used to find the beat. However, the relative timing deficits in PD patients were found using rhythmic sequences devoid of non-temporal factors. A selective impairment in perceiving the beat in a rhythmic context devoid of non-temporal facts may explain the relative timing deficits in PD patients.

To assess a participant's ability to perceive the beat in the absence of non-temporal factors, the intensity threshold test was developed. Tones in a rhythmic sequence that coincide with the beat are subjectively accented and, therefore larger external intensity changes might be needed for these tones to be perceived as louder than surrounding tones. A note that occurs off the beat is not subjectively accented and, therefore, there is nothing to mask an external intensity change (Large & Jones, 1999). The results of the intensity threshold test supported these assumptions. Larger external intensity changes on notes that coincide with the beat were needed to compensate for the subjective accents (i.e., MS-on had greater intensity threshold levels than MS-off). However, intensity threshold was not higher with the MS on-beat tones than for the MC off-beat tones. According to the dynamic attending theory (Large & Jones, 1999), in rhythms without beat (MC rhythms) there are no peaks of attention; therefore, attention remains steady throughout a MC rhythm. In contrast, MS rhythms have attentional oscillations, with attention being at its maximum at beat locations. Thus, comparing conditions where attention is maximal and minimal (comparing MS-on to MS-off), may give a stronger effect than comparing conditions where attention is maximal and attention is consistent throughout the rhythm (comparing MS-on to MC-off). In light of these data, greater intensity thresholds in the MS-on condition compared to the MS-off condition

may index beat sensitivity on an individual level; people who have higher intensity thresholds might have better perception of the beat. However, no significant correlations between the difference in MS-on and MS-off intensity thresholds and the other tests in this experiment were observed.

A dissociation between the intensity threshold test and the other tests in this experiment was found. The intensity threshold test requires participants to actively group the intervals in a rhythm to produce subjective accents or perceive the beat. However, it is possible that participants were focused on the detection of a intensity change rather than perceiving and forming an internal representation of the beat. Without an internal representation of the beat, participants will not create subjective accents that coincide with on-beat locations. No masking effect will be observed in participants who ignore the beat in a rhythm. Future studies should emphasize creating a representation of the beat while searching for a intensity change rather than just searching for a intensity change.

Using the intensity threshold test on PD patients could dissociate whether previous findings of deficient relative timing are due to impaired beat perception or, alternatively, impaired internal generation of the beat. If PD patients show no difference between the threshold levels in the MS-on and MS-off conditions, then their deficit in relative timing may be the result of poor perception of the beat. If PD patients do show a difference between the MS-on and MS-off conditions, then their deficit may lie in internal generation of the beat.

To test internal generation of the beat as independently as possible from perception of the beat, two tasks were developed. The first, the metronome tempo discrimination task measured how well participants internally generated a beat when

perceptual demands were minimized by the use of metronome sequences. Participants simply compared the two metronome rates. Given that the beat is defined as a regular pulse in music, the regularly spaced tones in the metronome sequences then act as a regular beat. By comparing two given beat rates (given as a metronome), internal generation ability can be measured in the absence of beat perception and production. Performance varied on the task, but it was not too difficult or easy. If PD patients show normal perception of the beat, but lower scores on the metronome tempo discrimination test, then a deficit in relative timing might be from impaired internal generation of the beat. However, if they show normal performance in the perception tests and the metronome tempo discrimination test, then it might be that PD patients are unable to internally generate a beat in a rhythmic context. To address this concern, the second test, the rhythm tempo discrimination test was developed.

The rhythm tempo discrimination test requires participants to compare a beat given by a metronome to a beat perceived in a comparison rhythm. This test requires participants to perceive the beat when listening to the rhythm. In addition, this test requires participants to internally generate a previously heard beat (given by the metronome sequence) and compare it to the perceived beat rate of the comparison rhythm (MS or MC). As MS rhythms contain a definitive beat, while MC rhythms do not, it was expected that performance in the MS condition would be greater than the MC condition. MC rhythms were used as a control rhythm to rule out explanations due to general difficulty of the test. Equal performance across MS and MC conditions might indicate that the test was too difficult. The results indicate that participants showed no difference in their ability to detect rate changes in MS and MC rhythms; thus, the test may be too

difficult. The negative results might be because participants could perceive different beat rates in the rhythm than the rate intended. If a participant perceived the beat at half of the expected beat rate (450, 500, or 550) then a 25% increase in the rhythm beat rate will still not approach their perceived beat rate, potentially causing participants to respond 'slower' when the correct response was 'faster'.

