BEAT PERCEPTION AND SYNCHRONIZATION ABILITIES IN CHILDREN

BEAT PERCEPTION AND SYNCHRONIZATION ABILITIES IN YOUNG CHILDREN

By

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Abstract

Even without formal training, adults can easily perceive, clap, tap, and move in time to a musical beat, but these behaviours are more difficult for children and the development of these abilities in childhood is not well understood. Until the present thesis, there were no developmentally appropriate tasks to separately assess musical beat perception and beat synchronization in children. In Chapter 2, I created a child friendly video judgment task to assess beat perception in the context of both simple and complex musical timing, and demonstrated that five-year-old children's ability to perceive both tempo- and phase-driven beat misalignments is affected by metric complexity. In Chapter 3, I again used the complex Beat Alignment Task (cBAT) to show that the detection of beat misalignment is not significantly affected by the inclusion of dynamic video stimuli compared to static images. Chapter 4 expanded the perception task by adding a tapping synchronization component, and tested both five- and seven-year-old children. The complex Beat Alignment and Tapping Task (cBATT) showed that although children's overall perceptual sensitivity improves with age, the perceptual bias for simple structures persists. However, although children were significantly better at tapping to metronomes than to songs, musical tapping synchronization was not obviously affected by metric complexity. Instead, performance related to other acoustic characteristics of the music, such as spectral flux, energy, and density. Together, these findings suggest that musically untrained children are sensitive to phase and tempo information in a perception-only task, and show perceptual specialization for culturally typical musical metres, but this is not the case for production. Thus, beat synchronization ability appears to be somewhat dissociated from beat perception in children. These studies represent the first use of a developmentally appropriate task to separately assess children's beat perception and synchronization while also examining the role of metre and early experience.

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On a day-to-day basis my time at McMaster was shaped most by the amazing people in the lab. In my early days, Katie, Rayna, Andrea, Blake, and Nicole taught me everything I needed to know about Trainorlab, the department, and life as a grad student. Later on, I was lucky to be surrounded by people like Laura, Haley, Andrew, Susan, and Sarah. Very special acknowledgement must go to Elaine, and to Dave, both of whom shared almost every moment of my years here – I absolutely couldn’t have done it without their expertise, or their kindness. And let us not forget the fantastic people who were not lab members at all, Tiff, Amy and Warren (and Julia!), Vivian, Dominique, and Savitri among them.

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Table of Contents

List of Figures

List of Tables

Declaration of Academic Achievement

This dissertation is organized in the sandwich format, as approved by the McMaster University School of Graduate Studies, and is comprised of five chapters. Each of the three empirical chapters (Chapters 2 through 4) constitutes a complete manuscript, either published or in preparation for submission. Chapters 2 and 3 have been previously published as peer-reviewed articles. In these chapters, the publication pages have been reformatted and renumbered for continuity within this dissertation, but the notation and references conventions of each journal have been retained. These publications are reprinted with permission from the copyright holders. Chapter 4 is a manuscript that has been prepared for submission.

I, Kathleen Einarson, am the primary author of each of the three manuscripts. As the creator of the complex Beat Alignment Test (cBAT) and complex Beat Alignment and Tapping Task (cBATT), I developed each research question and experimental paradigm in this dissertation in consultation with my doctoral supervisor, Laurel Trainor. I created the stimuli, collected the data myself and also in collaboration with undergraduate students completing work for academic credit within the Trainor Lab and under my direct supervision. Raw data were processed with the assistance of research staff member Dave Thomson, who also assisted with figure creation. Subsequently, I analyzed the data, and wrote each chapter presented herein. These three manuscripts accurately reflect my doctoral research, and therefore, they comprise the main body of this dissertation.

The chapters of the present dissertation are as follows:

CHAPTER 1: General Introduction

I am the sole author of this chapter.

CHAPTER 2: Einarson, K. M. & Trainor, L. J. (2016). Hearing the beat: Young children's perceptual sensitivity to beat alignment varies according to metric structure. *Music Perception, 34*(1), 56-70.

Research Conducted: 2011-12 (Experiment One); 2014-15 (Experiment Two)

CHAPTER 3: Einarson, K. M., & Trainor, L. J. (2015). The effect of visual information on young children's perceptual sensitivity to musical beat alignment. *Timing and Time Perception, 3*(1-2), 88-101.

Research Conducted: 2012-13

CHAPTER 4: Einarson, K. M., & Trainor, L. J. (in prep). Development of beat perception and synchronization in young children: examining effects of metric complexity and acoustic structure using the complex Beat Alignment and Tapping Test (cBATT)

Research Conducted: 2013-14 (Five-year-olds); 2014-15 (Seven-year-olds)

CHAPTER 5: General Discussion

I am the sole author of this chapter.

CHAPTER 1: Introduction

Processing and responding to streams of information that unfold over time is an essential component of the human experience. Every day, individuals engage in a wide variety of activities like talking and listening in conversation, moving in space from one place to another, and interacting with those around them (Zacks & Tversky, 2001). Each of these activities requires varying degrees of temporal coordination by single individuals, and often demands interpersonal coordination between two or more people. This is also true in another universal human pursuit where timing plays an essential role: music.

Music is a universal human behaviour, although musical structure varies cross-culturally. It has been argued that music's temporal structure is more fundamental than any of its other defining characteristics, such as pitch or timbre (Hannon & Trainor, 2007). Music is believed to have evolved as an essential component of complex human social behaviour, and timing structure provides the foundation for most shared musical behaviours. It would not be possible to sing, play instruments in a group, or to dance with one another without the ability to perceive and entrain to music's underlying temporal structure. However, the mechanisms underlying the ability to perceive and entrain to a beat are remarkably complex.

The temporal structure of musical systems: Beat, rhythm, and metre

The presence of a steady (*isochronous*) beat is thought to be near universal in human music (Savage, Brown, Sakai, & Currie, 2015) and the tendency to move in synchrony with a musical beat is also universal across human cultures (Nettl, 1983). However, this universality belies the complexity of both beat perception and beat synchronization behaviours, as well as the complexity of music more broadly; perception and synchronization require sensitivity to rhythm, beat, and metre, as well as the coordination of auditory perception, motor movement, and evaluative judgment. The ability to synchronize to a beat is rare in non-human animals (e.g. Large & Palmer, 2002), although it has been recently observed in some vocal-learning birds (e.g. Patel, Iversen, Bregman, & Schulz, 2009) and sea lions (Cook, Rouse, Wilson, & Reichmuth, 2013).

The surface-level pattern of sounds and silences makes up music's *rhythm*, and the listener infers the underlying beat based on this rhythmic pattern (Povel, 1981). It has been proposed that this beat serves as the cognitive framework around which listeners structure their comprehension of musical timing structures (Povel, 1981; Povel & Essens, 1985). Generally, this temporal framework of beats is hierarchically organized, with lower levels of the metrical hierarchy nested into higher levels (Jones, 1976) and, generally, at least one level of the hierarchy contains equally-spaced or isochronous beats. The *tactus beat level* of a particular piece is the beat tempo at which people most often clap their hands or tap their feet to that music. Beats at that level can be subdivided into smaller units forming a nested beat level at a faster tempo of the hierarchy. As well, two or three beats at the tactus level can be grouped together, forming larger units at a slower tempo of the hierarchy.

The ability to perceive the underlying steady repeating and predictable beat levels in music requires the listener to perceptually abstract the metrical hierarchy from the surface structure (Lerdahl & Jackendoff, 1983). This is evident in that a sound event may not necessarily be present on every beat, since beats can also be perceived during silences. Beats can be accented or unaccented, and accented beats typically occur in a regular pattern; the spacing and organization of accented beats determines music's *metre* and *metrical hierarchy* (London, 2012).

Most Western music uses so-called *simple* metric structures where accents occur on either every second beat (called *duple* metre, as in a march) or on every third beat (called *triple* metre, as in a waltz). These types of metric structures are referred to as simple because the recurring accents are always isochronous or equally spaced. However, music from other regions and cultures, including the Balkan region of Eastern Europe and some regions of Africa, Asia, and Latin America, employ *complex* metres (Rice, 1994). These metres are defined by accents that are not equally spaced (that is, *non-isochronous)* at some level of the metrical hierarchy, because they combine the isochronous beat into regular patterns of accented two-beat and three-beat groups to form repeating units of five, seven, and eleven beats, for example.

Beat perception and culture-general processing of music timing

It is interesting to note that although most people can both perceive and synchronize to a beat with ease, this ability has been documented in only a very limited number of non-human animals to date, including vocal learning birds (Patel, Iversen, Bregman, & Schulz, 2009), elephants (Schachner, Brady, Pepperberg, & Hauser, 2009), a sea lion (Cook, Rouse, Wilson, & Reichmuth, 2013), and possibly non-human primates (Hattori, Tomonaga, & Matsuzawa, 2013; Large & Gray, 2015). However, as noted by Kirschner and Ilari (2013), to date none of these animals has been observed synchronizing with rhythmic sounds in the wild. Thus, the widespread and spontaneous synchronization behaviour observed in humans remains somewhat unique.

A central theoretical issue when assessing timing perception is how our perceptual system measures time. There are two competing models to account for how we perceive time: information processing models, including interval theories (Gibbon, 1977; Wing & Kristofferson, 1973), and alternately, oscillator or dynamic entrainment theories (Large & Jones, 1999; Jones, 1976).

Interval theories posit a central internal clock that measures discrete time units. In this model, variability in human sensorimotor synchronization can be attributed to two sources: variance in the internal clock and variance in motor execution. Target time intervals in the 'clock' stage are represented based on estimates of interval duration, and then these individual estimates are stored in memory. The duration of subsequent intervals are compared to the stored reference estimates, and error correction happens on a cycle-to-cycle basis. Peripheral (motor) variability is related to response delays in the execution of repetitive motor movements; these delays are assumed to be random (Torre & Balasubramaniam, 2009). This model predicts that motor variability remains constant and does not vary systematically as the target inter-tap interval changes in size, whereas central (i.e. clock) variability increases at slower tempi (Wing & Kristofferson, 1973; Vorberg & Wing, 1996).

Entrainment theory, on the other hand, is based on a dynamic systems model. Oscillator processes are widespread in the nervous system, and manage communication between brain circuits, for example. According to entrainment theory, an external rhythm drives the moment-to-moment synchronization of an internal, self-sustaining oscillation of selective (focal) attention or attunement (Jones, 1976). In the case of music, the musical rhythm is the external stimulus that provokes entrainment of neural oscillatory circuits in the listener's brain. Rather than engaging in explicit comparison with a reference stored in memory, listeners make judgments about intervals based on how their internal (driven) rhythmic oscillators synchronize with the external (driving) rhythm (Jones & Boltz, 1989).

One perspective is that information processing and dynamic attending models are both valid approaches but account for different aspects of sensorimotor synchronization (Torre & Balasubramaniam, 2009). Indeed, research indicates that different parts of the brain are involved in the discrimination of differences in duration and the processing of beats (Cameron & Grahn, 2014a; Teki, Grube, Kumar, & Griffiths, 2011).

Of importance with respect to the present thesis, beat perception is not only universal across human cultures, but it develops very early; even newborn infants can detect the beat in a rhythm pattern (Winkler, Háden, Ladinig, Sziller, & Honing, 2009). At the same time, learning plays a role in beat perception. Although a steady beat is used in every known musical tradition at least at some level of the metrical hierarchy, timing perception in adults also varies as a function of training (Cameron & Grahn, 2014b; Drake, 1993) and musical culture (e.g., Hannon, Soley & Ullal, 2012; Hannon & Trehub, 2005b; Cameron, Bentley, & Grahn, 2015). Because beats are regular, beat perception differs from duration perception in that upcoming beats can be predicted. To detect regular relationships between successive events, preceding events must be assessed and expectations then generated about future events.

Even young infants possess sophisticated temporal processing abilities, and are quite sophisticated at statistical learning and pattern detection. For example, newborn infants can detect omitted downbeats in a rhythmic sequence (Winkler et al., 2009), 5-month-olds can tell apart simple rhythms (Chang & Trehub, 1977), and 6-month-old infants extract metric grouping patterns (Hannon & Trehub, 2005a) and detect statistical patterns in accent structures (Hannon & Johnson, 2005).

Sensorimotor synchronization and multisensory integration

In adults, spontaneous beat-based movements can include head nodding, foot tapping, clapping, and dancing, and even untrained adults synchronize these rhythmic movements to the beat (Nettl, 1983). Because of the ease with which adults generate these synchronized movements, beat perception is typically assessed in adults via sensorimotor synchronization (SMS) tasks.

This vast majority of this work relies on laboratory-based tasks where simple movements like finger tapping (see Repp, 2005 and Repp & Su, 2013, for reviews) are synchronized with pacing stimuli, although sometimes a musical instrument is used, such as a piano (Loehr & Palmer, 2009; Palmer, Koopmans, Loehr, & Carter, 2009) or drums (Manning & Schutz, 2016). Other investigations of synchronization have involved the entire body in tasks such as synchronized walking (Wiltermuth & Heath, 2009; van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008) or rocking in a chair (Demos, Chaffin, Begosh, Daniels, & Marsh, 2011). Motor performance is taken as an index of perceptual sensitivity in these tasks, meaning that by their nature these tasks confound perception with action.

Adults are capable of synchronizing their tapping to an isochronous beat across a wide range of tempos, although synchronization becomes difficult to tempos slower than approximately 30 beats per minute (bpm); this is equivalent to an intertap interval (ITI) of 2000 milliseconds, i.e., 2 seconds (Fraisse, 1982). At its fastest, human tapping seems limited largely by the ability to execute the required motor gestures, and this limit has been reported to be approximately 5 to 7 taps per second, equivalent to an ITI of 150 to 200 ms (Peters, 1982). Adults with musical training exhibit demonstrably better performance on SMS tasks (Cameron & Grahn, 2014b; Drake, Jones, & Baruch, 2000; Repp, London, & Keller, 2013) than untrained adults, tapping at a wider range of speeds and with lower variability (Drake, Penel, & Bigand, 2000).

Children, by comparison, are only able to synchronize their tapping within a much narrower range of speeds, and only when the metrical structure is simple (Drake, Jones, & Baruch, 2000). Although they are sensitive to changes in tempo, and may speed up movements in response to tempo changes even in early infancy (Bobin-Begue, Provasi, Marks & Pouthas, 2006), children are generally not able to synchronize their tapping outside a narrow range of approximately 400 to 500ms ITI until they are older (van Noorden, De Bruyn, van Noorden, & Leman, in prep). By age seven, untrained children's tapping has been reported to reach adult-like levels (McCauley, Jones, Holub, Johnston, & Miller, 2006; cf. Drake, Jones, & Baruch, 2000). Experience and training improve synchronization abilities in children (Drake, 1993; Slater, Tierney, & Kraus, 2013).

Children are most successful at synchronizing their tapping when the speed of the pacing stimulus is close to children's naturally occurring spontaneous motor tempo, or SMT (Provasi & Bobin-Begue, 2003). Spontaneous motor tempo is assessed by asking participants to tap steadily at a rate that feels comfortable to them in the absence of a pacing stimulus. Four-year-old children's SMT is approximately 400ms, equivalent to a 150 bpm (Drake, Jones, & Baruch, 2000). This is significantly faster than the SMT for adults, whose SMT is closer to 600ms or 100 bpm (McAuley et al., 2006; Fraisse, 1982).

Children younger than age four are also sensitive to the relation between auditory rhythms and movement; a musical stimulus provokes periodic movement by infants, including rhythmic sucking (Bobin-Begue, Provasi, Marks & Pouthas, 2006) and kicking of feet or other rhythmic movements (Zentner & Eerola, 2010). Some toddlers display bouncing, swaying, or jumping movements when exposed to music (Eerola, Luck, & Toiviainen, 2006). However, infants' and young children's movements are not typically matched to the tempo of the music presented, although they may speed up when stimulus tempo increases (Bobin-Begue, et al., 2006; Zentner & Eerola, 2010). Movements are also not phase-locked, although performance improves significantly in the presence of a social partner who is also tapping to the music (Kirschner & Tomasello, 2009; Kirschner & Ilari, 2013).

Difference in the variability of motor output between children and adults in synchronization is also of interest. Synchronization performance is highly variable in young children (Drewing, Aschersleben, & Li, 2006). Variability decreases throughout childhood, and remains relatively constant throughout adulthood (McAuley et al., 2006).

Variability when performing synchronization tasks may be high in childhood, at least in part due to motor immaturity and emerging motor skills. Other motor skills such as drawing (Ferrel-Chapus, Hay, Olivier, Bard, & Fleury, 2002), pointing (Lambert & Bard, 2005), and clapping (Fitzpatrick, Schmidt, & Lockman, 1996) also improve substantially between the ages of 5 and 12 before reaching adult-like levels in adolescence.

Adults' entrainment shows another interesting feature. Adults tend to tap slightly ahead of the beat. In fact, both musicians and non-musicians tend to anticipate the beat by 20 to 80ms when tapping along (Aschersleben, 1992), although this anticipatory negative asynchrony has not been observed in children below the age of five (Kirschner & Tomasello, 2009; Kirschner & Ilari, 2013).

By definition, sensorimotor synchronization is a multimodal behaviour requiring integration of the auditory and motor systems. Interestingly, allowing people to move to the beat compared to being stationary improves both novice and expert listeners' ability to locate the pulse in ambiguous sequences (Su & Pöppel, 2012), and helps listeners to judge the timing of intervals (Butler, & Trainor; 2015; Manning & Schutz, 2013, 2015). Not only can body movement improve auditory judgments, it can also alter them. Whole-body movement that induces vestibular stimulation influences the perception of accent structure in ambiguous rhythms for both infants (Philips-Silver & Trainor, 2005) and adults (Philips-Silver & Trainor, 2007).

In humans, there is a close connection between the auditory and motor systems; adults are better able to entrain to an auditory beat than a visual beat that is equally patterned and predictable (Patel, Iversen, Chen & Repp, 2005). Although some studies have found that synchronization to rhythmic tactile information is quite good for simple rhythms (Ammirante, Patel, & Russo, 2016), the advantage for auditory synchronization persists for more complex stimuli. The auditory and motor areas of the brain are so closely linked that listening to a steady beat induces brain activity not only in the auditory cortex but also in motor areas of the brain (Chen, Penhune, & Zatorre, 2008), even when participants are not physically moving, or even intending to move (Grahn & Brett, 2007; Fujioka, Trainor, Large, & Ross, 2012).

Perceptual specialization and musical enculturation

In vast majority of the research described so far, subjects tap either to isochronous metronomes or to musical stimuli with isochronously spaced accents, that is, music with simple metric structure. Complex musical metres with unequally spaced non-isochronous accents are much less common in the music of Western cultures (Palmer & Krumhansl, 1990). As such, most studies in the past century have looked at beat synchronization skills in adults in the context of simple metre music (e.g. Dunlap, 1910; Fraisse, Oleron, & Paillard, 1958; Woodrow, 1932; Drake, 1993; Iversen & Patel, 2008). Although it has been proposed that humans possess an innate processing bias for durations related by simple compared to complex ratios (Drake & Bertrand, 2001), more recently, biases for simple metre in Western listeners have been attributed to musical enculturation, a form of the more general developmental process of perceptual specialization.

Perceptual specialization is a domain-general experience-driven process whereby infants become attuned to auditory and visual stimuli that occur frequently in their native environment (see Scott, Pascalis & Nelson, 2007, and Maurer & Werker, 2014, for reviews). The idea is that infants are born able to process a diversity of perceptual contrasts (Trehub, 1976), but through exposure to particular socially relevant stimuli in their environment become better at perceptual contrasts that matter and worse at perceptual contrasts that do not matter. Specifically, as infants acquire day-to-day experience with language, faces, voices, or other stimuli like music, their discrimination of relevant contrasts improves. By comparison, their ability to distinguish non-native stimuli gradually worsens (see Lewkowicz & Ghazanfar, 2009 for review).

This process takes place during the first year after birth, with the most well studied type of specialization being for the speech sounds in one's native language (Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005; Kuhl, Stevens, Hayashi, Deguchi, Kiritani, & Iverson, 2006; Trehub, 1976; Werker & Tees, 1984; for reviews see Curtin & Werker, 2007; Kuhl, 2004, 2008). However, infants also become better at discriminating individual faces of their own race and worse at discriminating faces of a foreign race to which they are rarely exposed (Kelly, Liu, Lee, Quinn, Pascalis, Slater, & Ge, 2009; Kelly, Quinn, Slater, Lee, Ge, & Pascalis, 2007; Simpson, Varga, Frick, & Fragaszy, 2010). They also become better at discriminating individual human voices and worse at discriminating voices of another species (Friendly, Rendall, & Trainor, 2013; 2014). It is clear that this specialization process is driven by experience, because early exposure to non-native stimuli can delay or reinstate these discriminations (Friendly, Rendall, & Trainor, 2013; Hannon & Trehub, 2005b; Kuhl, Tsao, & Liu, 2003; Pascalis et al., 2005).

Perceptual specialization also occurs for several aspects of musical organization, including scale structure (Lynch & Eilers, 1992; Lynch, Eilers, Oller, & Urbano, 1990;

Trainor & Trehub, 1992) and, of particular interest to the work presented herein, metric structure (Hannon & Trehub, 2005a, b). As mentioned previously, music can have either simple or complex metric structure, with simple metres predominating in Western music. Hannon and Trehub (2005a) demonstrated that North American adults are better at detecting changes to simple metre sequences compared to complex metre sequences, but adults from Bulgaria and Macedonia, where the folk music tradition commonly employs complex metric structures, are equally good at detecting both types of alterations. The same is true of Turkish adults (Kalendar, Trehub, & Schellenberg, 2012), who also have greater experience with complex metres. Notably, six-month-old, but not 12-month-old, infants from North America were also equally sensitive to the two types of perturbations, suggesting equipotentiality early in life (Hannon & Trehub, 2005a).

This specialization process for musical timing follows a similar developmental timeline to the perceptual specialization in domains like speech processing (Scott, Pascalis, & Nelson, 2007), although the enculturation process may be accelerated by formal exposure to music in infancy (e.g. through Kindermusik classes; Gerry, Faux, & Trainor, 2010). By twelve months of age, North American infants show the same pattern of biases as adults, although at this young age infants are still receptive to conflicting input; two weeks of at-home exposure to non-isochronous complex metre music leads to a reinstatement of ability for one-year-olds but not for enculturated adults (Hannon & Trehub, 2005b). Similarly, 5-, 7-, and 9-year-old children show reduced bias after two weeks of exposure to complex metric structures, but 11-year-olds and adults maintain their biases (Hannon, Vanden Bosch der Nederlanden, & Tichko, 2012), suggesting that this plasticity diminishes with age. This research suggests that listeners gradually become enculturated as a result of this daily experience and exposure to culturally typical musical structures, and subsequently display a processing bias for these structures.

For infants, children, and adults, perception of complex metres remains largely unexamined within the field of music perception and cognition, to say nothing of more complex timing structures. For example, the perception of polyrhythms, which juxtapose two competing metres simultaneously within a musical work, remains almost utterly unstudied (cf. Vuust, Wallentin, Mouridsen, Østergaard, & Roepstorff, 2011). However, it has been established that there are limits, in that infants' equipotential processing of meters does not extend to artificially created highly complex meters (Hannon, Soley, & Levine, 2011), just as their capacity to process foreign speech sounds does not extend to arbitrary non-phonetic contrasts in speech (Werker & Lalonde, 1988).

Beyond perception, there are even fewer studies examine tapping synchronization to complex metres. However, studies to date indicate that Western adults and Western children are better at reproducing rhythms with simple than complex timing structure (Drake, 1993), and when North American adults tap in synchrony with a complex metre pattern and then continue tapping after the drum pattern stops, they are generally unable to mimic the complex timing. Instead, they produce beats in between complex metre timing ratios (e.g. 3:2) and their preferred 2:1 simple metre ratio (Snyder, Hannon, Large, & Christiansen, 2006). Compared to Indian adults who have experience with a wider variety of metric structures, North American adults are not only slower to bring their tapping into alignment with complex metres but also less likely to be affected by stimulus changes that move away from complex metric structure (Ullal-Gupta, Hannon, & Snyder, 2014), suggesting they are less robustly entrained. Although North American children have recently been shown to exhibit perceptual biases for music with simple metre (see Chapters 2 and 3 of this thesis: Einarson & Trainor, 2015, 2016; also see Hannon, Vanden Bosch der Nederlanden, & Tichko, 2012), we are aware of no work to date examining children's tapping synchronization to musical stimuli with complex metre.

Methodological issues in assessing beat perception and synchronization

Although temporal perception and auditory-motor synchronization have been studied extensively in adults (see London, 2012, Repp, 2005, Repp & Su, 2013), there is limited research into young school-age children's timing abilities. This is attributable, in part, to a lack of age-appropriate assessment techniques suitable for use with children.

There are an every-growing number of tests and measures to assess musical abilities with varying purposes. The well-known Montreal Battery for the Evaluation of Amusia (MBEA; Peretz, Champod, & Hyde, 2003) screens for musical deficits or deficiencies in typical adults, and the Clinical Assessment of Music Perception does so for adults with cochlear implants (CAMP; Kang, Nimmons, Drennan, Longnion, Ruffin, et al., 2009). Other tools assess musical aptitude (PROMS; Law & Zentner, 2012) or musical sophistication (MSI; Müllensiefen, Gingras, Musil, & Stewart, 2014), but are designed for use only with adults. Three recent tasks, the Beat Alignment Task (BAT; Iversen & Patel, 2008) and subsequent adaptations (BAASTA; Dalla Bella, Farrugia, Benoit, Begel, Verga, Harding, & Kotz, 2016; H-BAT; Fujii & Schlaug, 2013) focus specifically on timing perception and synchronization, but again, all are designed for use with adult subjects. There has been one attempt to adapt the BAT for use with infants (Patel, Iversen, Brandon, & Saffran, 2011), but we are aware of no adaptations for children to date.

The few music tasks designed to assess children (PMMA; Gordon, 1986) and adolescents (MBEMA; Peretz, Gosselin, Caron-Caplette, Trehub, & Beland, 2013) are narrow in scope, doing so exclusively in the context of Western musical norms. The MBEMA assesses rhythm in young children but ignores metre, and takes as long as 45 minutes. At the other end of the spectrum, tasks successfully used to assess language and music perception with young infants, including high-amplitude sucking (Trehub & Chang, 1997), the head turn preference procedure (Nelson, Jusczyk, Mandel, Myers, Turk, & Gerken, 1995; Trainor, Wu, & Tsang, 2004), and the conditioned head turn procedure (Folland, Butler, Smith, & Trainor, 2012; Saffran, Loman, & Robertson, 2000) are not appropriate for children, who can provide other types of responses by gesturing or speaking. There is a clear gap in the literature when it comes to assessing children's beat perception and synchronization. However, designing assessments for children can prove challenging.

Behavioural methods typically used with adults to assess different types of musical knowledge, including reaction time measures (see Bigand & Poulin-Charronnat, 2006 for a review) and probe tones (e.g. Krumhansl, 1990), generally require repeated trials over a prolonged period of time. This level of attention is difficult for young children to sustain, particularly when tasks are highly abstract. Information is often presented to adults in auditory-only formats (e.g. MBEA; Peretz, Champod, & Hyde, 2003; BAT; Iversen & Patel, 2008) without accompanying visual stimuli that would engage the child's attention fully, serve as motivation to complete a task with many trials, and make the task more concrete.

Adult tasks generally also require sophisticated behaviours that are too difficult for young children, such as consistently maintaining a motor response for sustained periods, making comparisons of several exemplars over periods of time that place demands on working memory, or using rating scales. For example, young children struggle to make evaluative judgments when simply asked to rate an unfamiliar musical exemplar as 'good' or 'bad' (Corrigall & Trainor, 2010).

An additional challenge is that many timing tasks use synchronization with an isochronous auditory stimulus, which is a motor task, as a way to index beat perception indirectly. Existing literature suggests that children's ability to produce stable, regular, and sustained fine-motor movements in response to an external auditory stimulus does not mature until at least seven or eight years of age (McAuley et al., 2006), and that the ability to adapt these responses to a wider range of tempi takes even longer (Drake et al., 2000).

Given children's comparatively immature motor skills, it is possible that measures obtained via overt motor synchrony (i.e. tapping tasks) underestimate children's perceptual sensitivity to timing generally, and to musical metres specifically (Tranchant & Vuvan, 2015). However, little work to date has attempted to dissociate perception from synchronization in young children. Taken together, these methodological challenges make clear that there is a need for age-appropriate, engaging tasks to assess children's temporal sensitivity, and to dissociate overt motor synchrony to an auditory stimulus from perceptual sensitivity to the information being presented.

This thesis seeks to assess children's beat perception and beat synchronization abilities, to explore interactions between beat perception and synchronization in childhood, and to examine the impact of musical timing structures on these sensitivities. Specifically, throughout these chapters I aim to describe the creation and expansion of a tool to assess beat perception and beat synchronization in children, as well as to explore the effects of age, metric structure, visual information, and acoustic structure on children's task performance. This is done using the complex Beat Alignment Task, or cBAT (in Chapters 2 and 3) and the expanded complex Beat Alignment and Tapping Task, or cBATT (in Chapter 4).

Significant contributions of thesis experiments

The complex Beat Alignment Test (cBAT) employed in Chapters 2 and 3 is designed to assess children's beat perception without requiring the child to produce a motor response. The task employs musical stimuli with both simple and complex metre, each with an isochronous beat superimposed in a way that is either aligned or misaligned relative to the musical excerpt. Children watch videos of puppets that appear to be producing the aligned or misaligned drumming, and judge the puppets' performance. Although the accent structures vary, with the simple metre structures having isochronous accents (on every second or third beat) but the complex metres having non-isochronous accents, in all cases the level of the metrical hierarchy where beat misalignments occur is an isochronous, steady beat.

The expanded complex Beat Alignment and Tapping Test (cBATT) used in Chapter 4 adds a production task where children engage in self-paced tapping, synchronize to a metronome at several speeds, and then synchronize their own tapping to a subset of the same excerpts used in the perception task. The cBAT and cBATT address several of the methodological challenges of assessing children's timing perception and sensorimotor synchronization, and contribute to the literature in several ways.

First, temporal misalignments in the perception task are presented for judgment within a single stimulus, since the beat being evaluated is superimposed over top of a particular musical excerpt. Thus, any individual video can be judged in isolation to determine the presence or absence of a temporal manipulation without requiring cognitively taxing comparisons between stimuli as is required, for example, in an error detection task. However, since children may find it difficult to rate a single exemplar in isolation (Corrigall & Trainor, 2010), the cBAT perception task employs paired presentation of videos to create a simple two-alternative forced-choice design.

Second, because the isochronous tone is superimposed over the beat of each musical excerpt in the perception task, there are no obvious strategies other than beat perception that could be used to judge whether the tone is correctly aligned with the pulse in the music. In other tasks assessing timing, it may be possible to use duration cues (Sowinski & Dalla Bella, 2013) or simple change detection (Hannon, et al., 2012) without truly extracting the beat from a stimulus. This makes the BAT a particularly strong candidate as a means to dissociate motor synchronization from purely perceptual sensitivity (Tranchant & Vuvan, 2015).

A third strength specific to the expanded cBATT is that in addition to the simple metronome stimuli it uses the *same* musical excerpts in the synchronization task as were employed for the perception task. This consistent stimulus set allows for more direct comparison between performance on the two halves of the task.

Finally, our task has the advantage of both brevity and simplicity, which are essential in order to obtain reliable data with children. The original BAT required no special expertise, was suitable for use with musically untrained adults (Iversen & Patel, 2008) and took less than 30 minutes for adult subjects, a fraction of the 90 minutes required for the more comprehensive MBEA. The cBAT takes less than 20 minutes, and the expanded cBATT takes less than 35 minutes to complete.

Chapters 2, 3, and 4 are aimed at addressing the issues that have limited the study of temporal sensitivity in young children, and refining our understanding of beat perception and synchronization in childhood. Chapter 2 presents a novel method for testing 5-year-old children's sensitivity to phase and tempo misalignments in both simple and complex metre music. The procedure displays videos of puppets drumming to music in a way that does or does not conform to the beat, and children award prizes to the puppets who are good drummers. The cBAT is engaging for children, uses ecologically valid musical stimuli drawn from commercially available recordings instead of beep tracks or synthesized MIDI recordings, and does not place undue demands on children's memory or cognitive skills. Using this task, Chapter 2 provides evidence for musically untrained 5-year-old children's sensitivity to both phase and tempo misalignments in the context of culturally typical simple metre music. Additionally, Chapter 3 demonstrates that children's performance on the task is not affected by the accompanying dynamic visual information (i.e., videos). It also replicates the simple metre perceptual bias that was observed in Chapter 2, a testament to the tool's replicability.

Chapter 4 extends the original task by adding a beat synchronization component to assess spontaneous motor tempo (SMT), metronome entrainment at different speeds, and the ability to synchronize with music from a variety of genres. The music for the expanded cBATT was drawn from the perception cBAT, and varied in tempo, instrumentation, timbre, and other acoustic features such as energy and event density. In addition to 5-year-olds (as in Chapters 2 and 3), this chapter also includes data from 7-year-olds in order to examine changes in both beat perception and beat synchronization with age. The cBATT synchronization task assesses entrainment not only to comparatively impoverished metronome stimuli but also in the richer context of simple and complex metre music. The tapping data in this chapter provides the first evidence that children's motor synchronization may be driven by factors other than metric structure, for example, acoustic features like event density.

This thesis contributes to our understanding of children's beat perception and synchronization abilities. Beat perception and beat synchronization are both essential to perceiving, predicting, and acting in accordance with musical timing, and thus play a fundamental role in human musical behaviour. I employ a perception-only task to assess timing perception with the youngest age group tested to date using explicit evaluative judgments. Additionally, I employ an overlapping stimulus set between perception and production tasks, allowing for comparisons of abilities in those two domains. Finally, although there are now several revisions and adaptations of the original BAT, this is the first version to examine the role of enculturation through the inclusion of culturally atypical complex metre music; this had not previously been investigated in infants, children, or adults. This thesis also provides evidence of a developmental dissociation in children's beat perception and beat synchronization abilities, and suggests that different aspects of naturalistic musical stimuli drive perception and synchronization. More generally, this thesis has implications for understanding the development of both beat perception and beat synchronization in childhood, and how these abilities are affected by metre, visual information, and acoustic structure in different contexts.

CHAPTER 2: Hearing the beat: Young children's perceptual sensitivity to beat alignment varies according to metric structure

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Preface

Adults can perceive a regular beat in music with ease, and sensitivity to timing information more generally is an essential human skill. Generally, humans are also good at synchronizing motor movements to periodic auditory stimuli. This type of synchronization is known as auditory-motor entrainment. Most research that explores human timing perception uses auditory-motor entrainment, such as finger tapping to a pulse or beat, as an index of perceptual sensitivity to timing information.

However, children's motor skills are less refined than those of adults, making most timing tasks used with adults inappropriate for use with young children. Although infants and very young children shown periodic motor movement when exposed to music, this movement is not synchronized to the stimulus. There are few techniques to assess auditory timing perception in the absence of an overt motor response.

In this chapter, I describe the creation of a novel task to assess children's sensitivity to a musical beat, call the complex Beat Alignment Test (cBAT). Children watch and listen to pairs of videos showing puppets drumming to the beat of music, and decide which of the two puppets was a better drummer. One puppet in each pair makes phase or tempo errors; if children can detect these beat misalignments, they should give the prize to the puppet whose drumming is correctly aligned with the musical beat. As such, the task indexes children's perceptual sensitivity without requiring motor synchrony the way existing tasks do.

In addition, the second novel aspect of this task is that it employs musical excerpts with both simple and complex metric structures. Western music is predominantly composed of simple metre music with equally spaced, or isochronous, accents. Music research almost exclusively employs stimuli with simple metric structures, notated by time signatures such as 3/4 and 4/4 time. However, half of the cBAT stimulus set is composed of music with complex metric structures. These structures have non-isochronous accents, and are represented by time signatures including 5/4 and 7/4. As such, the cBAT can assess timing sensitivity across both culturally typical and atypical contexts.

The results of this study demonstrated that by five years of age, musically untrained children are sensitive to both the phase and tempo of a beat in the context of rich and naturalistic recorded music with simple metric structure. However, performance descended to chance levels for excerpts with complex metric structure. Thus, the cBAT task provides an effective tool to investigate young children's perceptual sensitivity to musical timing and their enculturation to musical metric structure. The creation of a perception-only task also allows auditory perception to be assessed separately from motor synchronization, providing a means to investigate motor skills separately from auditory sensitivity in future work.

Abstract

Adults can extract the underlying beat from music, and entrain their movements with that beat. Although infants and children are poor at synchronizing their movements to auditory stimuli, recent findings suggest they are perceptually sensitive to the beat. We examined five-year-old children's perceptual sensitivity to musical beat alignment (adapting the adult task of Iversen & Patel, 2008). We also examined whether sensitivity is affected by metric complexity, and whether perceptual sensitivity correlates with cognitive skills. On each trial of the complex Beat Alignment Test (cBAT) children were presented with two successive videos of puppets drumming to music with simple or complex meter. One puppet's drumming was synchronized with the beat of the music while the other had either incorrect tempo or incorrect phase, and children were asked to select the better drummer. In two experiments, five-year-olds were able to detect beat misalignments in simple meter music significantly better than beat misalignments in complex meter music for both phase errors and tempo errors, with performance for complex meter music at chance levels. Although cBAT performance correlated with short-term memory in Experiment One, the relationship held for both simple and complex meter, so cannot explain the superior performance for culturally typical meters.

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Key words: music, entrainment, meter, enculturation, development

Introduction

Rhythm in the most basic sense consists of sequences of sound events and silences (London, 2004), and represents physical properties of sound in terms of timing. Musical timing typically has two aspects, a *grouping* structure, which corresponds to the perception of phrases, and a *metrical* structure, which corresponds to the regular underlying pulse, or beat, which is extracted from the rhythmic surface but not directly present in the physical stimulus (Gjerdingen, 1989; Lerdahl & Jackendoff, 1983). Adult listeners readily extract the metrical structure from music, as evidenced by the fact that they can easily tap or move to the beat of music (e.g., Repp, 2005). This ability to detect the regularities in external auditory stimuli and synchronize movements to a perceived beat is widespread in humans (Iversen & Patel, 2008) and is referred to as auditory-motor *entrainment*. Adults' ability to entrain motor behavior to periodic auditory patterns has been extensively studied and a smaller number of investigations have examined adult's beat perception abilities in the absence of an overt motor response (for reviews see Repp, 2005; Repp & Su, 2013; Zatorre, Chen, & Penhune, 2007).

In contrast to the adult literature, few investigations of motor entrainment have been conducted with young children. Most timing tests assess rhythm perception rather than beat perception or motor synchronization, and these rhythm perception tests have been developed for both younger and older children, as well as for typical adult populations (Gordon, 1979, 1980). Perception tests can also be used to identify those with serious timing deficits or general amusia (Peretz, Champod, & Hyde, 2003). In quantifying children's ability to motorically entrain to rhythms, the limited range of speeds to which children can synchronize (Provasi & Bobin-Bègue, 2003) must be considered, as well as children's generally poor motor skills (Drake, 1993), which makes the use of tapping synchronization tasks of the type typically used with adult subjects difficult. Most synchronization tasks used with adults involve tapping a single finger, which requires a high degree of fine motor control (Repp, 2005), and synchronization over a wide range of speeds over a prolonged period of time (Repp & Su, 2013). Children's ability to synchronize movements to an external auditory stimulus, and the range of tempi at which they can do so, is thought to improve gradually during childhood (Drake, Jones, & Baruch, 2000) although it has not yet reached adult-like levels by 12 years of age (van Noorden & De Bruyn, 2009). Children have a faster spontaneous motor tempo (SMT) than adults, and have been shown to prefer faster tempi perceptually and motorically. This preferred rate slows throughout adolescence and adulthood, although SMT remains correlated with tempo perception across the lifespan (McAuley, Jones, Holub, Johnston, & Miller, 2006).

However, there is a small body of work suggesting that infants and very young children exhibit periodic movement when listening to music, although this movement is rarely, if ever, synchronized to the music (Eerola, Luck, & Toiviainen, 2006; Zentner & Eerola, 2010). Furthermore, a preferential looking study using 7-month-old infants found that infants preferred to listen to music where metronomic beeps were overlaid on musical excerpts in a way that matched the beat, compared to where the overlaid beeps were too fast or too slow (Patel, Iversen, Brandon, & Saffran, 2011). This suggests that, although children have trouble synchronizing their movements to an external auditory stimulus, their perceptual systems are sensitive to the beat in music. Additionally, children may be particularly influenced by social aspects of the situation, as they show better synchronization with a human adult drumming partner than with a drumming machine (Kirschner & Tomasello, 2009).