Difficulty in perceiving the expected beat rate may have led to lower performance scores in the MS condition of the rhythm tempo discrimination test. Lower accuracy scores may be reflected in the non-significant correlations between the rhythm tempo discrimination test and the perception/production BATs. The rhythm tempo discrimination test might not be accurately measuring internal generation of the beat in a rhythmic context. To overcome this limitation, multiple metronome rates (at both half and double the expected beat rates of the rhythm) should be given to accommodate the variability in perceived beat rates.

Future application of both the metronome tempo discrimination task and the rhythm tempo discrimination task would provide a sensitive measure of a participant's ability to internally generate the beat. Selective impairments on the rhythm tempo discrimination test, but not the metronome tempo discrimination test, would suggest a selective deficit in internally generating the beat in a rhythmic context, but unimpaired ability in internally generating the beat in a metronome context.

To evaluate beat production separately from beat perception and internal generation, we used the production BAT test developed by Müllensiefen et al. (2011). Previous findings showed that tapping synchronization ability varied in the general population. The results of the production BAT replicated the original behavioural

findings, showing variability in beat tapping synchronization ability. Synchronization accuracy has been documented in PD patients using metronome sequences (Yahalom, Simon, Thorne, Peretz, & Giladi, 2004). PD patients have greater synchronization errors compared to healthy age-matched controls when tapping to a metronome sequence. To date there have been no studies examining the relationship between perception and motor synchronization to the beat of a rhythm in PD patients. Deficits in motor synchronization to the beat/metronome sequence could be due to the motor symptoms of the disease, or an inability to perceive the beat. Therefore, future studies should investigate both beat perception and production of the beat to determine at what stage PD deficits occur.

The purpose of developing tests of perception, internal generation, and motor production of the beat was to determine at what stage(s) of beat processing PD patients show impairments. Intuitively, internal generation and motor production of the beat require the perception of the beat, however, the question is whether these two stages only depend on one's perception of the beat? Or are there other mechanisms controlling internal generation and production of the beat? If the same mechanism underlies perception, internal generation, and motor production of the beat, then we should find strong correlations between each process. Significant positive correlations were found between the perception BAT and the metronome tempo discrimination test. In addition, good performance on the perception BAT was associated with good performance on the production BAT and the metronome tempo test. Significant correlations between tests measuring perception, internal generation and production of the beat provide support of a common timing mechanism guiding all three processes. However, four participants showed a dissociation between perception and production of the beat, and between

internal generation and production of the beat. Thus, perception and internal generation of the beat might be governed by one mechanism as no dissociation between these processes were seen, whereas beat production might require an additional process that perception does not use.

To investigate if a dissociation between perception and internal generation of the beat affects the use of a relative representation, a rhythm discrimination test was developed. This thesis replicates the results of Grahn and Brett (2009) in that MS rhythms elicited greater discrimination accuracy than MC rhythms. However, the paradigm used in this thesis had an extra manipulation during the comparison stage. In the paradigm used in this thesis, the third presentation (comparison rhythm) sometimes contained a change in the overall rate. The rate change was to be ignored by the participants when making their judgement of whether the comparison rhythm differed from the first two presentations. Thus, participants had to rescale their representation of the standard rhythm, then compare whether the order of time intervals in the rescaled rhythm and the comparison was the same or different. Previous work indicates that participants are able to rescale MS rhythms, but are unable to rescale MC rhythms (Collier & Wright, 1995). Introducing a rate change affects rhythms encoded using an absolute mechanism because all the absolute interval lengths between the standard and comparisons rhythms will differ when there is a rate change. This means that rhythms encoded using an absolute mechanism in the rhythm discrimination test cannot be discriminated accurately by comparing the absolute durations between the standard and comparison rhythms. However, rhythms encoded using a relative mechanism will not be affected because the relative relationships of the tones in the rhythm will be maintained.

Thus, if the MS condition shows better discrimination accuracy than the MC condition, we can be confident that performance in the MS condition indexes the use of a relative mechanism.

To determine if individual differences in perception and internal generation observed in a healthy population explain impaired relative timing in PD patients, each condition within a test was correlated with the MS condition of the rhythm discrimination test. The correlational analysis revealed a significant positive correlation between the perception BAT and the MS condition within the rhythm discrimination test. The results suggest that as beat perception ability increases, a more accurate representation of the rhythm is created when compared to weak beat-perceivers. Previous literature suggests better performance in participants with a strong perception of the beat is because of the use of an additional auditory-motor representation to encode a rhythm, rather than just an auditory code (Grahn & Brett, 2007). Thus, a deficit in the mechanism controlling beat perception might be the reason that PD patients show a deficit in relative timing. However, the importance of internal generation of the beat in forming a relative timing mechanism cannot be ruled out, as a dissociation between perception and internal generation of the beat was not found. A dissociation in some participants would indicate that preservation of beat perception, but impairment in internal generation can still enable participants to create a relative representation of a rhythm and discriminate changes in a rhythm.