Oscillatory models of attending suggest that neural entrainment is driven by attentional synchrony (Jones & Boltz, 1989) and that perceptual entrainment can occur to a regular stimulus (Jones, 1976). However, few studies have examined perceptual entrainment to the beat in children in a way that dissociates overt motor synchrony from perceptual sensitivity. Iversen and Patel (2008) developed a Beat Alignment Task (BAT) for adults that measures both perception of beat alignment, as well as ability to synchronize to a musical beat. Furthermore, it is suitable for musically untrained adults. In the BAT, subjects first tap isochronously at a self-selected tempo, then synchronize their tapping to an external, isochronous auditory metronome, then synchronize their own finger tapping to the beat of 12 short musical excerpts and, finally, perceptually judge whether an isochronous auditory tone superimposed over each of the 12 musical excerpts is correctly aligned with the beat of the underlying musical excerpt. In the last (perceptual) task, incorrectly assigned isochronous beat tracks were either 1) too fast or too slow by 10% of the interbeat interval, or 2) too early or too late by 25%. Iversen and Patel reported that for the beat synchronization task, the overall correlation between subjects' mean intertap interval and the tempo of the excerpts was $r = .98$ when calculated across all excerpts for all participants. This suggests that, on average, adult subjects were excellent at matching their tapping speed to a wide range of musical tempos. However, the experiment did not measure phase alignment between subjects' tapping and the beats of the excerpts so it is not known how closely the taps actually aligned with the music. Behavioral scores on the perception task varied much more than those for the synchronization task, and were distributed nearly uniformly from chance to perfect performance. Performance on the perception and synchronization tasks was moderately correlated (r = .56), and subjects' intertap interval variability in the beat synchronization task was highly negatively correlated with judgment accuracy on the beat perception task (r = -.61).

In the present study, we modified the beat perception component of the BAT measure used by Iversen and Patel in order to investigate five-year-old children's perceptual sensitivity to a musical beat, and their ability to perceive beat misalignment in the context of short musical samples. Our first goal was to ascertain the degree to which young children are perceptually sensitive to the beat in a musical stimulus, without requiring them to produce a motor response. Following the work of Corrigall and Trainor (2014), in which children watched videos of puppets playing the piano and judged which puppets play the best songs, we developed a novel and child-friendly testing paradigm called the complex Beat Alignment Test (cBAT). The task uses videos of hand puppets that drum along to short musical sequences (a drum beat is superimposed on musical tracks). On each trial, two videos are presented successively, each with the same musical track. On one video the puppet's drumming is correctly aligned to the beat of the music, while on the other, the puppet drums out of phase or at an incorrect tempo relative to the musical excerpt being presented. Children are required to choose which puppet in each pair drummed better. If five-year-old children are sensitive to the beat of the music, they should give the prize to the puppet whose drumming is correctly aligned more often than would be predicted by chance.

Our second goal in developing this task was to investigate the effect of metrical complexity on beat sensitivity. Metrical structure is hierarchical, with the beats at different levels occurring at faster or slower rates (Essens & Povel, 1985; Jones & Boltz, 1989; Lerdahl & Jackendoff, 1983). At a particular level, some beats are accented and thus are perceived as stronger than others, and only these accented beats are passed to the next level of the metrical hierarchy (Essens, 1986). Accents can be either physically present, as when some events are louder than others, or perceived based on how rhythmic and pitch features are temporally arranged (Grahn & Brett, 2007; Jones, 1976; Parncutt, 1994). For example, in a sequence of identical tones, the duration of silences between those tones can alter perceived accent structure (Povel & Okkerman, 1981), and harmonically important events can also be perceived as being accented (Dawe, Platt, & Racine, 1993). The metrical structure is perceptually abstracted from the rhythmic surface (Lerdahl & Jackendoff, 1983). Most often, at a particular level of the hierarchy, either every second beat or every third beat is perceived as accented (Jones & Boltz, 1989).

In simple metrical structures, accented beats occur at regular time intervals at each level of the hierarchy, and such regularly spaced beats are referred to as isochronous. Meter in Western music most commonly possesses an underlying binary structure, with a 2:1 ratio between beats at successive hierarchical levels being by far the most common (London, 2002). This music has familiar time signatures such as 4/4 and 2/4 when notated. Less commonly, Western music also employs a ternary structure, with a 3:1 ratio between beats at successive levels, which is notated as 3/4 or 6/8 time (Large & Palmer, 2002). However, not all music is composed of a pattern that produces equally spaced pulses at each level of the hierarchy. For example, at one level of the metrical hierarchy, accents can occur to form patterns containing groups of two or three beats and, thus, irregularly spaced accents. These complex metrical structures are referred to as non-isochronous. In music with more complex metric structure, the presence of two- and three-beat groupings produce ratios such as 3:2 and 4:3 between successive levels of the metrical hierarchy. Music notation reflects these complex patterns using notation such as 5/4 (which can consist of groups of 2 + 3 or 3 + 2 beats) and 7/8 (which can consist of groups of 3 + 2 + 2 or 2 + 3 + 2 or 2 + 2 + 3 beats).

In Western cultures, complex metrical structures are assumed to be beyond the limits of children's processing abilities, given that they remain challenging even for musically trained Western adults (Grahn & Brett, 2007). North American adults have difficulty reproducing complex metrical structures, especially in the absence of musical cues (Snyder, Hannon, Large & Christiansen, 2006). Drake (1993) investigated factors that influence rhythm reproduction, and found that both Western adults and Western children are better at reproducing rhythms that can be considered simpler in structure. Western music is primarily composed in simple meters, but music from a variety of other cultures employs complex metrical structures much more commonly. For example, folk music from parts of South Asia, Africa, the Middle East, and the Balkan region of southeastern Europe frequently contain a variety of complex meters such as 5/4, 7/4, and

7/8, and adults from cultures such as Bulgaria and Macedonia demonstrate equal perceptual sensitivity to both simple and complex metrical stimuli (Snyder et al., 2006). By the same token, in cultures where complex metric structures are common, children also learn them with ease from a young age, seemingly without difficulty (Rice, 1994).

Hannon and Trehub (2005a) showed that North American adults have difficulty detecting metrical changes in complex meters, but succeed at detecting such changes in culturally familiar simple meter stimuli. In contrast, adults from Bulgaria and Macedonia succeed in detecting violations to both simple and complex metrical structures. Interestingly, six-month-old infants from North America showed the same pattern of results as the Balkan region adults, demonstrating equal ability to process stimuli with simple and complex meters. However, by 12 months, North American infants showed the same pattern of perceptual biases as North American adults (Hannon & Trehub, 2005b). This suggests that humans are unlikely to have an innate perceptual bias favoring simple over complex meters, and suggests that exposure to particular metrical structures can result in perceptual specialization for those culturally typical meters. There are, however, limits, as extremely irregular meters remain difficult for listeners across cultures (Hannon, Soley, & Levine, 2011). In any case, this perceptual narrowing according to early perceptual experience is analogous to that seen across many domains such as faces (Kelly et al., 2007), voices (Friendly, Rendall, & Trainor, 2014), phonemes (e.g., Werker & Tees, 1984), and musical tonal structures (Hannon & Trainor, 2007; Lynch, Eilers, Oller & Urbano, 1990; Lynch & Eilers, 1992; Trainor & Hannon, 2012; Trainor & Trehub, 1992).

This perceptual specialization for culturally relevant musical meters, although robust in adulthood, appears to be fragile and easily altered in infancy. After North American 12-month-olds were passively exposed to rhythms with complex meters at home for two weeks, the ability to perceive changes to these rhythms was regained. A subsequent and similar experiment with adults found that this brief exposure period did not result in increased sensitivity to Balkan rhythms (Hannon & Trehub, 2005b). Although this small body of literature demonstrates that perceptual specialization for musical meter is underway in infancy, little is known about its developmental trajectory through childhood.

To address the question of whether young children's sensitivity to the beat is affected by the metric structure of the music, in our complex Beat Alignment Test (cBAT) we extended the original BAT paradigm by including music excerpts with both simple and complex meters. Here, we describe two experiments conducted to address the question of beat alignment and metric complexity. In Experiment One, half of the musical excerpts in the cBAT stimulus set were in 4/4 time (simple metric structure), while the other half were in 5/4 or 7/4 time (complex metric structure). In Experiment Two, half of the musical excerpts in the stimulus set were in 4/4 time (simple metric structure), while the other half were in 7/4 time only (complex metric structure) with no test excerpts having a 5/4 structure. This was done to ensure that children's performance on the cBAT task was not affected by the alternation of particular metric types within a category.

In addition to exploring the degree to which young children are perceptually sensitive to the beat and investigating the effect of metrical complexity on this sensitivity, our third goal in developing the cBAT was to examine whether children's performance on the beat perception task correlates with auditory memory. Adults' working memory capacity has been found to correlate with performance on rhythm reproduction tasks (Bailey & Penhune, 2010), and children's ability to discriminate rhythm sequences has been found to correlate with auditory working memory, as measured by a digit span task (Strait, Hornickel, & Kraus, 2011). Music training has been found to correlate with better memory in both children and adults (Kraus, Strait, & Parbery-Clark, 2012). Furthermore, short-term memory is necessarily involved when discriminating between two or more stimuli, as features of the stimulus presented first must be held in memory in order to be compared to subsequent presentations (Conway et al., 2005). Short-term memory and working memory are related processes but are thought to represent different cognitive constructs (Engle, Tuholski, Laughlin, & Conway, 1999). Short-term memory is a simple storage process, whereas working memory involves computational processes like the manipulation of information being held in short-term memory (Cantor, Engle, & Hamilton, 1991).

We examined the extent to which these two different aspects of memory were related to beat perception by having each child complete the forward and backward components of the digit span subtest from the Wechsler Intelligence Scale for Children (WISC-IV; Wechsler, 2003). The digits forward task is thought to measure short-term memory, and the digits backward task to measure working memory (Engle et al., 1999; Oberauer & Süß, 2000).

Because children needed to understand the instructions in order to perform the cBAT, we also administered the Peabody Picture Vocabulary Test (PPVT-4; Dunn & Dunn, 2007), which is a standardized measure of receptive vocabulary that can also serve as a proxy for verbal IQ, and correlates highly with various IQ instruments (Dunn & Dunn, 2007). In this way we could determine whether poor beat perception performance might be related to understanding the task.

Using our novel and child-friendly cBAT testing paradigm, we predicted that five-year-old children would be sensitive to beat alignment in the context of tempo- and phase-related errors, but that they would be more accurate at detecting beat alignment in musical excerpts with simple metric structures compared to in musical excerpts with complex metric structures. We also hypothesized that memory, as measured by the digit span task, would correlate with beat perception, as measure by performance on the cBAT.

Experiment 1

Methods

Participants

Participants were 32 five-year-old children (17 female, M_{age} = 5 years, 6 months) who were not enrolled in formal instrumental music lessons at the time of testing. None of the children had previous experience with formal music training and only one child had participated in an infant music class. Eleven of 32 households reported having a parent with some form of prior instrumental training. All children in the final sample had normal hearing and were in good health, as reported by their parents on a background questionnaire. An additional nine children were excluded from the sample for the following reasons: technical problems (*n* = 4), diagnosed developmental delays (*n* = 2), failure to complete all tasks (*n* = 2), and hearing impairment (*n* = 1). Annual family income was measured on a six-point scale (1 = *<$30,000*, 6 = *>$150,000*; Canadian dollars, data missing for five children). The average family income was between $90,000 and $120,000 per year for children in both conditions. Parent education was also measured on a six-point scale (1 = *no high school diploma*, 6 = *graduate or professional degree*; data missing for two children). For children in both conditions the average formal education was a completed college diploma or certificate both for mother/parent one and for father/parent two. All participants were recruited from the McMaster Infant Studies Group database, and all protocols were approved by the McMaster Research Ethics Board.

Stimuli

1. Complex Beat Alignment Test. The stimulus set for the complex Beat Alignment Test (cBAT) consisted of videos of hand puppets drumming along to 12 musical excerpts chosen from a variety of genres, including Western pop, rock, classical, and jazz, as well as East Indian and Hawaiian. Excerpts were organized in pairs that were matched according to genre, tempo, timbre, and overall musical style as well as metric structure type (see Table 1). Six of the musical excerpts had simple metric structure (in this case, 4/4 time signatures) common in Western music compositions. Complex meter excerpts had either 5/4 or 7/4 time signatures, which are less common in Western music compositions. Each excerpt ranged in length from 10 to 22 s. Length varied in order to preserve the phrase boundaries of each excerpt. Song tempos ranged from 88 to 172 beats per minute (see Table 1*)*. Audio files were created by combining existing commercial audio recordings with a series of isochronous woodblock taps, and then aligning the audio files with the video files of the puppets drumming. The creation of both components of these stimuli is detailed below (see Table 1).

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insert Table 1 approximately here

1a. Auditory Stimuli

The auditory components of the stimuli were created as follows. First, the average beats per minute (BPM) of each musical excerpt was determined using *MixMeister BPM Analyzer* software. Using *Apple Garageband 2009* software, a woodblock sound effect was used to create a series of isochronous metronomic taps that matched each excerpt's BPM. The isochronous tap sequences were then superimposed over each excerpt and manually inspected by a human rater. Small manual adjustments were made to a subset of individual woodblock taps to account for small deviations from isochrony as a result of the expressive timing in each recording.

The final stimulus set contained 54 audio files (2 standard practice trial tracks, 2 randomized practice trial tracks, 10 standard test trial tracks, 10 misaligned tracks that had been phase-shifted to be early, 10 misaligned tracks that had been phase-shifted to be late, 10 misaligned tracks that had been tempo-shifted to be fast, and 10 misaligned tracks that had been tempo-shifted to be slow). Each of these audio tracks served as the audio component that accompanied the visual stimulus of small puppets drumming on a toy drum (see below).

To create the standard, *correctly aligned* ("on-the-beat") tapping tracks for each excerpt, the woodblock tapping sound was superimposed over the musical excerpt to create a single auditory item where the woodblock tapping aligned with the beat of the musical sample. Following the creation of these standard tracks, four types of misaligned stimuli were created.

To create *phase error* tracks, the isochronous woodblock tracks from the original stimuli were phase shifted by 25% of each excerpt's average BPM to create audio files where the isochronous sequence of woodblock taps maintained the correct interbeat interval, but occurred either 25% too early or 25% too late relative to the beat of the music. To create the *tempo error* tracks, the speed of the woodblock tracks was increased or decreased by 10% of each excerpt's average BPM to create audio files where the woodblock taps occurred either 10% too fast or 10% too slow relative to the beat of the music. For both phase and tempo misalignments, the magnitude of the misalignment between the musical excerpt and the superimposed isochronous woodblock sequence (tempo shift of ±10% IBI or phase shift of ±25% IBI) remained constant for the duration of the excerpt.

One correctly aligned standard track, two out-of-phase tracks, and two incorrect-tempo tracks were created for each of ten of the twelve musical excerpts and were used to create the test trials in the cBAT. The remaining matched pair of musical excerpts, one with simple meter and one with complex meter, served as practice trials. Correctly aligned standard tracks were created for these remaining two musical excerpts. Additionally, *randomized* woodblock tracks were created to serve as the “wrong” answer for both of the practice excerpts, by superimposing the same number of woodblock taps as in the correctly aligned practice trial stimuli (32 taps for both the simple meter excerpt and complex meter excerpt) but randomizing the IBIs to generate pseudorandom non-isochronous sequences. A single ‘random’ woodblock track was created in *Apple GarageBand 2009*, containing 11 possible interbeat intervals ranging from 580 ms and 1280 ms, at intervals of 70 ms, randomly distributed throughout. The overall tempo of this random sequence was then adjusted to match to the average tempo of each of the two practice trial excerpts so that each randomized sequence could be superimposed over the corresponding musical excerpt. This process created two excerpts in which the woodblock tracks occurred randomly off the beat, but matched the total number of woodblocks taps and average tempo of the original musical excerpts.

To ensure that enculturated Western adults did indeed perceive the phase and tempo errors as being misaligned, and the standard sequences as being appropriately aligned, we first had adult listeners perform a shorter, modified version of the task. Twelve adults (7 females) between the ages of 18 and 27 years (M_{age} = 21.9 years, *SD* = 1.4 years) each listened to 4 correctly aligned musical tracks and 8 misaligned musical tracks. The error type of the misaligned tracks was balanced between subjects, with 6 receiving phase errors and 6 receiving tempo errors. Adults were asked to rate whether the woodblock tapping for each of the 12 excerpts sounded like it was aligned with the beat on a scale of 1 to 5, where 3 was perfect alignment. In the phase error condition, a rating of 1 indicated that the beat was very early and 5 that it was very late. In the tempo condition, a rating of 1 indicated that the beat was very slow, and 5 that it was very fast. Ratings were not significantly different from 3 for correctly aligned tracks ($M = 2.96$, $SD = .14$, $p = .23$), but were significantly different than 3 for both types of phase errors (early: $M = 2.63$, $SD = .55$, $p = .01$; late: $M = 3.23$, $SD = .25$, $p = .005$) and both types of tempo errors (slow: $M = 2.02$, $SD = .56$, $p < .001$; fast: $M = 4.13$, $SD = .52$, $p < .001$), confirming the appropriateness of our stimuli.

1b. Visual Stimuli

The visual stimuli were created by filming 24 hand puppets tapping on a toy drum along to the auditory stimuli described above. After filming, each of the auditory samples was individually aligned to the corresponding puppet video clip using *Apple's iMovie* software. The puppets' drumming movements occurred at tempi that matched the woodblock taps in the audio files, with the same number of drum taps in each video as there were woodblock taps in the corresponding audio file, so that after editing was complete each puppet appeared to be producing the tapping sounds. The two puppets on each trial were semantically related (e.g., lion and tiger), and each puppet in the pair drummed along to a single simple-meter musical excerpt in the first error condition, and a complex-meter excerpt for the other error condition.

Five types of test trial videos were created, corresponding to the audio types above. Each puppet drummed the standard version of one simple meter and one complex meter excerpt. Additionally, either two phase error videos (early and late) or two tempo error videos (fast and slow) were created for each puppet. Error presentation was balanced within each pair of puppets, so that the puppet who drummed the standard in the simple meter condition had misaligned drumming in the complex meter condition. Error type within each condition was balanced between subjects so that half of the children in each condition saw a particular puppet make one type of error (e.g., fast, or early) and the other half of the children saw that puppet make the other error type (e.g., slow or late). Tempo error videos were created by having the puppet drum at a different speed than the standard. Phase error videos were created by aligning the standard drumming video along with a misaligned audio track, since the tempo was the same in both cases.

To create practice trial videos, additional video clips were recorded to correspond to the two standard and two randomized practice trial audio files described above. Two pairs of puppets were filmed drumming to all four practice trial audio files, for a total of eight videos. Presentation of these pairs of videos was completely counterbalanced across subjects, so that half the children saw each pair drum each meter type, and half saw each puppet drum the standard versus the randomized version.

The results of this balanced design was the creation of 6 videos for each of the musical excerpts that was used as a test trial (one standard video of each puppet in the pair, two phase shifted error videos from one puppet, and two tempo shifted videos from the other puppet), for a total of 60 test videos, and 8 practice videos (4 standard and 4 randomized videos). Puppet pairs were kept constant across both the correct and incorrect error conditions, and balanced for order of presentation and frequency of beat misalignment errors.

2. Digit Span Test. All participants completed a subtest of the Working Memory Index (WMI) from the Wechsler Intelligence Scale for Children (WISC-IV, 4th edition; Wechsler, 2003). There are two parts to the task. In the digits forward section, the child is required to repeat back a string of digits uttered by the experimenter. The task begins with two digits, and the number of digits increases by one on every second trial. Testing stops once the child fails to correctly repeat both strings of digits of a given length. The digits backward section follows the same procedure, except that it requires the child to repeat the digits in the reverse order from the experimenter. Raw scores on the digits forward task were used as a measure of verbal short-term memory, and raw scores on the digits backward task were used as a measure of verbal working memory.

3. Peabody Picture Vocabulary Test. All participants completed the Peabody Picture Vocabulary Test (PPVT-IV, 4th edition; Dunn & Dunn, 2007), a standardized measure of receptive vocabulary. In this test, the experimenter says a word, and the child chooses the appropriate picture from a set of four provided in order to determine which image best represents the vocabulary item. Vocabulary items gradually increase in difficulty, and testing is terminated when the child incorrectly identifies eight or more of the words in a twelve-item set. Raw scores were standardized according to the subject's age, and normed as described in the Examiner's Manual.

4. Parental Questionnaire. While the child was being tested, parents completed a questionnaire covering such topics as their child's health, language experience, extracurricular activities, and formal or informal music experience. Demographic information regarding parental education and income was also requested, although these questions were answered by only a subset of parents.

Procedure

Children were tested during one session that was approximately 45 min in length. The cBAT was administered in two separate blocks, where one block consisted of the simple meter stimuli and the other the complex meter stimuli. Block order was counterbalanced across children.

Each trial of the cBAT consisted of a pair of two individual videos. In one video, the puppet drummed along to the beat of a particular musical excerpt (the correctly aligned stimuli). In the other video the puppet's drumming was either out of phase or out of tempo relative to the excerpt, as described above. Error type was a between-subjects variable, so that half of the 32 participants were presented with only tempo shift errors for all test trials, and the other half with only phase shift errors. As such, 16 children were tested in the tempo error condition, and 16 children in the phase error condition. Within each error condition, the error types were balanced so that each type (fast and slow tempo shift errors or early and late phase shift errors) occurred in equal proportion. For example, in the tempo shift group, three of the errors presented were beats that were too fast, and the other three were beats that were too slow. Additionally, three of the errors were presented first in the pair, and three were presented second. Each block consisted of one practice trial (with one puppet whose drumming was correctly aligned, and one that drummed along to the randomized woodblock stimuli), followed by five test trial pairs of puppet stimuli.

Before the cBAT was administered, participants were instructed that they were about to watch two puppets drumming along to the same song, and that they were going to be a judge who had to determine which puppet would be a better drummer for a band. Before each trial, the experimenter showed the child the two puppets that would be presented in the videos for that trial, and identified them by name (for example, “This is my friend the bunny, and this is my friend the dog”). After the child viewed each video in the pair one time, the experimenter placed the two actual puppets in front of the child on the table, and asked the child to place a ribbon on the puppet who should win the prize. The practice trial at the beginning of each block was repeated until the participant correctly identified the puppet whose drumming was correctly aligned to the music. Test trials were not repeated, and the child received no feedback regarding their choice. The order of tasks was Block 1 of the cBAT, Digit Span Task, Block 2 of the cBAT, followed by the PPVT. Upon completion, participants received a certificate of participation and a small prize.

Results

Complex Beat Alignment Test (cBAT)

The dependent measure was the proportion of the time the five-year-old children selected the puppet that played the standard version as the best drummer. To directly compare the children’s performance in detecting beat misalignment in the context of simple meter and complex meter, we conducted a 2 x 2 ANOVA with error type (phase, tempo) as a between-subjects factor and meter type (simple, complex) as a within-subjects factor. The only significant effect was meter type, $F(1, 30) = 23.78$, $p < .001$, indicating that five-year-old children are better at detecting beat misalignment in simple meters (proportion correct = .67, *SD* = .20) than complex meters (proportion correct = .46, *SD* =.22) and that this is not affected by whether the error is a phase or tempo error (Figure 1).

Examination of individual data for the cBAT task showed that 28 of 32 participants selected the puppet whose drumming was correctly aligned more often for the simple meter excerpts than they did for excerpts in complex meters (Figure 2). Thus, it is clear that a small subset of our sample was not driving our effect. There was no significant difference in judgment accuracy for simple meter excerpts between subjects who completed the simple block first (mean proportion correct = .66) or second (mean proportion correct = .69; $p = .87$). There was also no significant difference in judgment accuracy for complex meter excerpts between subjects who completed the simple block first (mean proportion correct = .53) or second (mean proportion correct = .42; $p = .21$). This suggests that there were no carry-over effects as a result of presentation order.

We conducted a series of *t*-tests to compare the children's performance to chance (.50). Performance on the simple meter stimuli was significantly better than chance for tempo errors, $t(15) = 3.01$, $p = .005$, $M = .66$, $SE = .05$, as well as for phase errors, $t(15) = 4.20$, $p = .001$, $M = .69$, $SE = .04$. Performance on the complex meter stimuli was not significantly different from chance for tempo errors, $t(15) = -0.94$, $p = .36$, $M = .45$, $SE = .05$, or for phase errors, $t(15) = 0.001$, $p = 1.00$, $M = .50$, $SE = .06$. Despite children's inability as a group to judge beat alignment in complex meter stimuli, judgment accuracy for the simple meter stimuli was significantly correlated with judgment accuracy for the complex meter stimuli, r = .37, p = .02, suggesting that there are underlying factors that affect performance on both.

Relation Between cBAT and the Cognitive Tasks

PPVT standard scores did not significantly correlate with overall performance on the cBAT, r = .20, p = .14 and this correlation did not reach significance when considering only the simple meter portion of the cBAT, r = .12, p = .26, or only the complex meter portion of the cBAT r = .21, p = .13. There was variability in PPVT scores across children, M = 114.28, SD = 9.30, so the lack of correlation is not because all children performed equally well on the PPVT. Thus, performance differences between children do not appear to be driven by general differences in language ability that could underlie understanding the task.

However, overall cBAT performance was significantly correlated with performance on the forward digit span test (M = 6.80 SD = 1.42), r = .51, n = 32, p = .001. Furthermore, performance on the forward digit span test was correlated with both cBAT simple meter scores, r = .45, n = 32, p = .005, and with cBAT complex meter scores, r = .39, n = 32, p = .01 (Figure 3).

On the other hand, overall cBAT performance did not correlate significantly with the backward digit span test (M = 4.56, SD = 1.56), r = -.09, p = .31. This was also true for correlations between performance on the backward digit span test and cBAT simple meter scores alone (r = -.07, p = .36) and cBAT complex meter scores alone (r = -.08, p = .33; Figure 3). If we exclude two subjects whose backward digit span scores were more than 2.5 standard deviations below the mean in an outlier analysis, the significance of these correlations does not change. Thus, performance on the cBAT appears to be related to short-term memory but not to working memory.

Neither maternal education nor paternal education correlated with individual children's overall beat perception, simple meter beat perception, complex beat perception, or any of the cognitive measures (all p's > .05). Household income level was also not significantly correlated with any of these measures (all p's > .05). A post hoc comparison of cBAT performance for children whose parents either did or did not have formal music training revealed no difference between groups (p = .98). However, given that only one child had taken music lessons and none of the parents had extensive music training, more research is needed to determine whether early musical experience affects performance on these tasks.

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insert Figures 1, 2, 3 approximately here

Experiment 2

The simple meter music and complex meter music in the cBAT perception task were matched according to genre, tempo, and timbre in order to minimize differences between paired excerpts that were unrelated to metric structure. All simple meter excerpts had 4/4 metric structures; however, excerpts from the complex meter category were in either 5/4 or 7/4 time. As such, participants were required to make judgments about more than one meter type within the complex meter block of test trials.

Although we found no effects of presentation order on judgment accuracy *between* the simple and complex meter blocks in Experiment One, it is possible that there was an effect of presentation order *within* the complex meter block. To ensure that less accurate performance in the complex meter condition was not a result of making judgments about both 5/4 and 7/4 structures within the same block, we created a modified version of the cBAT for Experiment Two. In this modified version the two excerpts with 5/4 metric structure were removed along with their corresponding 4/4 pairs. As a result, test trials in the simple meter block were in 4/4 time only, and paired test trials in the complex meter block were in 7/4 time only.

Methods

Participants

Participants were 24 five-year-old children (12 female, M_{age} = 5 years, 6 months) who were not enrolled in formal music lessons at the time of testing. No children had taken music lessons previously, and no children had participated in an infant music class. Seventeen of 24 households in our sample reported having a parent with some form of prior instrumental training. All children in the final sample had normal hearing and were in good health, as reported by their parents on a background questionnaire. An additional 5 children were excluded from the sample because of diagnosed developmental delays (n = 2), or failure to complete all tasks (n = 3). Annual family income and parental education were measured the same way as in Experiment One. Neither family income nor parental education levels were significantly different between children in the phase condition or the tempo condition of Experiment Two (all p's > .50). There was also no difference between average family income or parental education of children in Experiments One and Two (all p's > .50). All participants were recruited from the McMaster Infant Studies Group database, and the McMaster Research Ethics Board approved all protocols.

Stimuli

The stimulus set for the modified version of the complex Beat Alignment Test (cBAT) used in Experiment Two consisted of a subset of the same videos of drumming hand puppets used in Experiment One. In the modified version of the cBAT, the two excerpts in 5/4 time and their corresponding genre- and style-matched excerpts in 4/4 time were removed from the modified version of the task, so that test trials in both blocks contained only one meter type (either 4/4 in the simple block or 7/4 in the complex block).

As such, the modified cBAT used the same videos as the original cBAT, presented in the same manner. Each block in the modified cBAT consisted of one practice trial (with one puppet whose drumming was correctly aligned, and one that drummed along to the randomized woodblock stimuli), followed by four test trial pairs of puppet stimuli. In the simple meter block, all excerpts had 4/4 time signatures. In the complex meter block, all excerpts had 7/4 time signatures. The digit span task, receptive vocabulary task, and parent questionnaire did not differ from those used in Experiment One, and the equipment and software used were also the same.

Procedure

Children were tested during one session that was approximately 45 minutes in length. The tasks, order of presentation, and test procedure were identical to Experiment One, except for the alterations made to the complex meter block of the cBAT. The order of tasks was Block 1 of the cBAT, Digit Span task, Block 2 of the cBAT, followed by the PPVT. Upon completion, participants received a certificate of participation and a small prize.

As in Experiment One, error type was a between-subjects variable in the cBAT perception task, so that half the participants were presented with only tempo shift errors for all test trials, and the other half with only phase shift errors. As such, 12 children were tested in the tempo error condition, and 12 children in the phase error condition.

Results

As in Experiment One, the dependent measure was the proportion of the time the five-year-old children selected the puppet that played the standard version as the best drummer. To directly compare the children's performance in detecting beat misalignment in the context of simple meter and complex meter, we conducted a 2 x 2 ANOVA with error type (phase, tempo) as a between-subjects factor and meter type (simple, complex) as a within-subjects factor. The only significant effect was meter type, $F(1, 22) = 8.25$, $p = .009$, indicating that five-year-old children are better at detecting beat misalignment in simple meters (proportion correct = .74, $SD = .21$) than complex meters (proportion correct = .61, $SD = .20$) and that this is not affected by whether the error is a phase or tempo error. This is consistent with the results of Experiment 1.

As in Experiment 1, performance on the simple meter stimuli was significantly better than chance for tempo errors, $t(11) = 4.01$, $p = .002$, $M = .73$, $SE = .06$, as well as for phase errors, $t(11) = 4.06$, $p = .002$, $M = .75$, $SE = .06$. Performance on the modified complex meter stimuli (containing only 7/4 meter) was not significantly better than chance for tempo errors, $t(11) = -2.16$, $p = .05$, $M = .59$, $SE = .05$, or for phase errors, $t(11) = 1.92$, $p = .08$, $M = .62$, $SE = .07$. Judgment accuracy for the simple meter stimuli was again correlated with judgment accuracy for the complex meter stimuli, $r = .45$, $p = .03$, suggesting that there are underlying factors that affect performance on both types of judgments for the modified task.

Like in Experiment 1, PPVT standard scores in Experiment 2 also did not significantly correlate with overall performance on the modified cBAT, $p = .23$ and this correlation did not reach significance when considering only the simple meter portion of the cBAT, $p = .82$, or only the complex meter portion of the cBAT $p = .07$. Unlike in Experiment One, however, in Experiment Two overall performance on the cBAT was *not* significantly correlated with children's total score on the digit span test ($M = 11.89$, $SD = 1.19$), $p = .17$. Judgment accuracy for simple meter stimuli only was not correlated with forward digit span, $p = .35$, or backward digit span, $p = .40$. Judgment accuracy for complex meter stimuli only was also not significantly correlated with forward digit span, $p = .87$, or backward digit span, $p = .16$.

We also compared the judgment accuracy of children from Experiments 1 and 2 directly, to determine whether there were significant differences in performance between the two versions of the cBAT. This was done using a 2 x 2 x 2 ANOVA with cBAT version (Experiment 1, 2) and error type (phase, tempo) as between-subjects factors and meter type (simple, complex) as a within-subjects factor. The only significant effect was meter type, $F(1, 52) = 29.07$, $p < .0001$, indicating that judgment accuracy was not significantly different for children who completed the original version of the cBAT (with two types of complex metric structures) compared to children who completed the modified version (with only one type of structure in the complex meter block of the task).

Neither maternal education nor paternal education correlated with individual children's overall beat perception or any of the cognitive measures (all *p*'s >.15). Household income level was also not significantly correlated with any of the cognitive measures (all *p*'s > .15), although it did correlate with children's overall beat perception ($p = .02$). A post hoc comparison of cBAT performance for children whose parents either did or did not have formal music training revealed no difference between groups ($p = .45$).

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insert Figure 4 approximately here

General Discussion

We set out to examine the degree to which 5-year-old Western children are perceptually sensitive to a musical beat in the absence of requiring overt motor synchronization, and whether they show better beat processing for culturally typical simple, compared to culturally atypical complex, musical meters. We developed a novel method of assessing sensitivity to the alignment of musical beats, in the form of a child-appropriate version of the original BAT test (Iversen & Patel, 2008), named the complex Beat Alignment Test (cBAT) in which children were asked to listen to pairs of videos of puppets, one of whom drummed on time and one of whom did not, and to judge which one drummed better. We also expanded the original BAT test to include independent measures of the ability to detect phase and tempo misalignment as well as to include musical excerpts with both simple and complex meters.

When musical excerpts had simple metric structure, children were able to detect drumming that was out of phase with the music (either earlier or later than the beat by 25%) or at the wrong tempo (either 10% too fast or too slow). This demonstrates that by the age of five, children have the ability to make explicit judgments about beat alignment and it extends previous literature on children (Bobin-Bègue & Provasi, 2009; Drake, 1993; Kirschner & Tomasello, 2009; Provasi & Bobin-Bègue, 2003; van Noorden & De Bruyn, 2009; Zentner & Eerola, 2010) by showing that 5-year-olds are sensitive to both phase and tempo misalignment in the context of simple-metered music.

However, when musical excerpts had complex metric structures, performance was significantly worse than when excerpts had simple metric structures, and performance was not above chance when metrical structure was in five or seven. This is despite the fact that for both the simple meter and the complex meter stimuli, the drumming was composed solely of isochronous woodblock taps with no accents or other distinguishing characteristics. Subsequent work (Einarson & Trainor, 2015) has also demonstrated that children's performance on the task is not driven by the visual component of the stimulus, and remains comparable even when children are shown static images accompanied by the same auditory information. It is possible, however, that the tempo and phase misalignment manipulations in the cBAT index overlapping aspects of timing sensitivity. The tempo error created by an inappropriate interbeat interval also necessarily has inappropriate phase alignment with the beat of the musical excerpt, although the magnitude of this misalignment will not be constant as it is in the phase misalignment condition.

Previous studies have shown that 6-month-old Western infants are equally able to process simple and complex metrical structure, but by 12 months are better able to process the simple meters common in Western music (Hannon & Trehub, 2005a; 2005b). In a rhythm reproduction task, Drake (1993) found that Western children also performed better on rhythms with simple compared to complex meters. The present results are consistent with these findings, and extend them by showing that young Western children also show better perception of *beat alignment* in music with simple compared to complex meters, supporting the notion that an enculturation-based perceptual bias is maintained into childhood. A full test of this hypothesis would, of course, require a crossover design in which children from a culture where complex meters are prevalent were also tested. Interestingly, despite the fact that the 5-year-olds as a group were at chance levels with excerpts with complex meters, the correlation between performance with simple and complex meters was significant. This suggests that, despite overall better performance with simple meter stimuli, there is overlap in the skills needed to perceive beat alignments in stimuli with simple and complex meters.

Although the cBAT test likely depends less on memory than a rhythm reproduction task, children's performance on the cBAT was correlated with forward digit span in Experiment One, suggesting that sensitivity to beat misalignment may be related to children's short-term memory. It is not clear whether this whether this would represent a better ability to remember whether or not the first puppet was a good drummer while watching the second puppet, or whether it is more directly related to the ability to perceive beat alignment itself. Indeed, previous studies have linked musical abilities in young children to auditory working memory (Kraus et al., 2012; Strait et al., 2011) and particularly to the digit span subtest of the WISC (Anvari, Trainor, Woodside, & Levy, 2002). However, the fact that digit span forward was significantly correlated with cBAT performance on musical excerpts with both simple and complex meters suggests that the correlation was not related to the difficulty of the beat alignment task itself and, thus, perhaps simply reflects that ability to remember from one video to the next. However, given that the correlation with forward digit span did not reach significance in Experiment Two with a smaller sample size, this relationship remains unclear.

Furthermore, digit span backwards was not significantly correlated with cBAT performance in Experiment 1 or 2, suggesting that any relationship would involve short-term memory as opposed to the ability to manipulate auditory information in working memory. It is possible that short average backward digit span length and the low variability in raw backward span scores in our sample (M = 4.56, SD = 1.56), although typical for young children, made it difficult to observe the relationship between working memory and beat perception. However, it also is worth noting that a subsequent study using the same stimuli with a larger population of 84 five-year-old children (Einarson & Trainor, 2015) found no relationship between children's forward or backward digit span and their performance on the cBAT perception task. This held true for overall score, simple meter only, or complex meter only.

Children's PPVT standard score did not correlate with beat perception in Experiment 1 or Experiment 2. However, the correlation between receptive vocabulary and complex meter performance approached significance in Experiment 2 (p =.07). Using a similar video-based task in a musical tonality test with four- and five-year-old children, Corrigall and Trainor (2014) also found a weak (nonsignificant) correlation between PPVT standard scores and performance (p = .08). They posited that children with better vocabularies might be better able to understand the instructions of the task. However, as in the case with our data, any such relationship is weak and not found consistently, suggesting that vocabulary is not having a strong influence on performance in this task.

While information on the development of musical perception in general in preschool children is sparse, a recent study using similar behavioral methodology to the present study indicates that 5-year-old children can also make explicit judgments about key membership, that is, whether or not a particular note belongs in the key or set of pitches used in a particular melody (Corrigall & Trainor, 2014). As indicated by event-related potential (ERP) measures, the same work has shown that some knowledge of key membership and harmony is present as young as 3 years of age. Little work on the rhythmic abilities of toddlers has been done (but see Eerola et al., 2006; Provasi & Bobin-

Bègue, 2003), but finding behavioral and ERP paradigms in which to test children between 2 and 4 years of age remains a challenge for future research.

The development of the cBAT test enables further testing of a number of important questions in the development of rhythm skills. For example, the development of a purely perceptual task opens the possibility for testing perception and production separately and determining whether there is a dissociation between these skills in young children. In adults, Iversen and Patel (2008) found that beat perception and synchronization abilities were highly correlated, and there is some evidence that beat perception and production abilities are related in children as well (Corriveau & Goswami, 2009). In addition, auditory and motor areas of the brain appear to be connected in infants and adults, even in the absence of self-generated movements (e.g., Fujioka, Trainor, Large, & Ross, 2012; Iversen, Repp, & Patel, 2009; Phillips-Silver & Trainor, 2005; Trainor, Gao, Lei, Lehtovarara, & Harris, 2009). However, recent evidence for a dissociation between deficits in pitch perception and pitch production has been reported (Dalla Bella, Giguere, & Peretz, 2007; Loui, Guenther, Mathys, & Schlaug, 2008). Given that existing literature suggests that children's motor skills and auditory-visual coordination are somewhat limited (Drake, 1993; Eerola et al., 2006; Kirschner & Tomasello, 2009; Provasi & Bobin-Bègue, 2003), combined with our finding that children are fairly proficient at detecting beat alignment in music with simple meter, it is important to explore the developmental relation between beat perception and production.

The cBAT also offers a means to test metrical enculturation in young children across cultures without confounds from different motor experience and ability. Children from some Balkan regions, for example, grow up being exposed to a much wider variety of musical meters, and it has been claimed that they learn these structures from a young age, and seemingly with ease (Rice, 1994). However, the only cross-cultural investigation of simple and complex musical meter processing to date tested Bulgarian and Macedonian adults (Hannon & Trehub, 2005a). If the better performance of Western children in the present study on musical excerpts with simple compared to complex meter is a function of enculturation, then children who are raised in a culture where complex meter music is widespread should show equal ability for beat alignment in music with simple and complex meters.