In Experiment 1, we showed a relationship between beat perception ability and tapping synchronization to the beat. Experiment 2 was developed to assess if a similar relationship exists between beat perception and synchronization of footfalls to the beat. In

addition, we measured how different stimulus types affected walking synchronization accuracy. Understanding how perception of the beat affects synchronization, and what stimuli are optimal (e.g., high groove music, low groove music, MS, or metronome) for beat synchronization, could lead to more effective applications of acoustic cues in gait rehabilitation.

The results show that strong beat-perceivers were more accurate than weak beat-perceivers at synchronizing their steps to the beat. However, a correlational analysis was not performed because of a small sample size, thus a dissociation between perception and production cannot be determined. The relationship between beat perception and tapping/walking synchronization suggest that perception of the beat may explain the variability in synchronization accuracies across different movements. Many gait rehabilitation studies suggest that synchronizing footfalls to metronome sequences improves gait performance (Spaulding et al., 2013; Thaut, 2003). Despite this finding, previous research has not considered the contribution of individual beat perception abilities, which affect how well an individual can use the beat in music to adjust their gait. As beat perception was shown to affect synchronization accuracy, the next question is whether there an optimal stimulus to adjust gait exists across or within different levels of beat perception ability. Specifically, is there one stimulus that improves synchronization over another stimulus? Do weak beat-beat perceives benefit from one stimulus type over strong beat-perceivers?

To investigate which stimuli produced optimal walking synchronization, CDEV values between high groove music, low groove music, MS, and metronome conditions were analyzed. It was predicted that non-temporal factors in high groove music would

accentuate the beat, resulting in better synchronization accuracy than low groove music. Contrary to the predictions, high groove music evoked the least accurate synchronization followed by low groove music, MS rhythms, and metronome sequences. The metronome condition showed significantly lower CDEV values than high and low groove music. Synchronization accuracies in each condition might be explained by perceptual demands and number of distractors associated with a particular stimulus. The metronome sequence presents a given beat, thus minimizing the cognitive demands associated with perceiving the beat. High CDEV values in the music and MS rhythm conditions compared to the metronome condition might be attributed to greater difficulty in perceiving the beat in music and MS stimuli. Perceiving the beat within a stimulus might place additional cognitive demands on the participant, acting as a distractor (de Bruin et al., 2010).

In addition, music created greater CDEV values than a MS rhythm. This result suggests that the non-temporal factors in low and high groove music may further distract participants. Therefore, as perceptual demands and groove levels increase, synchronization accuracy decreases. The aim of some gait rehabilitation practices is to have participant's synchronization to a beat to improve speed and other gait parameters. The data in this experiment suggest that across all beat perception ability, a metronome sequence may be more optimal than music to improve speed and other gait parameters.

Overall, both high and low groove music produced the greatest CDEV values compared to both MS and metronome sequences. However, both high and low groove produced significantly greater CDEV values in the faster condition than the MS and metronome sequence. In the preferred and slower beat rate condition, high and low groove music did not show greater CDEV values than the MS and metronome sequences.

These data suggest that metronome and MS rhythms are optimal stimuli to improve synchronization accuracy when using a faster beat rate and might be optimal for adjusting a patient's gait to a faster pacing frequency.

Limitations of current work

Although the individual differences investigated in this thesis are consistent with the concept of a common mechanism guiding perception and production of the beat, certain limitations must be considered before making strong conclusions. All significant correlations found between perception and other processes (i.e., metronome tempo discrimination test, rhythm discrimination test, and production BAT) were found with the perception BAT. However, the scores on the perception BAT might be indicative of how well an individual can compare their internal representation of the beat to the superimposed beeps. Thus, the perception BAT introduces an additional timing component. It is not possible to determine if performance on the perception BAT indicates a participant's ability to perceive the beat or a participant's ability to time their perception of the beat to the superimposed tones.

To remove additional timing requirements of the BAT, we developed the intensity threshold test, however, no correlations were found between the intensity threshold test and the conditions in the other tests. It may be that individual differences in intensity threshold between on and off conditions do not reflect individual differences in beat perception. Participants may have been focused on detecting an intensity change rather than grouping intervals to create subjective accents. Without subjective accents, participants will not mask on beat intensity changes.

Another limitation of this study was the small sample size used in Experiment 2. Only 16 (9 strong beat-perceivers, 7 weak beat-perceivers) participants returned for the walking part of the study. A three-way interaction between beat perception ability, beat rate, and stimulus type was not found and might be explained by low statistical power. Therefore, a larger sample size might be necessary to determine if weak beat-perceivers benefit more from non-temporal factors in low and high groove music when compared to strong beat-perceivers.

In addition, music contains expressive variations (subtle temporal nuances that convey a structural event such as the beat) which can lead to minor time differences between inter-beat-intervals making the beat non-isochronous (Snyder & Krumhansl, 2001). As these temporal nuances can be very small (10-20 ms), an isochronous beat rate can be used to represent beat rates. Therefore, I calculate the CDEV (the difference between inter-step-intervals and IBIs divided by the average inter-step-interval) assuming an isochronous beat rate in music. However, an isochronous beat rate is not an accurate representation of the expected footfall times. Using the exact IBI to calculate synchronization accuracy may lower the CDEV values in high and low groove music conditions.

Future directions

The findings presented in this thesis suggest several areas for future research in behavioural and neuropsychological domains.

Previous studies showing impaired discrimination of MS rhythms in PD suggests that the BG is critical for processing the beat (Grahn & Brett, 2009). However, the BG's specific role in beat perception, internal generation, and production remains unclear.

Through future testing of PD patients with the paradigm in this thesis, it should be possible to determine whether their deficit is in perceiving the beat during initial presentations of the rhythm, internally generating the beat during the discrimination phase of a rhythm discrimination task, or in motor timing (synchronization to the beat). A dissociation between perception, internal generation, and production might indicate that these processes are not all governed by the same mechanism, and that PD patients might show a deficit in perception or a deficit in internal generation. Therefore, it is possible that patients with PD deficits show preserved beat perception, but show a deficit in internal generation of the beat. Previous literature using neuroimaging found that the BG activity is greatest during beat prediction (where participants must internally generate the beat) compared to beat finding (perception). Testing PD patients with the paradigm in Experiment 1 will show if the BG is selectively involved in beat prediction and not finding the beat.

The results in Experiment 1 suggest a common timing mechanism controlling perception and production of the beat. There was a significant correlation between perception BAT and production BAT, suggesting that strong beat-perceivers have lower synchronization variability than weak beat-perceivers. A similar trend was shown in Experiment 2 as strong beat-perceivers showed lower CDEV values during walking than weak beat-perceivers. Many studies use auditory stimuli as cues for gait rehabilitation in clinical populations with disordered walking, such as PD patients. However, the effect of individual differences in beat perception on gait synchronization to rhythmic auditory cues has yet to be examined. The current findings suggest that healthy participants vary in their ability to adjust their gait to an auditory stimulus, and variability is reduced in

strong beat-perceivers compared to weak beat-perceivers. If PD patients show the ability to perceive the beat then music therapy might be more beneficial for participants with a stronger perception of the beat than those who have a weaker perception of the beat. Therefore, future studies are needed to examine the progression of gait rehabilitation outcomes in strong and weak beat-perceivers.

Conclusions

The experiments in this thesis were designed to test beat perception, internal generation of the beat, and production of the beat to explore the relationship between each process. All tasks, with the exception of the rhythm tempo discrimination test, appeared successful in testing their respective goals. Significant correlations were found between perception, internal generation, and production of the beat. However, a few participants failed to show a correlation in performance between production and perception/internal generation. This result suggests beat perception, internal generation, and production of the beat are controlled by a common mechanism. Production of the beat may require an extra stage that perception does not use. Given no dissociation was found between perception and internal generation of the beat, it might be that PD patients perform poorly in the rhythm discrimination test because of an impaired ability to perceive or internally generate the beat. However, it might be the case that we were unable to find participants with dissociation between perception and internal generation of the beat. In addition, we sought to determine the optimal stimulus for eliciting the best synchronization to the beat. Stimuli with minimal perceptual demands and devoid of non-temporal factors were optimal for improving synchronization. Gait training in a patient

population with strong and weak beat perception abilities must be assessed to determine the viability of music as a stimulus.