In sum, we found that Western five-year-old children are sensitive to a musical beat, and can detect misalignments in both the tempo and phase of a beat relative to a musical sample with culturally typical simple meter. However, in the context of less familiar complex meter music, children's ability to detect misalignments in both the tempo and phase of a musical beat was at chance levels. The development of the cBAT enables future investigation of the relation between children's perceptual sensitivity and their ability to produce a musical beat by synchronizing to music. It also provides a means by which to investigate effects of enculturation on beat sensitivity by comparing the performance of children in cultures where complex meters are rare to those where complex meters are widespread.

References

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing and early reading ability in preschool children. *Journal of Experimental Child Psychology, 83*, 111-130.

Bailey, J. A., & Penhune, V. B. (2010). Rhythm synchronization performance and auditory working memory in early-and late-trained musicians. *Experimental Brain Research*, *204*, 91-101.

Bobin-Bègue, A., & Provasi, J. (2009). Tempo discrimination in 3- and 4-year-old children: Performances and threshold. *Current Psychology Letters*, *2*(2005), 1-13.

Cantor, J., Engle, R. W., & Hamilton, G. (1991). Short-term memory, working memory, and verbal abilities: How do they relate? *Intelligence*, *15*, 229-246.

Conway, A. R., Kane, M. J., Bunting, M. F., Hambrick, D. Z., Wilhelm, O., & Engle, R. W. (2005). Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin and Review*, *12*, 769-786.

Corrigall, K. A., & Trainor, L. J. (2014). Enculturation to musical pitch structure in young children: Evidence from behavioral and electrophysiological methods. *Developmental Science*, *17*, 142-158.

Corriveau, K. H., & Goswami, U. (2009). Rhythmic motor entrainment in children with speech and language impairments: tapping to the beat. *Cortex, 45*, 119-130.

Dalla Bella, S., Giguere, J-F., & Peretz, I. (2007). Singing proficiency in the general population. *Journal of the Acoustical Society of America, 121*, 1182-1189.

Dawe, L. A., Platt, J. R., & Racine, R. J. (1993) Harmonic accents in inference of metrical structure and perception of rhythm patterns. *Perception and Psychophysics, 54*, 794-807.

Drake, C. (1993). Reproduction of musical rhythms by children, adult musicians, and adult nonmusicians. *Perception and Psychophysics*, *53*, 25-33.

Drake, C., Jones, M. R., & Baruch, C. (2000). The development of rhythmic attending in auditory sequences: attunement, referent period, focal attending. *Cognition*, *77*, 251-288.

Dunn, L. M., & Dunn, D. M. (2007). *Peabody Picture Vocabulary Test fourth edition, Manual*. Minneapolis, MN: Pearson Assessments.

Eerola, T., Luck, G., & Toiviainen, P. (2006). An investigation of pre-schoolers' corporeal synchronization with music. In M. Baroni A. R. Addessi, R. Caterina, & M. Costa (Eds.), *Proceedings of the 9th International Conference on Music Perception and Cognition (ICMPC9)* (pp. 472-476). Bologna, Italy: ICMPC.

Einarson, K. M., & Trainor, L. J. (2015). The effect of visual information on young children's perceptual sensitivity to musical beat alignment. *Timing and Time Perception, 3*, 88-101.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology. General*, *128*, 309-331.

Essens, P. J. (1986). Hierarchical organization of temporal patterns. *Perception and Psychophysics*, *40*, 69-73.

Essens, P. J., & Povel, D. J. (1985). Metrical and nonmetrical representations of temporal patterns. *Perception and Psychophysics*, *37*, 1-7.

Friendly, R. H., Rendall, D., & Trainor, L. J. (2014). Learning to differentiate individuals by their voices: Infants' individuation of native- and foreign-species voices. *Developmental Psychobiology, 56*, 228-237.

Fujioka, T., Trainor, L. J., Large, E. W., & Ross, B. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic beta oscillations. *The Journal of Neuroscience, 32,* 1791-1802.

Gjerdingen, R. O. (1989). Meter as a mode of attending: A network simulation of attentional rhythmicity in music. *Intégral*, *3*, 67-91.

Gordon, E. E. (1979). Developmental music aptitude as measured by the Primary Measures of Music Audiation. *Psychology of Music*, *7*, 42-49.

Gordon, E. E., (1980). *Manual for the Primary Measures of Music Audition and the Intermediate Measures of Music Audiation*. Chicago: G.I.A.

Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience*, *19*, 893-906.

Hannon, E. E., Soley, G., & Levine, R. S. (2011). Constraints on infants' musical rhythm perception: Effects of interval ratio complexity and enculturation. *Developmental Science, 14*, 865-872.

Hannon, E. E., & Trainor, L. J. (2007). Music acquisition: effects of enculturation and formal training on development. *Trends in Cognitive Sciences*, *11*, 466-472.

Hannon, E. E., & Trehub, S. E. (2005a). Metrical categories in infancy and adulthood. *Psychological Science*, *16*, 48-55.

Hannon, E. E., & Trehub, S. E. (2005b). Tuning in to musical rhythms: Infants learn more readily than adults. *Proceedings of the National Academy of Sciences, 102*, 12639-12644.

Iversen, J. R., & Patel, A. D. (2008). The Beat Alignment Test (BAT): Surveying beat processing abilities in the general population. In K. Miyazaki, M. Adachi, Y. Hiraga, Y. Nakajima, & M. Tsuzaki (Eds.), *Proceedings of the 10th International Conference on Music Perception and Cognition (ICMPC10)* (pp. 465-468). Sapporo, Japan. Adelaide: Causal Productions.

Iversen, J. R., Repp, B. H., & Patel, A. D. (2009). Top-down control of rhythm perception modulates early auditory responses. *Annals of the New York Academy of Sciences*, *1169*, 58-73.

Jones, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychological Review*, *83*, 323-355.

Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review*, *96*, 459-491.

Kelly, D. J., Quinn, P. C., Slater, A. M., Lee, K., Ge, L., & Pascalis, O. (2007). The other-race effect develops during infancy: Evidence of perceptual narrowing. *Psychological Science*, *18*, 1084-1089.

Kirschner, S., & Tomasello, M. (2009). Joint drumming: Social context facilitates synchronization in preschool children**.** *Journal of Experimental Child Psychology, 102*, 299-314.

Kraus, N., Strait, D. L., & Parbery-Clark, A. (2012). Cognitive factors shape brain networks for auditory skills: Spotlight on auditory working memory. *Annals of the New York Academy of Sciences*, *1252*, 100-107.

Large, E. W., & Palmer, C. (2002). Perceiving temporal regularity in music. *Cognitive Science*, *26*, 1-37.

Lerdahl, F., & Jackendoff , R. (1983). *A generative theory of tonal music*. Cambridge, MA: MIT Press.

London, J. (2002). Cognitive Constraints on Metric Systems: Some Observations and Hypotheses. *Music Perception*, *19*, 529-550.

London, J. (2004). *Hearing in time: Psychological aspects of musical meter*. New York: Oxford University Press.

Loui, P., Guenther, F. H., Mathys, C., & Schlaug, G. (2008). Action–perception mismatch in tone-deafness. *Current Biology*, *18*, R331-R332.

Lynch, M. P., Eilers, R. E., Oller, D. K., & Urbano, R. C. (1990). Innateness, experience, and music perception. *Psychological Science*, *1*, 272-276.

Lynch, M. P., & Eilers, R. E. (1992). A study of perceptual development for musical tuning. *Perception and Psychophysics, 52,* 599-608.

McAuley, J. D., Jones, M. R., Holub, S., Johnston, H. M., & Miller, N. S. (2006). The time of our lives: Life span development of timing and event tracking. *Journal of Experimental Psychology. General*, *135*, 348-367.

Oberauer, K., & Süß, H. M. (2000). Working memory and interference: A comment on Jenkins, Myerson, Hale, and Fry (1999). *Psychonomic Bulletin and Review*, *7*, 727-733.

Parncutt, R. (1994). A perceptual model of pulse salience and metrical accent in musical rhythms. *Music Perception, 11*, 409-464.

Patel, A. D., Iversen, J. R., Brandon, M., & Saffran, J. (2011). Do infants perceive the beat in music? A new perceptual test. Abstract in *Proceedings of the 2011 Biennial Meeting of the Society for Music Perception and Cognition (SMPC 2011)*. Rochester, NY: SMPC.

Peretz, I., Champod, S., & Hyde, K. (2003) Varieties of musical disorders: The Montreal Battery of Evaluation of Amusia. *Annals of the New York Academy of Sciences*, *999*, 58-75.

Phillips-Silver, J., & Trainor, L. J. (2005). Feeling the beat: Movement influences infant rhythm perception. *Science*, *308*, 1430.

Povel, D. J., & Okkerman, H. (1981). Accents in equitone sequences. *Perception and Psychophysics*, *30*, 565-572.

Provasi, J., & Bobin-Bègue, A. (2003). Spontaneous motor tempo and rhythmical synchronisation in 2½- and 4-year-old children. *International Journal of Behavioral Development*, *27*, 220-231.

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin and Review*, *12*, 969-992.

Repp, B. H., & Su, Y. H. (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic Bulletin and Review.* DOI: 10.3758/s13423-012-0371-2

Rice, T. (1994). *May it fill your soul: Experiencing Bulgarian music*. Chicago, IL: University of Chicago Press.

Snyder, J. S., Hannon, E. E., Large, E. W., & Christiansen, M. H. (2006). Synchronization and continuation tapping to complex meters. *Music Perception*, *24*, 135-146.

Strait, D. L., Hornickel, J., & Kraus, N. (2011). Subcortical processing of speech regularities underlies reading and music aptitude in children. *Behavioral and Brain Functions*, *7*, 1-11.

Trainor, L. J., Gao, X., Lei, J., Lehtovarara, K., & Harris, L. R. (2009). The primal role of the vestibular system in determining musical rhythm. *Cortex, 45,* 35-43.

Trainor, L. J., & Hannon, E. E. (2012). Musical development. In D. Deutsch (Ed.), *The psychology of music* (3rd ed., pp. 423-497. San Diego, CA: Academic Press.

Trainor, L. J., & Trehub, S. E. (1992). A comparison of infants' and adults' sensitivity to Western musical structure. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 394-402.

van Noorden, L., & De Bruyn, L. (2009). The development of synchronization skills of children 3 to 11 years old. In P. Toiviainen (Ed.), *Proceedings of ESCOM—7th Triennial Conference of the European Society for the Cognitive Sciences of Music*. Jyväskylä, Finland: University of Jyväskylä.

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children* (4th ed.). San Antonio, TX: The Psychological Corporation.

Werker, J. F., & Tees, R. C. (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development*, *7*, 49-63.

Zentner, M., & Eerola, T. (2010). Rhythmic engagement with music in infancy. *Proceedings of the National Academy of Sciences*, *107*, 5768-5773.

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Table 1: Characteristics of Musical Stimulus Set for cBAT

Musical Excerpt *(Length in seconds)*	**Genre**	**Artist/Composer**	**Meter Type**	**Average BPM**
The Spam Song *(12)*	Hawaiian	Tia Carrere & Daniel Ho	Simple	87.8
Undercurrent *(18)*	Indian	Toronto Tabla Ensemble	Simple	114.1
Alice in Wonderland *(12)*	Jazz	Dave Brubeck	Simple	170.2
Holst Suite No. 1 *(22)*	Classical	Gustav Holst	Simple	130.3
One Way or Another *(12)*	Pop	Blondie	Simple	164.6
Hurt So Good *(18)*	Rock	John Mellencamp	Simple	126.3
Hula in Seven *(10)*	Hawaiian	Tia Carrere & Daniel Ho	Complex	159.5
Joyfully in Seven *(13)*	Indian	Toronto Tabla Ensemble	Complex	129.2
Take Five *(15)*	Jazz	Dave Brubeck	Complex	171.7
Planets Suite: Mars *(15)*	Classical	Gustav Holst	Complex	150.8
Money *(18)*	Pop	Pink Floyd	Complex	100.9
Solsbury Hill *(19)*	Rock	Peter Gabriel	Complex	120

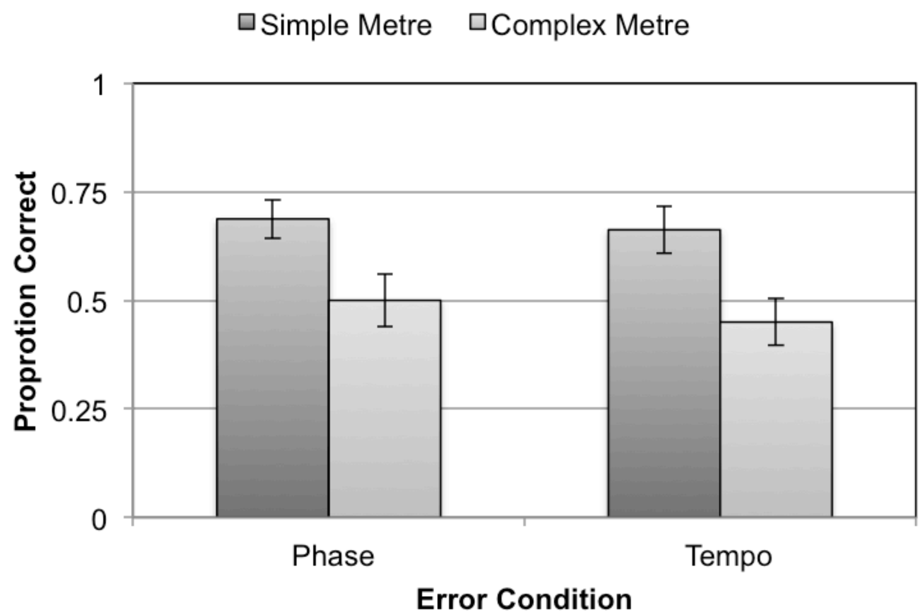

Figure 1: Perception scores from cBAT in Experiment One. The proportion of trials on which 5-year-old children chose the correctly aligned drumming is shown for phase and tempo conditions for simple and complex meter stimuli. Error bars represent standard error.

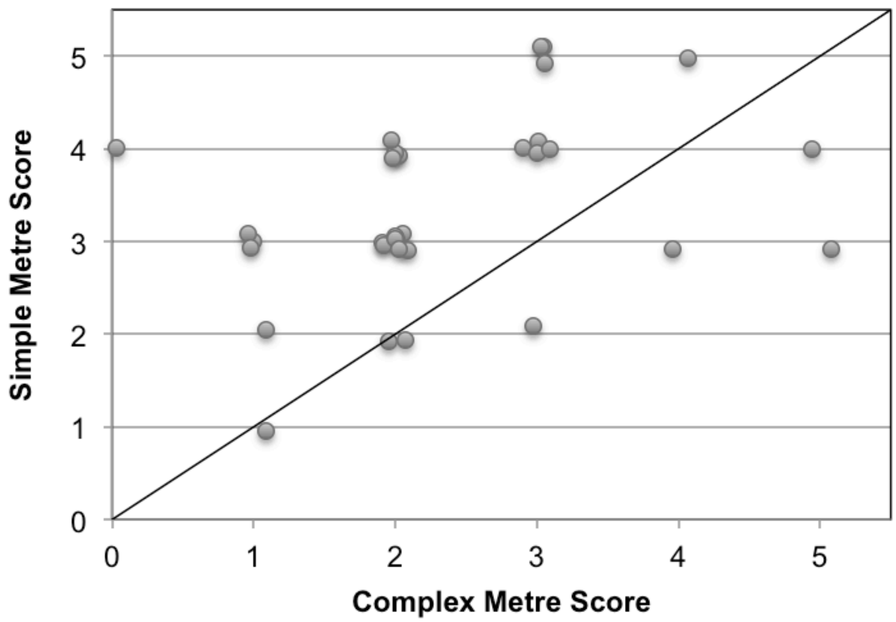

Figure 2: Individual results for the cBAT in Experiment One. Each point represents the data for one child, with the x-axis showing the number of trials on which the correctly aligned drumming excerpt was chosen for simple meter stimuli and the y-axis for complex meter stimuli. The preponderance of data above the diagonal indicates that performance was better for excerpts with simple compared to complex meter for the majority of children.

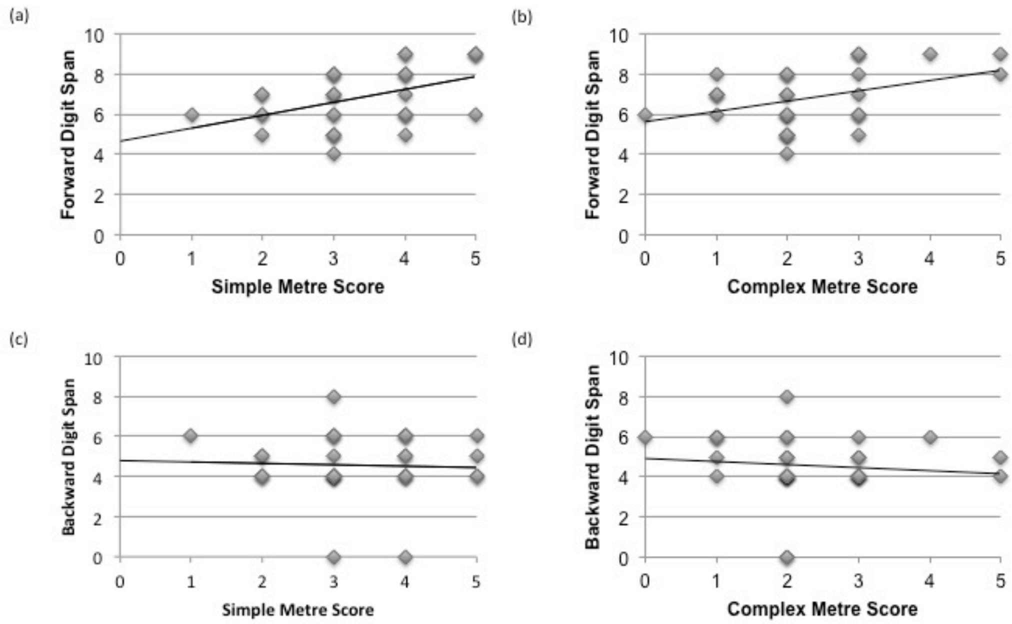

Figure 3: Correlations between performance on cBAT (including phase and tempo conditions) and forward and backward digit span in Experiment One. (a) cBAT simple meter scores and forward digit span, (b) cBAT complex meter scores and forward digit span, (c) cBAT simple meter scores and backward digit span, (d) cBAT complex meter scores and backward digit span. It can be seen that cBAT correlated with performance on forward digit span but not backward digit span.

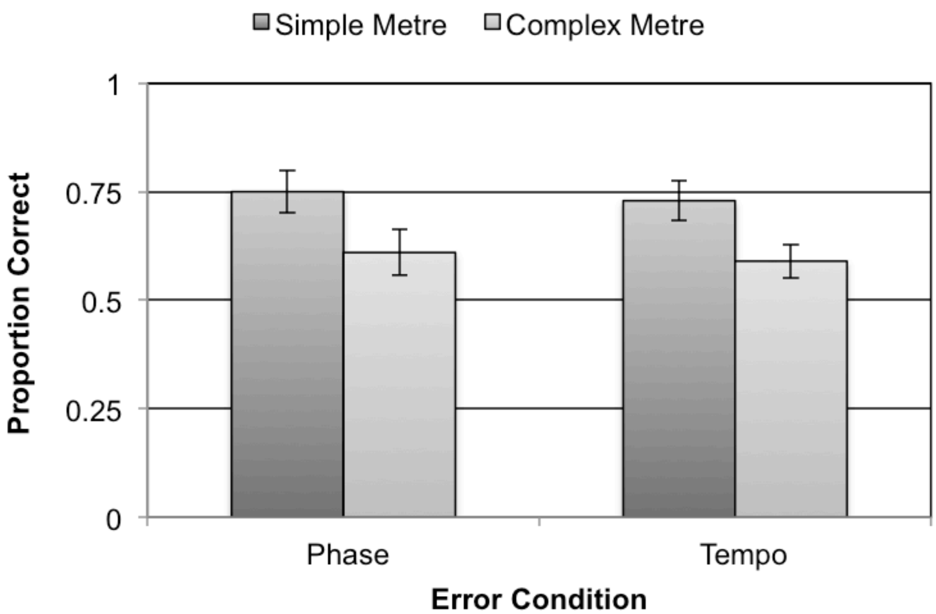

Figure 4: Perception scores from cBAT in Experiment Two. The proportion of trials on which 5-year-old children chose the correctly aligned drumming is shown for phase and tempo conditions for simple and complex meter stimuli. Error bars represent standard error.

CHAPTER 3: The effect of visual information on young children's perceptual sensitivity to musical beat alignment.

Einarson, K. M., & Trainor, L. J. (2015). The effect of visual information on young children's perceptual sensitivity to musical beat alignment. *Timing and Time Perception, 3*(1-2)*,* 88-101.

Preface

The previous chapter described a newly created test to assess children's sensitivity to auditory temporal information in the context of familiar and unfamiliar musical timing structures. The results of Chapter 2 suggest that musically untrained children are sensitive to both phase and tempo-driven misalignments of an auditory beat when the musical context has simple metric structure.

However, the musical stimuli in the original cBAT were not limited to the auditory modality, since they combined the auditory manipulations of interest with dynamic video footage of puppets playing drums. This multimodal presentation served to make the somewhat abstract nature of the auditory judgments more concrete for young children, by linking the auditory stimulus presentation to actual puppets that the child was able to see and touch as part of the task. Perhaps even more crucially, the videos helped maintain children's engagement in the listening task.

Given that the cBAT is designed to assess auditory sensitivity, the dynamic visual component raises the question of whether children's auditory perception could be influenced by the concurrently presented visual information. It has been established in adults that visual cues can alter both the temporal perception of auditory events (Schutz & Lipscomb, 2007) as well as judgments of music performance quality (Tsay, 2013). The auditory and visual cues being presented were congruent within each trial of the cBAT, so that the drumming sounds in the auditory stimulus always aligned with the drumming gestures in the visual stimulus in each trial. Although the videos did not provide conflicting sensory input, it was still possible that the multisensory nature of the stimuli had an effect on children's ability to judge the auditory manipulation of interest.

The study in Chapter 3 tested whether children demonstrate comparable sensitivity to auditory temporal information in the absence of the accompanying dynamic visual stimuli. Sensitivity was again assessed in the context of both simple and complex metre musical stimuli, but auditory stimuli were presented in conjunction with static images of puppets that did not exhibit any movement. This chapter replicates the finding that musically untrained children are sensitive to both phase and tempo misalignment in the context of musical excerpts with simple metre. Furthermore, the results suggest that children's ability to detect alignment errors in the auditory stimuli was not appreciably influenced by the presence of the concurrently presented dynamic visual information.

As such, these findings bolster the assertion that the cBAT is an effective means to assess young children's temporal sensitivity without requiring them to generate an overt motor response, and thus, provides a means of dissociating timing perception from motor synchronization.

Abstract

Recent work examined five-year-old children's perceptual sensitivity to musical beat alignment. In this work, children watched pairs of videos of puppets drumming to music with simple or complex metre, where one puppet's drumming sounds (and movements) were synchronized with the beat of the music and the other drummed with incorrect tempo or phase. The videos were used to maintain children's interest in the task. Five-year-olds were better able to detect beat misalignments in simple than complex metre music. However, adults can perform poorly when attempting to detect misalignment of sound and movement in audiovisual tasks, so it is possible that the moving stimuli actually hindered children's performance. Here we compared children's sensitivity to beat misalignment in conditions with dynamic visual movement versus still (static) visual images. 84 five-year-old children performed either the same task as described above or a task that employed identical auditory stimuli accompanied by a motionless picture of the puppet with the drum. There was a significant main effect of metre type, $p < 0.001$, replicating the finding that five-year-olds are better able to detect beat misalignment in simple metre music. There was no main effect of visual condition, $p = 0.63$. These results suggest that, given identical auditory information, children's ability to judge beat misalignment in this task is not affected by the presence or absence of dynamic visual stimuli. We conclude that at five years of age, children can tell if drumming is aligned to the musical beat when the music has simple metric structure.

Introduction

Music is socially pervasive, and much musical experience is amassed via exposure, such as in the context of formal events like weddings, or of everyday experiences like watching television. These types of experiences do not typically involve music as an isolated auditory stimulus, but are instead multimodal experiences. For example, dancing to music requires coordination of motor movements on the part of the listener, and in live or video recorded music performances people see as well as hear performers. Despite such everyday multisensory musical experiences, people are quite tolerant of timing misalignments between auditory and visual stimuli (e.g., Phillips-Silver et al., 2011; Sekuler et al., 1997; Vatakis & Spence, 2006a, b). In a previous study (Einarson & Trainor, 2016), we found that five- year-old children were able to detect phase and tempo errors in puppets' drumming to musical excerpts with simple metrical structures. Here we replicate this finding and investigate whether concurrent dynamic visual information affects children's performance on this task.

Musical timing has a *grouping* structure, which corresponds to the perception of phrases, as well as a *metrical* structure, which corresponds to the regular underlying beats and can be perceptually abstracted from the rhythmic surface (Gjerdingen, 1989; Lerdahl & Jackendoff, 1983). Rhythm and metre are universal aspects of music that vary between and across human cultures, and this paper is concerned with perception of metrical structure. Metrical structure is hierarchically organized, with the beats at different levels occurring at faster or slower rates (Essens & Povel, 1985). Some beats are accented and thus are perceived as stronger than others at a given level (Jones, 1976) and only accented beats are passed to the next level of the metrical hierarchy (Essens, 1986).

In simple metrical structures, accented beats occur at regular time intervals at each level of the hierarchy. Such regularly spaced beats are referred to as isochronous. Metre in Western music typically has simple metric structure, and most commonly possesses an underlying binary structure with a 2:1 ratio between beats at successive hierarchical levels (London, 2004). When notated, this music has time signatures such as 4/4 or 2/4. However, not all music is composed of a pattern that produces equally spaced pulses at each level of the hierarchy. For example, at one level of the metrical hierarchy, accents can occur to form patterns containing successive groups of two or three beats and, thus, irregularly spaced accents. These complex metrical structures are referred to as non-isochronous. Music notation reflects these complex patterns using notation such as 5/4 and 7/8.

Although Western music is primarily composed in simple metres, music from many other cultures (e.g. South Asia, Africa, the Middle East, and the Balkan region of southeastern Europe) commonly employs complex metrical structures. Adults from cultures such as Bulgaria and Macedonia demonstrate equal perceptual sensitivity to both simple and complex metrical stimuli (Snyder et al., 2006), and in cultures where complex metric structures are common, children also learn them from a young age, seemingly without difficulty (Rice, 1994). Infants are also sensitive to the beat of music very early in development (Patel et al., 2011;Winkler et al., 2009; Zentner & Eerola, 2010), and exposure over the course of the first year after birth to culturally typical metrical structures results in perceptual specialization for those metres (Hannon & Trehub, 2005; Soley & Hannon, 2010). This experience-guided perceptual narrowing in infancy is analogous to that seen across many domains, including the perception of phonemes (e.g. Trehub, 1976), faces (Kelly et al., 2007), voices (Friendly et al., 2013, 2014), and musical tonal structures (Hannon & Trainor, 2007; Lynch & Eilers, 1992; Lynch et al., 1990; Trainor & Hannon, 2012; Trainor & Trehub, 1992).

Despite the studies of metre perception in infancy, little work has examined children's ability to process metrical information. Some timing assessments have been developed for older children and for adults (Gordon, 1980) or have been designed to identify those with serious musical deficits (Peretz et al., 2003). Children's poor motor skills make it difficult to adapt the type of tapping synchronization tasks typically used with adult subjects (Drake, 1993); most involve tapping a single finger, which requires a high degree of fine motor control (Repp, 2005), and measure synchronization over a wide range of tempos over a prolonged period of time (Repp & Su, 2013). When infants and very young children are given the opportunity to move to music, they appear not to synchronize movements with the beat of the music (Eerola et al., 2006; Zentner & Eerola, 2010), indicating that movement synchronization tasks might underestimate young children's ability to perceive synchronization. Drake (1993) investigated factors that influence rhythm reproduction, and found that both Western adults and Western children are better at reproducing rhythms that can be considered simpler in structure. Other work (Einarson & Trainor, 2016; Hannon et al., 2012) has demonstrated that Western children are also better at perceiving timing information in music with simple metric structure, compared to music with complex metric structure.

However, musical timing perception has typically been challenging to measure independent from production or motor synchronization, and few studies have examined beat perception abilities in the absence of an overt motor response in either adults or children (see Repp, 2005 and Repp & Su, 2013 for reviews). Iversen and Patel (2008) developed a Beat Alignment Task (BAT) for adults that measures both perception of beat alignment as well as ability to synchronize to a musical beat and, as such, dissociates overt motor synchrony from perceptual sensitivity. In the perception portion of the BAT, adult subjects judge whether an isochronous auditory tone superimposed over each of 12 musical excerpts is correctly aligned with the beat. Incorrect beats were either too fast or too slow by 10% of the inter-beat interval, or too early or too late by 25%.

We developed a child-friendly complex Beat Alignment Task (cBAT; Einarson & Trainor, 2016) that can be used with both children and adults. It extends the perception component of the BAT paradigm (Iversen & Patel, 2008) in two notable ways: first, by adding dynamic visual stimuli to accompany short musical excerpts and, second, by including music excerpts with both simple and complex metres. Half of the musical excerpts in the stimulus set are in 4/4 time (simple metric structure), while the other half are in 5/4 or 7/4 time (complex metric structure).

The original cBAT from Einarson and Trainor (2016) uses dynamic videos of hand puppets that drum along to short musical sequences. An isochronous drumbeat is superimposed on each of the musical tracks such that a wood- block tapping sound matches the drumming movements of the puppets. On each trial, two videos are presented successively, each with the same musical track, but a different puppet. In one video the sound of the puppet's drumming is correctly aligned to the beat of the music; in the other, the puppet drums out of phase (25% too early or too late) or at an incorrect tempo (10% too fast or too slow) relative to the musical excerpt being presented. Participants choose which puppet in each pair is the better drummer. Einarson and Trainor (2016) found that five-year- old children were sensitive to both phase and tempo misalignments under these conditions, but only in the context of simple metre music. Error detection was not significantly different from chance for complex metre music. As such, we expect that children will show the same perceptual bias for music with culturally typical simple metric structures in the present study.

Using drumming puppets is very engaging and these stimuli kept children attentive through the procedure. However, the stimuli do contain both auditory and visual cues to beat alignment, because trials combine musical examples with video clips of moving puppets. On the one hand, it is possible, though unlikely, that children were relying on visual rather than auditory cues to make their judgments. On the other hand, research has shown that adults perform poorly when attempting to detect misalignment of music and movement in audiovisual tasks (e.g., Phillips-Silver et al., 2011; Vatakis & Spence, 2006a, b). Perception of auditory and visual simultaneity is also vulnerable to the effects of exposure to stimulus asynchrony (Harrar & Harris, 2008), suggesting the perception of synchrony can be modified by experience. Further studies show that visual cues can influence the perception of temporal aspects of music (Schutz & Lipscomb, 2007) and the processing of speech sounds in auditory cortex (Sams et al., 1991).

Most studies of multimodal integration focus on situations where two sensory modalities receive incongruent information about a source (De Gelder & Bertelson, 2003). In addition to those already described, one of the best-known examples of this type of multisensory integration is the McGurk effect (McGurk & MacDonald, 1976), in which there is a mismatch between the presented speech sound and lip movements. In audiovisual tasks designed to promote a perception of simultaneity, there is considerable perceptual tolerance of asynchrony between auditory and visual information (e.g., Sekuler et al., 1997).

It is important to note, however, that in the dynamic cBAT stimuli, the auditory stimulus (isochronous woodblock taps) and visual stimulus (puppet tapping gestures) were synchronous and congruent. As such, there was no misalignment between the auditory and visual modalities. One puppet in every pair simply produced audio-visual drumming that had either incorrect phase or inappropriate tempo relative to the beat of the musical excerpt being presented, leading to mismatched information *within* the auditory stimulus. Even so, it has been established that even congruent visual information can influence perception of simultaneously presented auditory information (Schutz & Lipscomb, 2007) and judgments about musical performance (Tsay, 2013). If auditory perception is, in fact, vulnerable to the effects of simultaneously presented visual information, it is possible that the dynamic visual stimuli could have impaired children's ability to detect beat misalignment in the auditory stimulus.

To address the question of whether young children's sensitivity to the beat as measured in in the cBAT is affected by the presence of dynamic visual information (i.e., moving videos), we tested five-year-old children using either the original cBAT, or a modified version of the cBAT that used static visual images accompanied by the same auditory stimuli.

In addition to administering either the dynamic or static version of the cBAT, we also assessed children's cognitive abilities using standardized measures of memory and vocabulary. Adults' working memory capacity has been found to correlate with their performance on rhythm reproduction tasks (Bailey & Penhune, 2010), and children's ability to discriminate rhythm sequences has been found to correlate with auditory working memory, as measured by a digit span task (Strait et al., 2011). It is also possible that the moving video stimuli would place greater demands on children's working memory than the comparatively impoverished static images, in which case children's memory capacity would contribute to differences in performance between conditions. We examined the relationship between memory span and beat perception by having each child complete the forward and backward components of the digit span subtest from the Wechsler Intelligence Scale for Children (WISC-IV; Wechsler, 2003). Because children needed to understand the instructions in order to perform the cBAT, we also administered the Peabody Picture Vocabulary Test (PPVT-4; Dunn & Dunn, 2007), which is a standardized measure of receptive vocabulary. The PPVT can also serve as a proxy for verbal IQ as it correlates highly with various IQ instruments (Dunn & Dunn, 2007). This allowed us to determine whether beat perception ability might be related to cognitive ability more generally.

The present experiment used two versions of the complex Beat Alignment Task (cBAT) to assess whether visual condition (either dynamic or static) would influence five-year-old children's beat alignment sensitivity. We predicted that, as in previous work (Einarson & Trainor, 2016), children would be sensitive to beat alignment in the context of both tempo- and phase-related errors, but that they would be better able to detect beat alignment in musical excerpts with simple metric structures compared to in musical excerpts with complex metric structures. Additionally, we investigated whether there would be an improvement in children's beat alignment sensitivity when dynamic visual information was removed from the cBAT task, as a result of reduced perceptual inference with the auditory stimuli.

Methods

Participants

The final sample included 84 five-year-old children (41 female, Mage = 5 years, 6 months) who were not enrolled in formal music lessons at the time of testing, and had no previous formal instrumental training. An additional 25 children were excluded from the final analyses because of failure to complete all tasks ($n = 7$), equipment failure ($n = 7$), having formal musical training ($n = 3$), having a diagnosed developmental disorder ($n = 3$), experimenter error ($n = 3$), or vocabulary scores more than two standard deviations below the mean ($n = 2$).

Subjects were assigned to a cBAT condition with either dynamic videos ($n = 48$, 24 female) or static images ($n = 36$, 17 female). Within the dynamic video condition, participants were randomly assigned to either the phase error ($n = 24$, 12 female) or tempo error ($n = 24$, 12 female) condition. In the static image condition, participants were also randomly assigned to either the phase error ($n = 18$, 9 female) or tempo error ($n = 18$, 8 female) condition.

All participants were recruited from the McMaster Infant Studies Group database. Annual family income was measured on a six-point scale (1=<$30,000, 6=>$150,000; Canadian dollars, data missing for nine children). The average family income was between $90,000 and $120,000 per year for children in both conditions. All protocols were approved by the McMaster Research Ethics Board, and informed consent was obtained from all parents.

Stimuli

1. Complex Beat Alignment Test

The stimulus set for the *dynamic version* of the complex Beat Alignment Test (cBAT) was identical to that used in Einarson and Trainor (2016). Stimuli consisted of videos of hand puppets drumming along to 12 musical excerpts. Each excerpt ranged in length from 10 to 22 seconds, and tempo ranged from 88 to 172 beats per minute. The excerpts were organized into six pairs that were matched according to genre, tempo, and instrumentation, and all excerpts were selected from existing commercial audio recordings. One excerpt in each pair had simple metric structure (4/4 time signature) common in Western music compositions. The other had a complex metric structure (either a 5/4 or 7/4 time signature). These complex structures are less common in Western music compositions.

In all cases, the visual stimuli were accompanied by a musical excerpt with superimposed isochronous woodblock tapping sounds. The accompanying audio stimuli were created by determining average tempo of each musical sample using *MixMeister BPM Analyzer* software, and then creating woodblock tapping sounds with the same tempo in *Apple GarageBand 2009*. The tapping was aligned with the music by a human listener to create a *correctly aligned* ('on-the-beat') woodblock tapping track for each excerpt, as well as two *phase error* tapping tracks (woodblock taps were phase shifted to be either 25% too early or 25% too late relative to the beat of the music) and two *tempo error* tapping tracks (speed of the woodblock taps was either 10% too fast or 10% too slow relative to the beat of the music).

The standard track, two out-of-phase tracks, and two incorrect-tempo tracks were created for ten of the twelve musical excerpts and were used to create the test trials in both versions of the cBAT. The remaining pair of musical excerpts (one with simple metre and one with complex metre) served as practice trials in the simple metre and complex metre blocks, respectively. Correctly aligned standard tracks were created for these remaining two musical excerpts. Additionally, *randomized* wood- block tracks with pseudo-random non-isochronous taps were created to serve as the "wrong" answer for each of the practice excerpts.

The accompanying visual stimuli were created by filming 24 hand puppets tapping on a toy drum along to the auditory stimuli described above. The two paired puppets on each trial were semantically related (e.g., horse and cow), and each puppet in the pair drummed along to a single simple-metre musical excerpt in the first error condition, and a complex-metre excerpt for the other error condition. Error type within each condition was balanced between subjects so that half of the children in each condition saw a particular puppet make one type of error (e.g., fast or early) and the other half of the children saw that puppet make the other error type (e.g., slow or late).

The result of this balanced design was the creation of six videos for each of the ten musical excerpts that were used in test trials in the dynamic condition (two standard videos, one for of each puppet in the pair, two phase shifted error videos from one puppet, and two tempo shifted videos from the other puppet), for a total of 60 test videos, and eight practice videos (four standard and four randomized). In the static condition, there were a total of 68 matched still images accompanied by the same auditory stimuli used in the dynamic condition.

The *static version* of the cBAT was identical to the dynamic version, except that still images of the puppets replaced the videos. Specifically, the images were created by taking a single frame from the beginning of each video from the dynamic condition, and pairing the appropriate audio track with this matched still image. In both conditions, visual stimuli were presented to the child on a 24-inch Samsung SyncMaster 2494 widescreen LCD monitor, and the audio files were played at a comfortable volume, adjusted according to each child's preference, through M-Audio AV-40 monitor speakers. The experimenter managed the playlists through iTunes 11.0.2(26) on a 21.5-inch Apple iMac (11.2) Core i5.

2. Digit Span Test

All participants completed a subtest of the Working Memory Index (WMI) from the Wechsler Intelligence Scale for Children, 4th edition (WISC-IV; Wechsler, 2003). This test requires the child to repeat strings of digits produced by the experimenter. In the digits forward section, the child is required to repeat back digits in the same order they are provided. The digits backward section requires the child to repeat the digits in the reverse order from the experimenter. The task begins with a two-digit string, and the number of digits increases by one on every second trial. In each section, testing stops when the child fails to correctly repeat both strings of digits of a given length.

3. Peabody Picture Vocabulary Test

All participants completed the Peabody Picture Vocabulary Test, 4th edition (PPVT-IV; Dunn & Dunn, 2007), a standardized measure of receptive vocabulary. In this test, the experimenter says a word, and the child chooses which image best represents the vocabulary item from a set of four cartoon pictures. Vocabulary items gradually increase in difficulty. Raw scores were standardized according to the subject's age, and normed as described in the Examiner's Manual.

4. Parental Questionnaire

While the child was tested, parents completed a questionnaire about their child's health, language experience, extracurricular activities, and formal or informal music experience. Optional demographic questions regarding parental education and income were answered by only a subset of parents.

Procedure

Children were tested during one session that was approximately 45 minutes in length. The cBAT (either dynamic or static) was administered in two separate blocks, where one block consisted of the simple metre stimuli and the other the complex metre stimuli. Block order was counterbalanced across children.