References

- Artieda, J., Pastor, M., Lacruz, F., & Obeso, J. (1992). Temporal discrimination is abnormal in Parkinson's disease. *Brain*, *115*(1), 199–210.
- Bangert, A. S., Reuter-Lorenz, P. a, & Seidler, R. D. (2011). Dissecting the clock: understanding the mechanisms of timing across tasks and temporal intervals. *Acta psychologica*, *136*(1), 20–34.
- Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008). Moving on time: brain network for auditory-motor synchronization is modulated by rhythm complexity and musical training. *Journal of cognitive neuroscience*, *20*(2), 226–239.
- Chen, J. L., Zatorre, R. J., & Penhune, V. B. (2006). Interactions between auditory and dorsal premotor cortex during synchronization to musical rhythms. *NeuroImage*, *32*(4), 1771–1781.
- Church, R. M., & Broadbent, H. a. (1990). Alternative representations of time, number, and rate. *Cognition*, *37*, 55–81.
- Collier, G., & Wright, C. (1995). Temporal rescaling of simple and complex ratios in rhythmic tapping. *Journal of Experimental Psychology*, *21*(3), 606–627.
- De Bruin, N., Doan, J. B., Turnbull, G., Suchowersky, O., Bonfield, S., Hu, B., & Brown, L. A. (2010). Walking with music is a safe and viable tool for gait training in Parkinson's disease: the effect of a 13-week feasibility study on single and dual task walking. *Parkinson's disease*, 483530.
- Ellis, D. P. W. (2007). Beat Tracking by Dynamic Programming. *Journal of New Music Research*, *36*(1), 51–60.

- Essens, P. J., & Povel, D. J. (1985). Metrical and nonmetrical representations of temporal patterns. *Perception & psychophysics*, *37*(1), 1–7.
- Gibbon, J., Malapani, C., Dale, C. L., & Gallistel, C. (1997). Toward a neurobiology of temporal cognition: advances and challenges. *Current opinion in neurobiology*, *7*(2), 170–184.
- Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of cognitive neuroscience*, *19*(5), 893–906.
- Grahn, J. A., & Brett, M. (2009). Impairment of beat-based rhythm discrimination in Parkinson's disease. *Cortex*, *45*(1), 54–61.
- Grahn, J. A., & Rowe, J. B. (2012). Finding and Feeling the Musical Beat: Striatal Dissociations between Detection and Prediction of Regularity. *Cerebral cortex*, *23*(4), 913–921.
- Grahn, J., & Schuit, D. (2012). Individual Differences in Rhythmic Ability: Behavioral and Neuroimaging Investigations. *psychomusicology*, *22*(2), 105–121.
- Graybiel, A. M. (1998). The basal ganglia and chunking of action repertoires. *Neurobiology of learning and memory*, *70*(1-2), 119–136.
doi:10.1006/nlme.1998.3843
- Grube, M., Cooper, F. E., Chinnery, P. F., & Griffiths, T. D. (2010). Dissociation of duration-based and beat-based auditory timing in cerebellar degeneration. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(25), 597–601.
- Grube, M., Lee, K. H., Griffiths, T. D., Barker, A. T., & Woodruff, P. W. (2010). Transcranial magnetic theta-burst stimulation of the human cerebellum distinguishes

- absolute, duration-based from relative, beat-based perception of subsecond time intervals. *Frontiers in psychology*, *1*, 171.
- Hickok, G., Buchsbaum, B., Humphries, C., & Muftuler, T. (2003). Auditory-motor interaction revealed by fMRI: speech, music, and working memory in area Spt. *Journal of cognitive neuroscience*, *15*(5), 673–682.
- Hove, M. J., Suzuki, K., Uchitomi, H., Orimo, S., & Miyake, Y. (2012). Interactive rhythmic auditory stimulation reinstates natural 1/f timing in gait of Parkinson's patients. *PloS one*, *7*(3), 1–8.
- Iversen, J. (2008). The Beat Alignment Test (BAT): Surveying beat processing abilities in the general population. *Proceedings of the 10th International Conference on Music and Cognition*, 465–468.
- Ivry, R. B., & Hazeltine, R. E. (1995). Perception and production of temporal intervals across a range of durations: evidence for a common timing mechanism. *Journal of experimental psychology. Human perception and performance*, *21*(1), 3–18.
- Janata, P., Tomic, S. T., & Haberman, J. M. (2012). Sensorimotor coupling in music and the psychology of the groove. *Journal of experimental psychology. General*, *141*(1), 54–75.
- Keele, S., Pokorny, R., Corcos, D., & Ivry, R. (1985). Do perception and motor production share common timing mechanisms: A correlational analysis. *Acta psychologica*, *60*, 173–191.
- Large, E., & Jones, M. (1999). The dynamics of attending: How people track time-varying events. *Psychological review*, *106*(1), 119–159.