Each trial consisted of a pair of two musical excerpts accompanied by drumming. In one, the drumming was correctly aligned to the music. In the other the drumming was either out of phase or out of tempo relative to the excerpt, as described above. In the dynamic cBAT condition, the audio tracks were accompanied by the videos of the puppets drumming whereas in the static cBAT condition, the audio tracks were accompanied by a static image rather than a dynamic video of the puppets drumming. Error type was a between-subjects variable, so that half of the participants were presented with only tempo shift errors for all test trials, and the other half with only phase shift errors. In all four conditions (error-type condition crossed with visual condition), each block consisted of one practice trial (with one puppet whose drumming was correctly aligned, and one that drummed along to the randomized woodblock stimuli), followed by five test trial pairs of puppet stimuli. For each condition, half the children heard two trials on which one puppet was too fast (or early) and three that were too slow (or late); in the other half of children these were reversed. Additionally, half the trials had errors presented by the first puppet in the pair, and half by the second puppet.

Before the cBAT was administered, participants were instructed that they were about to hear two puppets drumming along to the same song, and that they had to determine which puppet would be a better drummer for a band. Before each trial, the experimenter showed the child the two puppets that would be presented in that trial, and identified them by name (for example, “This is my friend the bunny, and this is my friend the dog”). After the child heard both performances, the experimenter placed the two actual puppets in front of the child on the table, and asked the child to place a ribbon on the puppet who should win the prize. The practice trial at the beginning of each block was repeated until the participant correctly identified the puppet whose drumming was correctly aligned to the music. Test trials were not repeated, and the child received no feedback regarding their choices. The order of tasks was the same for all subjects: Block 1 of the cBAT, Digit Span task, Block 2 of the cBAT, followed by the PPVT. At the end of the testing session, each participant received a certificate of participation and a small prize.

Results

We first examined children's ability to detect musical beat misalignment when presented with either dynamic visual movement or static visual images. The dependent measure was the proportion of the time the five-year-old children selected the puppet that played the standard version as the best drummer.

We conducted a 2×2×2 ANOVA with visual condition (dynamic, static) and error type (phase, tempo) as between-subjects factors and metre type (simple, complex) as a within-subjects factor. There was a significant main effect of metre type, $F(1,46) = 14.25$, $p < 0.001$, but no main effect of visual condition, $F(1,46) = 0.23$, $p = 0.63$ and no main effect of error type, $F(1,46) = 0.06$, $p = 0.81$. There were also no significant interactions (all $p > 0.2$). These results suggest that, given identical auditory information, children's ability to judge beat misalignment is not affected by whether accompanying visual information is static or dynamic (see Fig. 1).

Although there was no main effect or interactions involving visual condition, we examined each visual condition separately in order to verify that the effect of metre type was present in both visual conditions, and to determine in which conditions performance was significantly above chance levels. For the dynamic visual condition, a 2×2 ANOVA with error type (phase, tempo) as a between-subjects factor and metre type (simple, complex) as a within-subjects factor revealed only a significant main effect of metre type, $F(1,46) = 6.40$, $p = 0.013$. Children were better at detecting beat misalignment in simple metres (proportion correct = 0.65, $SD = 0.22$) than complex metres (proportion correct = 0.54, $SD = .25$) and this was not affected by whether the error was a phase or tempo error. Furthermore, performance was above chance levels for simple meter for both error types (tempo error: $p < 0.001$; phase error: $p = 0.014$) but not for complex meter (tempo error: $p = 0.18$; phase error $p = 0.30$). These results replicate those of Einarson and Trainor (2016).

For the static visual condition, the 2×2 ANOVA again revealed a significant main effect of metre type, $F(1,34) = 4.66$, $p = 0.038$. As in the dynamic visual condition, children were better at detecting beat misalignment in simple metres (proportion correct = 0.64, $SD = 0.23$) than complex metres (proportion correct = 0.52, $SD = 0.26$). Furthermore, performance was above chance levels for simple meter for both error types (tempo error: $p = 0.02$; phase error: $p = 0.005$) but not for complex meter (tempo error: $p = 0.42$; phase error: $p = 0.37$). These results replicate those of Einarson and Trainor (2016) and suggest that, given identical auditory information, children's ability to judge beat misalignment is not affected by whether an accompanying visual stimulus is static or dynamic.

Overall performance on the cBAT (combined across visual conditions) was not significantly correlated with children's total score on the Digit Span test (M =10.63, SD = 2.41), $p = 0.65$. Judgment accuracy for simple metre stimuli was not correlated with forward digit span, $p = 0.50$, or backward digit span, $p = 0.86$. Judgment accuracy for complex metre stimuli was also not correlated with forward digit span, $p = 0.38$, or backward digit span, $p = 0.33$. These results suggest that children's working memory, as indexed by the digit span task, does not relate to performance on the cBAT task.

PPVT standard scores (M =117.45, SD =10.44) did not significantly correlate with the simple metre portion of the cBAT, $p = 0.39$, but were significantly correlated with children's performance on the complex metre portion of the cBAT, $r = 0.28$, $n = 88$, $p = 0.01$.

Discussion

We set out to examine the degree to which five-year-old Western children show better perceptual sensitivity for culturally typical simple metre music, compared to culturally atypical complex metres, in the presence or absence of dynamic visual information. We used a perceptual measure of beat sensitivity, the cBAT (Einarson & Trainor, 2016), which assessed children's ability to detect phase and tempo misalignment and included musical excerpts with both simple and complex metres. The original cBAT (Einarson & Trainor, 2016) requires children to watch paired videos of puppets, one of whom drums on time relative to accompanying music and one of whom does not. Children are then asked to judge which puppet drummed better. Drumming errors involved either a tempo error (10% too fast or too slow) or a phase error (25% too early or too late) and in all cases, the movements of the puppets were aligned with the drumming sounds that they made. In the present study, we created a modified version of the cBAT that used static visual images accompanied by the same auditory stimuli.

In both versions of the task, children were able to detect drumming that was out of phase with the music or at the wrong tempo when musical excerpts had simple metric structure. This demonstrates that by the age of five, children have the ability to make explicit judgments about beat alignment, and that given identical auditory information, children's ability to judge beat misalignment is not affected by whether an accompanying visual stimulus is static or dynamic. These findings extend previous literature on children's timing development (Bobin-Bègue & Provasi, 2009; Drake, 1993; Einarson & Trainor, 2016; Kirschner & Tomasello, 2009; Provasi & Bobin-Bègue, 2003; van Noorden & De Bruyn, 2009; Zentner & Eerola, 2010) by showing that five-year-olds are sensitive to both tempo misalignment and phase misalignment in the context of simple-metered music. Replicating Einarson & Trainor (2016), for both static and dynamic stimuli, judgment accuracy was significantly worse when musical excerpts had complex metric structures compared to simple metric structures, and performance was not above chance for excerpts with complex metre.

Interestingly, children's performance on the complex metre portion, but not the simple meter portion, of the cBAT in the present study was correlated with receptive vocabulary, as measured by the Peabody Picture Vocabulary Task (Dunn & Dunn, 2007). It is possible that having a larger vocabulary leads to a better ability to comprehend and follow the verbal instructions that accompany the beat perception task, leading to improved task performance. However, this is unlikely, as vocabulary score did not affect performance on the simple meter portion, and the instructions were identical for both portions. Alternately, given that the PPVT correlates highly with other assessments of verbal IQ (Dunn & Dunn, 2007), receptive vocabulary scores may reflect children's cognitive ability more generally. This correlation was not significant in the original cBAT study with five-year-old children (Einarson & Trainor, 2016), so further investigation is needed of the factors that contribute to young children's ability to process complex meters that are not prevalent in their cultural environment.

The development of the cBAT enables further testing several important questions regarding the development of timing abilities. Because the cBAT is a purely perceptual task, it is now possible to test perception and production separately to determine whether there is a dissociation between these skills in young children. The cBAT also offers a means to test metrical enculturation in young children across cultures. Children from some Balkan regions, for example, grow up being exposed to a much wider variety of musical metres, and it has been observed that they learn these structures easily from a young age (Rice, 1994).

However, the only cross-cultural investigation of simple and complex musical metre processing to date tested Bulgarian and Macedonian adults (Hannon & Trehub, 2005). If the better performance of Western children in the present study on musical excerpts with simple compared to complex meter is a function of enculturation, then children who are raised in a culture where complex metre music is widespread should show equal ability for beat alignment in music with simple and complex metres.

In sum, we found that Western five-year-old children can detect misalignments in both the tempo and phase of a beat relative to a musical sample with culturally typical simple metre, and that judgment accuracy is not affected by characteristics of the accompanying visual stimulus; children do equally well when the visual display is static or dynamic. For both types of visual stimuli, children's ability to detect misalignments in both the tempo and phase of a musical beat was at chance levels in the context of less familiar complex metre music. The design of the cBAT enables future investigation of the relation between children's perceptual sensitivity and their ability to synchronize movements to a musical beat. It also provides a means to investigate effects of enculturation on metre sensitivity, for example, by comparing the performance of Western children to children from cultures where complex meters are widespread.

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References

Bailey, J. A., & Penhune, V. B. (2010). Rhythm synchronization performance and auditory working memory in early-and late-trained musicians. *Exp. Brain Res.*, *204*, 91–101.

Bobin-Bègue, A., & Provasi, J. (2009). Tempo discrimination in 3- and 4-year-old children: Performances and threshold. *Curr. Psychol. Lett.*, *2*, 1–13.

De Gelder, B., & Bertelson, P. (2003). Multisensory integration, perception and ecological validity. *Trends Cogn. Sci.*, *7*, 460–467.

Drake, C. (1993). Reproduction of musical rhythms by children, adult musicians, and adult nonmusicians. *Percept. Psychophys.*, *53*, 25–33.

Dunn, L. M., & Dunn, D. M. (2007). *Peabody Picture Vocabulary Test fourth edition, Manual*. Minneapolis, MN, USA: Pearson Assessments.

Eerola, T., Luck, G., & Toiviainen, P. (2006). An investigation of pre-schoolers' corporeal synchronization with music. In M. Baroni, A. R. Addessi, R. Caterina, & M. Costa (Eds), *Proceedings of the 9th International Conference on Music Perception & Cognition (ICMPC9)*, *August 2006, Bologna, Italy* (pp. 472–476). Bologna, Italy: Bononia University Press.

Einarson, K. M., & Trainor, L. J. (2016). Hearing the beat: Young children's perceptual sensitivity to beat alignment varies according to metric structure. *Music Percept. 34*, 56-70.

Essens, P. J. (1986). Hierarchical organization of temporal patterns. *Percept Psychophys*, *40*, 69–73.

Essens, P. J., & Povel, D. J. (1985). Metrical and nonmetrical representations of temporal patterns. *Percept. Psychophys.*, *37*, 1–7.

Friendly, R. H., Rendall, D., & Trainor, L. J. (2013). Plasticity after perceptual narrowing for voice perception: Reinstating the ability to discriminate monkeys by their voices at 12 months of age. *Front. Auditory Cogn. Neurosci., 4*, 1–18.

Friendly, R. H., Rendall, D., & Trainor, L. J. (2014). Learning to differentiate individuals by their voices: Infants' individuation of native- and foreign-species voices. *Dev. Psychobiol. 56*, 228–237.

Gordon, E. E., (1980). *Manual for the primary measures of music audition and* *the intermediate measures of music audiation*. Chicago, IL, USA: G.I.A.

Gjerdingen, R. O. (1989). Meter as a mode of attending: A network simulation of attentional rhythmicity in music. *Intégral*, *3*, 67–91.

Hannon, E. E., & Trehub, S. E. (2005). Metrical categories in infancy and adulthood. *Psychol. Sci.*, *16*, 48–55.

Hannon, E. E., & Trainor, L. J. (2007). Music acquisition: Effects of enculturation and formal training on development. *Trends Cogn. Sci.*, *11*, 466–472.

Hannon, E.E., der Nederlanden, C.M.V.B., & Tichko, P. (2012). Effects of perceptual experience on children's and adults' perception of unfamiliar rhythms. *Ann. N. Y. Acad. Sci., 1252*, 92–99.

Harrar, V., & Harris, L. R. (2008). The effect of exposure to asynchronous audio, visual, and tactile stimulus combinations on the perception of simultaneity. *Exp. Brain Res.*, *186*, 517–524.

Iversen, J. R., & Patel, A. D. (2008). The Beat Alignment Test (BAT): Surveying beat processing abilities in the general population. In K. Miyazaki, M. Adachi, Y. Hiraga, Y. Nakajima, & M. Tsuzaki (Eds), *Proceedings of the 10th International Conference on Music Perception & Cognition (ICMPC10), August 2008, Sapporo, Japan* (p. 465–468). Adelaide, Australia: Causal Productions.

Jones, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychol. Rev.*, *83*, 323.

Kelly, D. J., Quinn, P. C., Slater, A. M., Lee, K., Ge, L., & Pascalis, O. (2007). The other-race effect develops during infancy: Evidence of perceptual narrowing. *Psychol. Sci.*, *18*, 1084–1089.

Kirschner, S., & Tomasello, M. (2009). Joint drumming: Social context facilitates synchronization in preschool children. *J. Exp. Child Psychol., 102*: 299–314.

Lerdahl, F., and Jackendoff, R. (1983). *A generative theory of tonal music*. Cambridge, MA, USA: MIT Press.

London, J. (2004). *Hearing in time: Psychological aspects of musical meter*. Oxford, UK and New York, NY, USA: Oxford University Press.

Lynch, M. P., & Eilers, R. E. (1992). A study of perceptual development for musical tuning. *Percept. Psychophys., 52,* 599–608.

Lynch, M. P., Eilers, R. E., Oller, D. K., & Urbano, R. C. (1990). Innateness, experience, and music perception. *Psychol. Sci.*, *1*, 272–276.

McGurk, H., & MacDonald, J. (1976) Hearing lips and seeing voices. *Nature 264*(5588): 746–748.

Patel, A. D., Iversen, J. R., Brandon, M., & Saffran, J. (2011). Do infants perceive the beat in music? A new perceptual test. In *Proceedings of the 2011 Biennial Meeting of the Society for Music Perception & Cognition (SMPC 2011), August 2011,* Rochester, NY, USA.

Peretz, I., Champod, S., & Hyde, K. (2003) Varieties of musical disorders: The Montreal battery of evaluation of amusia. *Ann. N. Y. Acad. Sci.*, *999*, 58–75.

Phillips-Silver, J., Toiviainen, P., Gosselin, N., Piché, O., Nozaradan, S., Palmer, C., & Peretz, I. (2011). Born to dance but beat deaf: A new form of congenital amusia. *Neuropsychologia*, *49*, 961–969.

Provasi, J., & Bobin-Bègue, A. (2003). Spontaneous motor tempo and rhythmical synchronisation in 21⁄2- and 4-year-old children. *Int. J. Behav. Dev.*, *27*, 220–231.

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonom. Bull. Rev.*, *12*, 969–992.

Repp, B. H., & Su, Y. H. (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonom. Bull. Rev.*, *20*, 403–452.

Rice, T. (1994). *May it fill your soul: Experiencing Bulgarian music*. Chicago, IL, USA: University of Chicago Press.

Sams, M., Aulanko, R., Hämäläinen, M., Hari, R., Lounasmaa, O. V., Lu, S. T., & Simola, J. (1991). Seeing speech: Visual information from lip movements modifies activity in the human auditory cortex. *Neurosci. Lett.*, *127*, 141.

Schutz, M., & Lipscomb, S. (2007). Hearing gestures, seeing music – Vision influences perceived tone duration. *Perception, 36*, 888–897.

Sekuler, R., Sekuler, A. B., & Lau, R. (1997). Sound alters visual motion perception. *Nature*, *385*(6614), 308.

Snyder, J. S., Hannon, E. E., Large, E. W., & Christiansen, M. H. (2006).

Synchronization and continuation tapping to complex meters. *Music Percept.*, *24*, 135–146.

Soley, G., & Hannon, E. E. (2010). Infants prefer the musical meter of their own culture: A cross- cultural comparison. *Dev. Psychol., 46*, 286–292.

Strait, D. L., Hornickel, J., & Kraus, N. (2011). Subcortical processing of speech regularities underlies reading and music aptitude in children. *Behav. Brain Funct.*, *7*, 1–11.

Trainor, L. J., & Hannon, E. E. (2012). Musical development. In D. Deutsch (Ed.), *The psychology of music* (3rd ed.). San Diego, CA, USA: Academic Press.

Trainor, L. J., & Trehub, S. E. (1992). A comparison of infants' and adults' sensitivity to Western musical structure. *J. Exp. Psychol. Hum. Percept. Perform., 18*, 394–402.

Trehub, S. E. (1976). The discrimination of foreign speech contrasts by infants and adults. *Child Dev., 47*, 466–472.

Tsay, C. J. (2013). Sight over sound in the judgment of music performance. *Proc. Natl Acad. Sci.*, *110*, 14580–14585.

van Noorden, L., & De Bruyn, L. (2009). The development of synchronization skills of children 3 to 11 years old. In P. Toiviainen (Ed.), *Proceedings of ESCOM—7th Triennial Conference of the European Society for the Cognitive Sciences of Music*. Jyväskylä, Finland: University of Jyväskylä.

Vatakis, A., & Spence, C. (2006a). Audiovisual synchrony perception for speech and music assessed using a temporal order judgment task. *Neurosci. Lett.*, *393*, 40–44.

Vatakis, A., & Spence, C. (2006b). Audiovisual synchrony perception for music, speech, and object actions. *Brain Res.*, *1111*, 134–142.

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children fourth edition*. San Antonio, TX, USA: The Psychological Corporation.

Winkler, I., Háden, G. P., Ladinig, O., Sziller, I., & Honing, H. (2009). Newborn infants detect the beat in music. *Proc. Natl Acad. Sci.*, *106*, 2468–2471.

Zentner, M., & Eerola, T. (2010). Rhythmic engagement with music in infancy. *Proc. Natl Acad. Sci.*, *107*, 5768–5773.

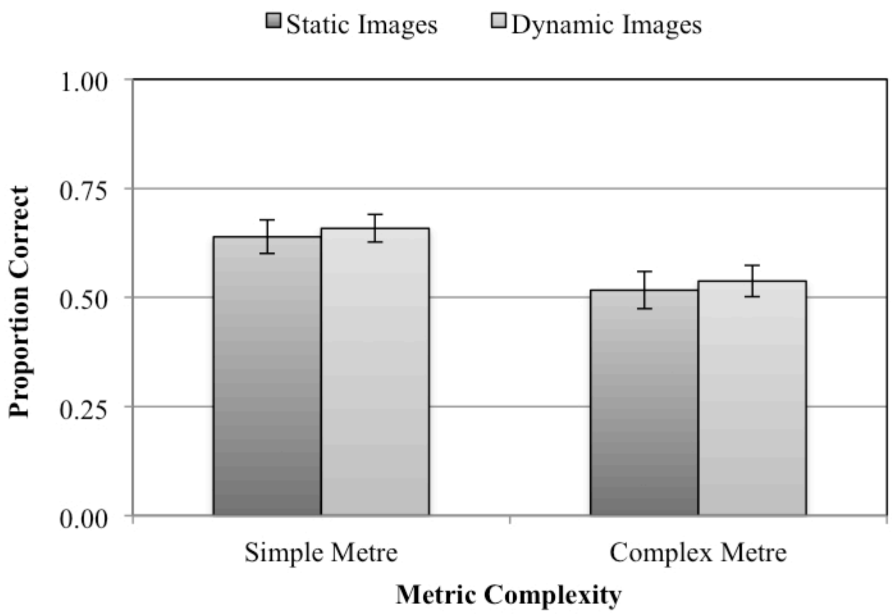

Figure 1: Perception scores from the dynamic and static versions of the cBAT. Because there was no main effect of error type, data have been collapsed across phase and tempo conditions. The proportion of trials on which 5-year-old children chose the correctly aligned drumming is not significantly different for static versus dynamic visual conditions (p = .63), for either simple or complex metre stimuli, but there is a significant main effect of metre type (p < .001). Error bars represent standard error.

CHAPTER 4: Development of beat perception and synchronization in young children: examining effects of metric complexity and acoustic structure using the complex Beat Alignment and Tapping Test (cBATT)

Einarson, K. M. & Trainor, L. J. (in preparation for submission). Development of beat perception and synchronization in young children: examining effects of metric complexity and acoustic structure using the complex Beat Alignment and Tapping Test (cBATT)

Preface

Chapter 3 replicated the finding that children assessed using the cBAT show perceptual sensitivity to temporal information in music, and also demonstrated that this sensitivity is neither driven by nor impaired as a result of the presence of dynamic visual information. Together, Chapters 2 and 3 establish the cBAT as the first task in the literature to successfully characterize children's perceptual sensitivity to a musical beat in the context of both simple and complex metre music without requiring an overt motor synchronization response.