- Large, E. W., & Palmer, C. (2002). Perceiving temporal regularity in music. *Cognitive Science*, 26(1), 1–37.
- Large, E. W., & Snyder, J. S. (2009). Pulse and meter as neural resonance. *Annals of the New York Academy of Sciences*, 1169, 46–57.
- Lim, I., van Wegen, E., de Goede, C., Deutekom, M., Nieuwboer, A., Willems, A., Kwakkel, G. (2005). Effects of external rhythmical cueing on gait in patients with Parkinson's disease: a systematic review. *Clinical Rehabilitation*, 19(7), 695–713.
- Madison, G. (2006). Experiencing groove induced by music: consistency and phenomenology. *Music perception*, 24(2), 201–209.
- Madison, G., Gouyon, F., Ullén, F., & Hörnström, K. (2011). Modeling the tendency for music to induce movement in humans: first correlations with low-level audio descriptors across music genres. *Journal of experimental psychology: Human perception and performance*, 37(5), 1578–1594.
- McIntosh, G., & Brown, S. (1997). Rhythmic auditory-motor facilitation of gait patterns in patients with Parkinson's disease. *Journal of Neurology*, 62, 22–26.
- Moelants, D. (2002). Preferred tempo reconsidered. *Proceedings of the 7th International Conference on music perception and cognition*, 580–583.
- Nessler, J. A., Kephart, G., Cowell, J., & De Leone, C. J. (2011). Varying treadmill speed and inclination affects spontaneous synchronization when two individuals walk side by side. *Journal of applied biomechanics*, 27(4), 322–9.
- Pastor, M., Artieda, J., Jahanshahi, M., & Obeso, J. (1992). Time estimation and reproduction is abnormal in Parkinson's disease. *Brain*, 115(1), 211–225.

- Povel, D. J. (1981). Internal representation of simple temporal patterns. *Journal of experimental psychology. Human perception and performance*, 7(1), 3–18.
- Povel, D. J., & Okkerman, H. (1981). Accents in equitone sequences. *Perception & psychophysics*, 30(6), 565–572.
- Repp, B. (2010). Do metrical accents create illusory phenomenal accents ? *Attention, Perception, & Psychophysics*, 72(5), 1390–1403.
- Repp, B. H. (2005). Sensorimotor synchronization: a review of the tapping literature. *Psychonomic bulletin & review*, 12(6), 969–992.
- Repp, B. H. (2007). Tapping to a very slow beat: A comparison of musicians and nonmusicians. *Music Perception*, 24(4), 367–377.
- Repp, B. H. (2010). Sensorimotor synchronization and perception of timing: effects of music training and task experience. *Human movement science*, 29(2), 200–213.
- Repp, B. H., & Su, Y.-H. (2013). Sensorimotor synchronization: A review of recent research (2006-2012). *Psychonomic bulletin & review*, 20(3), 403–452.
- Roerdink, M., Bank, P. J. M., Peper, C. L. E., & Beek, P. J. (2011). Walking to the beat of different drums: practical implications for the use of acoustic rhythms in gait rehabilitation. *Gait & posture*, 33(4), 690–4.
- Schubotz, R. I., Friederici, a D., & von Cramon, D. Y. (2000). Time perception and motor timing: a common cortical and subcortical basis revealed by fMRI. *NeuroImage*, 11(1), 1–12.
- Snyder, J., & Krumhansl, C. (2001). Tapping to ragtime: Cues to pulse finding. *Music Perception*, 18(4), 455–489.

- Snyder, J. S., Hannon, E., Large, E., & Christiansen, M. (2006). Synchronization and continuation tapping to complex meters. *Music Perception, 24*(2), 135–146.
- Spaulding, S. J., Barber, B., Colby, M., Cormack, B., Mick, T., & Jenkins, M. E. (2013). Cueing and gait improvement among people with Parkinson's disease: a meta-analysis. *Archives of physical medicine and rehabilitation, 94*(3), 562–570.
- Styns, F., van Noorden, L., Moelants, D., & Leman, M. (2007). Walking on music. *Human movement science, 26*(5), 769–785.
- Teki, S., Grube, M., Kumar, S., & Griffiths, T. D. (2011). Distinct neural substrates of duration-based and beat-based auditory timing. *The Journal of neuroscience : the official journal of the Society for Neuroscience, 31*(10), 3805–3812.
- Thaut, M H, McIntosh, G. C., & Rice, R. R. (1997). Rhythmic facilitation of gait training in hemiparetic stroke rehabilitation. *Journal of the neurological sciences, 151*(2), 207–212.
- Thaut, M H, Miller, R. A., & Schauer, L. M. (1998). Multiple synchronization strategies in rhythmic sensorimotor tasks: phase vs period correction. *Biological cybernetics, 79*(3), 241–250.
- Thaut, M. (2003). Neural basis of rhythmic timing networks in the human brain. *Annals of the New York Academy of Sciences, 999*, 364–373.
- Thaut, M. H., Rathbun, J. A., & Miller, R. A. (1997). Music versus metronome timekeeper in a rhythmic motor task. *International Journal of Arts Medicine, 5*, 4–12.

- Thaut, M., McIntosh, G., Rice, R., Miller, R., Rathbun, J., & Brault, J. (1996). Rhythmic auditory stimulation in gait training for Parkinson's disease patients. *Movement Disorders, 11*(2), 193–200.
- Tomic, S. T., & Janata, P. (2008). Beyond the beat: modeling metric structure in music and performance. *The Journal of the Acoustical Society of America, 124*(6), 4024–4041.
- Van Noorden, L., & Moelants, D. (1999). Resonance in the perception of musical pulse. *Journal of New Music Research, 28*(1), 43–66.
- Wittwer, J. E., Webster, K. E., & Hill, K. (2012). Music and metronome cues produce different effects on gait spatiotemporal measures but not gait variability in healthy older adults. *Gait & posture, 37*(2), 219–222.
- Yahalom, G., Simon, E. S., Thorne, R., Peretz, C., & Giladi, N. (2004). Hand rhythmic tapping and timing in Parkinson's disease. *Parkinsonism & related disorders, 10*(3), 143–148.

**Appendix
Appendix A**

Table 1. *Correlational Matrix*

Task	Condition in task	1	2	3	4	5	6	7	8	9	10
Perception BAT	1) Perception BAT	-									
Intensity threshold test	2) M _{Son} - M _{Soff}	0.235	-								
	3) M _{Son} - MC	0.203	.447**	-							
	4) M _{Soff} - MC	-0.049	-.589**	.460**	-						
Metronome tempo discrimination test	5) Metronome	.364*	0.218	0.124	-0.104	-					
Rhythm tempo discrimination test	6) Rhythm tempo MS	0.198	0.121	0.189	0.05	.330*	-				
	7) Rhythm tempo MC	0.026	0.218	-0.007	-0.222	0.268	.407**	-			
Production BAT	8) Production BAT	-.467**	-0.039	-0.223	-0.163	-.312*	-.343*	-0.084	-		
Rhythm discrimination test	9) Rhythm MS	.360*	0.061	0.155	0.08	0.224	.319*	0.185	-.305*	-	
	10) Rhythm MC	0.24	0.085	.306*	0.192	.311*	0.294	0.16	-.304*	.521**	-

Note: Values represent correlation coefficients (r). Rhythm MS and rhythm MC represent MS and MC conditions with the rhythm discrimination task. Rhythm tempo MS and rhythm tempo MC represent MS and MC conditions within the rhythm tempo discrimination task. Difference scores between each condition in the intensity threshold test were to correlate with the other test conditions. Negative correlations are seen in the production BAT as smaller CDEV scores represent accurate synchronization. * $p < 0.05$, ** $p < 0.01$.

Appendix B

Ethics



Department of Psychology The University of Western Ontario
 Room 7418 Social Sciences Centre,
 London, ON, Canada N6A 5C1
 Telephone: (519) 661-2067 Fax: (519) 661-3961

Use of Human Subjects - Ethics Approval Notice

Review Number	12 10 04	Approval Date	12 10 09
Principal Investigator	Jessica Grahn/Taylor Parrott	End Date	13 04 30
Protocol Title	Examining memory for beat based rhythms		
Sponsor	n/a		

This is to notify you that The University of Western Ontario Department of Psychology Research Ethics Board (PREB) has granted expedited ethics approval to the above named research study on the date noted above.

The PREB is a sub-REB of The University of Western Ontario's Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB) which is organized and operates according to the Tri-Council Policy Statement and the applicable laws and regulations of Ontario. (See Office of Research Ethics web site: <http://www.uwo.ca/research/ethics/>)

This approval shall remain valid until end date noted above assuming timely and acceptable responses to the University's periodic requests for surveillance and monitoring information.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the PREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of research assistant, telephone number etc). Subjects must receive a copy of the information/consent documentation.

Investigators must promptly also report to the PREB:

- a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
- b) all adverse and unexpected experiences or events that are both serious and unexpected;
- c) new information that may adversely affect the safety of the subjects or the conduct of the study.

If these changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the newly revised information/consent documentation, and/or advertisement, must be submitted to the PREB for approval.

Members of the PREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the PREB.

Chair, Psychology Expedited Research Ethics Board (PREB)

The other members of the 2012-2013 PREB are: Mike Atkinson (Introductory Psychology Coordinator), Rick Goffin, Riley Hinson Albert Katz (Department Chair), Steve Lupker, and TBA (Graduate Student Representative)

CC: UWO Office of Research Ethics

This is an official document. Please retain the original in your files

Appendix C

Letter of Information and Participant Consent

Letter of Information – Music Memory

Title of Research:

Examining memory for beat based rhythms

This study is investigating the flexibility of beat perception in the auditory modality and is being conducted by Taylor Parrott and Dr. Jessica Grahn.

During this study, you will be asked to complete a series of rhythmic tasks. The first five tasks will require you to listen to a variety of rhythmic sequences and either detect a beat, or detect a change in a given musical parameter such as tempo. The sixth task is a rhythm production task that will require you to tap along to a variety of music clips to the best of your ability. All tasks will be clearly explained, and all of your responses will be made using a computer keyboard.

The information gathered in this study is kept confidential and anonymous and is used for research purposes only. The study will take approximately one hour and a half to complete, and participants will receive compensation of one and a half credit for their participation. Participants are free to refuse response to any questions and are free to withdraw from the experiment at any time without loss of promised compensation. There are no known risks to participating in this study.

Upon completion of the study, you will be asked if you would like to return for a follow-up study if you meet a certain criteria. You will also receive a debriefing form that will educate you about this experiment. At this time, you will also have the chance to ask any questions in regards to the study answered.

Should you have any further questions or concerns regarding this study, please contact the principle investigators. If you have any questions about the conduct of this study or your rights as a research participant you may contact the Office of Research Ethics, The University of Western Ontario.

Letter of Information – Sensor Walkway

Title of Research:

Examining memory for beat based rhythms

This study is investigating the flexibility of beat perception in the auditory modality and is being conducted by Taylor Parrott and Dr. Jessica Grahn.

During this study, you will be asked to rate various music characteristics on a scale from 1-10. Once you have rated all the clips, you will walk on a sensor walkway while listening to different kinds of music. Responses will be made on a keyboard and gait parameters will be measured using a sensor walkway.

The information gathered in this study is kept confidential and anonymous and is used for research purposes only. The study will take approximately one hour and a half to complete, and participants will receive compensation of one and a half credit for their participation. Participants are free to refuse response to any questions and are free to withdraw from the experiment at any time without loss of promised compensation. There are no known risks to participating in this study.

Upon completion of the study, you will receive a debriefing form that will educate you about this experiment. At this time, you will also have the chance to ask any questions in regards to the study.

Should you have any further questions or concerns regarding this study, please contact principle investigators. If you have any questions about the conduct of this study or your rights as a research participant you may contact the Office of Research Ethics, The University of Western Ontario.

Consent Statement

Title of Research:
Examining memory for beat based rhythms

Research Investigators:

I have read the Letter of Information, have had the nature of the study explained to me, and I agree to participate. All questions have been answered to my satisfaction.

Participant's Name (Please Print)

Participant's Signature

Date

Researcher's Name (Please Print)

Researcher's Signature

Date

Curriculum Vitae

- Name:** Taylor Parrott
- Post-secondary Education and Degrees:** The University of Western Ontario
London, Ontario, Canada
2007-2011 B.M.Sc. (Honors Specialization)
- The University of Western Ontario
London, Ontario, Canada
2011-2013 M.Sc. (Neuroscience)
- Honours and Awards:** Graduate Teaching Assistant Scholarship nominee
2011-2012
- Western Graduate Research Stipends
2011-2013
- Related Work Experience:** Research Assistant
The University of Western Ontario
2006-2007
- Graduate Teaching Assistant
The University of Western Ontario
2011-2013
- Invited Speaker
The University of Western Ontario
2012
- Presentations:**
- Parrott, T.,** Grahn, A. J. (2012). Examining memory for beat based rhythms. Poster presentation at Canadian Society for Brain, Behaviour and Cognitive Science, Kingston, Ontario.
- Parrott, T.,** Watson, S., Grahn, A. J. (2013). How metrical structure affects detection of volume changes. Poster presentation at Lake Ontario Visionary Establishment, Niagara, Ontario.