Having established both the tool's usefulness as a perceptual assessment and also its replicability, Chapter 4 expands the cBAT in two relevant ways. First, the addition of an adapted, child-friendly beat synchronization measure allows for the assessment of children's sensorimotor synchronization to both simple and complex metre music. These synchronization data allow us to investigate the relationship between timing perception and production abilities in childhood, and to compare with the adult literature. The cBAT tapping task is designed to assess children's synchronization across diverse contexts, including relatively impoverished metronome stimuli, culturally typical simple metre music, and culturally atypical complex metre music.

Second, this chapter uses the expanded cBATT to assess not only 5-year-old children, as in previous work, but also 7-year-old children. Children's spontaneous motor tempo, tapping performance, and other motor coordination skills all change over the course of early childhood (e.g. Drake et al., 2000, McAuley et al., 2006, Provasi & Bobin-Begue, 2003). This work adds to that literature by examining the changing relationship between musical beat perception and sensorimotor synchronization as children develop, and characterizes how perception and synchronization improve with age.

While examinations of children's tapping synchronization have been reported previously, this study represents a first attempt to relate them to music timing perception data, by using the cBAT behavioural task. Moreover, the data suggest that different aspects of music affect success in beat perception and sensorimotor synchronization tasks. Finally, results of this chapter suggest that children's ability to synchronize movements to external auditory stimuli may be affected by acoustic characteristics of the stimulus, including event density, spectral flux, RMS energy, and pulse clarity.

Abstract

Recent work (Einarson & Trainor, 2015; 2016) examined 5-year-old children's ability to perceive the beat in music using the complex Beat Alignment Task (cBAT). The present study expanded the cBAT to include a production beat synchronization tapping task, creating the complex Beat Alignment and Tapping Test (cBATT). 48 5-year-old and 40 7-year-old children completed both the perception and production parts of the cBATT. For the perception part, a trial consisted of two consecutive videos of puppets drumming to a short musical excerpt in either simple or complex metre. One puppet drummed in synchrony with the beat of the music, and the other, either out of phase or out of tempo. Children gave a prize to the puppet that drummed better. To assess beat synchronization tapping, a new task was created in which children first tapped on an electronic drum at a self-paced steady speed, then along with a metronome at three speeds, and finally along with the same musical excerpts used in the perception task. Performance improved overall with age, but beat perception was significantly better in music with simple than complex metre for both 5-year-olds ($p < .001$) and 7-year-olds ($p = .004$). Only 7-year-olds detected errors in complex metre music at above-chance levels. Circular statistics were used to assess the synchronization consistency (vector length, R) and phase alignment accuracy (vector angle, θ) of children's tapping. Both synchronization consistency and phase accuracy were significantly better for metronome synchronization tapping than tapping to songs for both age groups. 7-year-olds were significantly better

than 5-year-olds for synchronization consistency ($p < .001$) but there was no difference across age for phase accuracy ($p = .77$). Phase alignment accuracy at both ages was correlated with acoustic characteristics like event density and spectral flux. We conclude that overall perceptual sensitivity to a musical beat is significantly better in 7-year-old children than in 5-year-old children, and both groups perform better with simple than complex metres. For the synchronization task, better performance in the context of simple metre music was not observed, a difference suggesting a dissociation between beat perception and beat synchronization in early development.

Introduction

Speech and music are both complex, hierarchically organized systems that convey meaning via streams of auditory information. It has been suggested that music, like language, is a species-specific behaviour important for complex human interaction (Trehub, 2000). Effective communication via either system requires both the ability to perceive input and also the ability to produce output that conforms to the rules that govern each system. For speech, these organizational rules have to do not only with low-level features like phoneme contrasts, but also high-level rules about morphology and syntax, and physical or articulatory constraints on phonotactics and speech effectors (Saffran, Werker, & Werner, 2006). Musical organization is analogous in many ways, affected by surface features like duration, pitch and timbre, higher-level rules about rhythm, metre and key membership, and physical constraints related to producing or synchronizing with sounds (Hannon & Trainor, 2007). The development of speech perception and production is well studied, but the development of the perception and production of music in childhood is less well understood.

In the context of language development, human infants perceive speech in the world around them for many months before they produce speech-like sounds. Despite the fact that young infants do not yet speak, they have enormous perceptual sensitivity, and during this time they are learning the rules and conventions of the language being spoken in their native environment (Saffran, et al., 2006). Such experience-guided processes, called perceptual narrowing or perceptual specialization, take place during the first year after birth across a number of domains. This includes specialization for the sounds of the particular language (e.g. Maurer & Werker, 2014, Trehub, 1976), species of the faces (Kelly Quinn, Slater, Lee, Ge, & Pascalis, 2007), and species of voices (Friendly, Rendall, & Trainor, 2013, 2014) experienced by the infant. Perceptual specialization also occurs for several aspects of musical organization, including scale structure (Gerry, Unrau & Trainor, 2012; Hannon & Trainor, 2007; Trainor & Hannon, 2013; Lynch & Eilers, 1992; Trainor & Trehub, 1992) and metric structure (Hannon & Trehub, 2005a, b).

Although infants are sensitive to some auditory characteristics of language from before they are born (DeCasper & Spence, 1986), only after many months of exposure to spoken language after birth do infants start to produce identifiable and consistent approximations of individual words (Werker & Tees, 1999). Even later, between 18 to 24 months, they start to string together multiple lexical items according to the rules of their native grammar (Hirsch-Pasek & Golinkoff, 1996). However, infants can reliably comprehend individual words, phrases, and syntactic relationships used by others long before they produce such verbalizations themselves (Jusczyk, 1997; Saffran, Senghas, & Trueswell, 2001).

The maxim ‘perception precedes production’ is often invoked to characterize this seemingly passive learning process. That is, children’s perceptual systems are sensitive to the characteristics of information in their environment long before they can successfully replicate that input by imitating or producing it themselves, and the ability to produce follows a protracted developmental timeline. This developmental trajectory, in which sensitivity to auditory or visual information precedes a child's ability to produce it, has been documented in domains ranging from grammatical constructions (e.g. Goodwin, Fein, & Naigles, 2012) to facial expressions (Field & Walden, 1982; Gosselin, Maassarani, Younger, & Perron, 2011; Odom & Lemond, 1972).

Infants' ability to produce speech is particularly constrained by the necessity of coordinating speech effectors like the lips and tongue. For example, it is not until approximately six months of age that infants display coordination of the vocal articulatory gestures required to form a consonant-vowel (CV) syllable (Oller, 1980). Similarly, although infants can perceive a wide variety of relevant phoneme contrasts, the necessary articulatory control to produce contrasting phoneme pairs (e.g. voiced /b/ versus unvoiced /p/) emerges only gradually over the course of maturation and after repeated practice (Werker & Tees, 1999).

A similarly lengthy developmental timeline can be observed in other types of non-speech motor skills. Many motor tasks require the integration of visual or auditory input with motor movements; coordination of a rhythmic motor action with an external rhythmic stimulus is referred to as *sensorimotor synchronization* (Repp, 2005). As an example, children's ability to coordinate their motor movements with an external stimulus is poor before the age of five, but develops markedly between the ages of five and twelve as sensorimotor integration improves (Drewing, 2006; McAuley, Jones, Holub, Johnston, & Miller, 2006;

Smoll, 1974; 1975; van Noorden, De Bruyn, van Noorden, & Leman, in prep). Substantial improvements have also been demonstrated between the ages of five and twelve in other perceptual-motor skills like drawing (Ferrel-Chapus, Hay, Olivier, Bard, & Fleury, 2002), pointing (Lambert & Bard, 2005), bouncing (Bazile & Siegler, 2013), clapping (Fitzpatrick, Schmidt, & Lockman, 1996), and intercepting objects (Olivier, Ripoll, & Audiffren, 1997). For example, infants initially begin to use their hands together in a coordinated way and then learn to catch moving objects (von Hofsten, 1980). Single-handed catching ability emerges around the age of five and reaches adult-like levels around age twelve (Fischman, Moore, & Steele, 1992).

Studies of music have tended to focus on the perception of music rather than the production of music through singing or playing an instrument, perhaps because not all people in Western society are comfortable producing music. In fact, the unique ability to *perceive* a musical beat is present even in newborns (Winkler, Háden, Ladinig, Sziller, & Honing, 2009), and young infants show great perceptual sensitivity to temporal information. For example, by 5 months infants can discriminate among simple rhythms (Chang & Trehub, 1977) and by 7 to 9 months infants can recognize rhythmic patterns despite changes to the key or tempo of presentation (Trehub & Thorpe, 1989). Although use of a steady beat is present in every known musical tradition, timing perception in adults also varies as a function of training (Cameron and Grahn, 2014; Drake, 1993) and musical culture (e.g., Hannon, Soley and Ullal, 2012; Hannon & Trehub, 2005b; Cameron, Bentley and Grahn, 2015).

The tendency to move in synchrony with a musical beat is a universal across cultures (Nettl, 1983) that arises without explicit training. However, the ability to accurately synchronize one's movements with a beat is not present early in life, suggesting that it emerges over the course of development. Although infants listening to rhythmic stimuli like music will demonstrate rhythmic motor movement when they are only five months old, suggesting that they can perceive the underlying regularity, their movements are not synchronized to the speed (tempo) of the musical beat (Zentner & Eerola, 2010).

Generally, coordination of an action with a predictable stimulus is referred to as *sensorimotor synchronization*; more specifically, the ability to synchronize self-generated movements with an isochronous pulse or musical beat is known as *auditory-motor entrainment* (Grahn, 2009). Tapping in synchrony with an auditory stimulus is different from a simple imitation or reaction task because the listener must extract the regular pulse or beat, predict when subsequent beats will occur, and then plan the motor gestures to occur both at the correct time relative to the stimulus and with high consistency. If a listener is robustly entrained to a stimulus, each tap will align with (or actually anticipate) the individual beats in the target stimulus, and the interval between each successive tap (the intertap interval, or ITI) will be relatively consistent (Peters, 1989).

As such, adults' movement quality in tapping tasks is typically assessed in two ways: first, by assessing the degree to which taps align with an external sound; and second, by measuring the variability of the inter-tap interval (see Repp, 2005 and Repp & Su, 2013, for reviews). Like beat perception, tapping performance is also affected by expertise; for example, trained musicians tap more regularly to musical excerpts than non-musicians (Drake, Penel, & Bigand, 2000). Task-specific sensorimotor training for naïve, untrained adults improves encoding of rhythms (Lappe, Trainor, Herholz, & Pantev, 2011) and adults' ability to perform behavioural rhythm tasks in as little as one week (Butler & Trainor, 2015) or in repeated sessions over the course of three weeks (Madison, Karampela, Ullén, & Holm, 2013). Tapping performance is also affected by mode of response; tapping responses that use a drumstick are generally less variable than finger tapping (Fujii & Oda, 2009; Madison & Delignières, 2009).

In adults, spontaneous beat-based movements include head bobbing, toe tapping, drumming, and dancing. Humans are capable of this type of auditory-motor entrainment, in part, because their auditory and motor systems are closely linked (Grahn & Brett, 2007; Zatorre, Chen & Penhune, 2007; Phillips-Silver, 2009; Fujioka, Trainor, Large, & Ross, 2012). This affinity between auditory and motor processing is evident in imaging studies; tapping along with a steady beat induces activity in both auditory and motor regions of the brain (Chen, Penhune, & Zatorre, 2008). In fact, when adults passively listen to musical rhythms without moving or even intending to move, motor regions including the mid-premotor cortex (PMC), supplementary motor area (SMA) and cerebellum are activated in the absence of overt motor responses (Chen et al., 2008; Fujioka et al., 2012; Grahn & Brett, 2007). Thus, the perception of a musical beat recruits not only auditory areas, but also motor regions of the brain typically associated with actual physical movement.

Tapping performance is less good early in life, but since the motor system is immature in infants and children, it is unclear the extent to which their comparatively poor ability to synchronize movements with an auditory stimulus is a result of deficits in beat perception, motor immaturity or connections between auditory and motor systems (Drake, Jones, & Baruch, 2000; Fitzpatrick, Schmidt, & Lockman, 1996). As young as two-and-a-half years of age, children's tapping is most consistent at speeds close to their own spontaneous motor tempo (SMT) of approximately 400 ms, equivalent to 150 beats per minute (Provasi & Bobin-Begue, 2003). SMT slows throughout childhood (Drake et al., 2000; Fraisse & Oleron, 1954) and into adulthood. By comparison, adults' SMT is approximately 600ms, or 100 beats per minute (Fraisse, 1982) and SMT slows further for older adults (Vanneste, Pouthas, and Wearden, 2001). Synchronization variability also decreases throughout childhood and then remains relatively constant in adulthood (Drewing, Aschersleben, & Li, 2006).

Musically untrained adults are capable of synchronizing taps between approximately 30 and 300 beats per minute (Fraisse, 1982) but children struggle to entrain to tempi outside their preferred range. However, the absolute limits of children's abilities have not been established. Previous attempts to assess children's sensorimotor synchronization to music have shown that both infants (Bobin-Begue, Provasi, Marks & Pouthas, 2006; Zentner & Eerola, 2010) and toddlers (Eerola, Luck, & Toiviainen, 2006) exhibit periodic movements, including rhythmic sucking, kicking of feet, swaying, or jumping when presented with a musical stimulus. Although infants and children may adjust the overall speed of their movements when the tempo increases (Bobin-Begue et al., 2006), young children's movements are neither phase locked nor precisely tempo matched to the music presented. However, the ability to coordinate motor movement with perceptual information from the environment improves with age (Volman & Geuze, 2000), and even preschool children's drumming is significantly better in the presence of a social partner (Kirschner & Tomasello, 2009; Kirschner & Ilari, 2013).

Work with older children has shown that 5-year-olds have an improved ability to synchronize movements to an auditory stimulus, although they can only do so within a narrow tempo range and when the temporal structure is simple (Drake, Jones, & Baruch, 2000). Children's tapping synchronization, as measured by both stability of performance and tapping accuracy, improves substantially between the ages of 5 and 12 (Drake et al., 2000; Greene & Williams, 1993; McAuley et al., 2006).

The original Beat Alignment Task (BAT) provided evidence of a strong positive correlation between adults' beat perception ability and mean intertap interval (i.e. tempo matching) in a tapping synchronization task. However, there was only a weak correlation between adults' beat perception ability and phase alignment when tapping to simple metre music as part of the same task (Iversen & Patel, 2008), likely because synchronization performance varied much more than perceptual sensitivity. It remains unknown to what extent adults' ability to detect whether taps are on or off the beat is related to the ability to produce isochronous taps synchronized to music. To date, the two abilities have also never been assessed independently in young children in an experimental context.

Another important variable affecting beat perception is the complexity of the stimulus. The surface-level pattern of sounds and silences makes up music's *rhythm*, and the listener infers the underlying beat based on the rhythmic patterns (Povel, 1981). Beat structures are hierarchically organized, with lower levels nested into higher levels (Jones, 1976). Beats can be accented or unaccented, and accented beats typically occur at regular intervals; the spacing and organization of accented beats determines music's *metre* (London, 2012).

Simple metric structure has equally spaced (*isochronous)* perceptual accents at each level of the metrical hierarchy and is notated with time signatures such as 3/4 or 4/4. Complex metres, on the other hand, have unequally spaced (*non-isochronous)* accents at one or more levels of the metrical hierarchy and are notated with time signatures like 5/4 or 7/4. These are much less common than simple metres in the music of Western cultures (Palmer & Krumhansl, 1990) although they are widespread in folk music from Africa, south Asia, and southeastern Europe (Rice, 1994). Many previous studies have examined beat synchronization skills in adults in the context of simple metre music (e.g. Dunlap, 1910; Fraisse, Oleron, & Paillard, 1958; Woodrow, 1932; Drake, 1993; Iversen & Patel, 2008).

Although some have proposed an innate processing advantage for durations related by simple ratios (Drake & Bertrand, 2001) recent research suggests it is largely attributable instead to enculturation and perceptual specialization. Hannon and Trehub (2005a) showed that North American adults are less good at detecting metrical changes in complex meters, but adults from cultures where complex metres are more common are equally good in detecting violations to both simple and complex metrical structures. Importantly, six-month-old infants are perceptually sensitive to errors in rhythms in both types of meters, but by 12 months North American infants show the same pattern of perceptual biases as North American adults (Hannon & Trehub, 2005b). This early equipotentiality and later emergence of culture specific sensitivity suggest that the bias for simple metres is acquired rather than innate.

Few studies have examined synchronization to complex metres, but it has been demonstrated that both Western adults and Western children are better at reproducing rhythms with simpler timing structure (Drake, 1993). When North American adults are asked to tap to the beat of rhythm patterns in complex metres, and then continue tapping after the pattern stops, they produce beats with ratios in between the target ratio of 3:2 (complex metre) and their preferred simple metre ratio of 2:1 (Snyder, Hannon, Large, & Christiansen, 2006). Subjects with formal (Western) music training show a stronger bias than those without training toward the simple metre ratio of 2:1 (Collier & Wright, 1995), suggesting that formal training in a musical culture strengthens the enculturation process.

This perceptual specialization for culturally relevant musical meters is robust in adulthood, but appears to be more easily altered early in life. Although Western 12-month-old infants are enculturated to simple metres, with brief training, they regain perceptual sensitivity to complex metres (Hannon & Trehub, 2005b). Musically untrained 5-year-olds show a similar enculturated bias for simple metre perception (Einarson & Trainor, 2015). However, enculturated 5-, 7-, and 9-year-old children show reduced bias after two weeks of exposure to culturally atypical metric structures, but 11-year-olds and adults do not (Hannon, Vanden Bosch der Nederlanden, & Tichko, 2012), a pattern suggesting that plasticity diminishes with age.

Taken together, the existing literature on beat perception and synchronization leaves several questions unanswered. First, although it is established that children's tapping is both less accurate and less consistent than that of adults on sensorimotor synchronization tasks, it is not clear how much of this deficit is attributable to limited perceptual sensitivity, immature motor development, or the connections between perceptual and motor systems. Children's perceptual sensitivity is evident well in advance of production capability in other domains; beat perception and synchronization may be additional areas where ‘perception precedes production’. Iversen and Patel (2008) have demonstrated that perception and synchronization are dissociable in adults; when perception is assessed without requiring overt motor synchrony, some participants who show comparatively poor motor entrainment still demonstrate typical perceptual sensitivity. However, these abilities have not been assessed separately in children to date.

Second, many questions remain about the effect of metrical complexity on tapping synchronization. Enculturated Western adults are less able to synchronize tapping with complex metre rhythms, and reproduce them less accurately than simple rhythms (Snyder et al., 2006), consistent with their experience-driven perceptual biases. North American children exhibit similar perceptual biases for simple metre music (Einarson 2015, 2016; Hannon, Vanden Bosch der Nederlanden, & Tichko, 2012), but no work has examined children’s tapping synchronization in these contexts.

Third, other types of motor coordination are undergoing refinement in early and middle childhood; skills like intercepting objects (Olivier, Ripoll, & Audiffren, 1997), bouncing (Bazile & Siegler, 2013), clapping (Fitzpatrick, Schmidt, & Lockman, 1996), and drawing (Ferrel-Chapus, Hay, Olivier, Bard, & Fleury, 2002) all show rapid change between the ages of 5 and 8. Children’s auditory-motor synchronization also changes between the ages of 5 and 8 (McAuley et al., 2006), but it has not been established how this synchronization performance is affected by metre, or related to perceptual sensitivity.

In the experiment described here we employ a newly expanded tool called the complex Beat Alignment Task (cBAT), which attempts to dissociate perception and synchronization ability. This provides a way to explore the degree to which poor performance at sensorimotor synchronization tasks reflects impaired perceptual sensitivity. Since children are able to detect and distinguish other types of environmental stimuli before they are able to mimic or produce them, it is also possible that children's poor ability to synchronize motor movements represents a motor constraint, and that perception is more mature.

To address this question the newly expanded cBATT paradigm now assesses not only beat perception (cBAT, Einarson & Trainor, 2015; 2016) but also children's spontaneous motor tempo (SMT), and their ability to synchronize tapping to a metronome at several tempos and to musical excerpts drawn from the existing cBAT perception task. These excerpts, used for both tasks to allow for comparisons in performance, have both simple and complex metric structures. Notably, although the metric structures differ among excerpts (i.e. the excerpts have different accent structures), for both simple and complex metres the beats at the tapping level of the metrical hierarchy are isochronous. This means that both the beat perception task and the beat synchronization task should not be motorically more difficult to execute for one metre type over the other. As in previous studies employing the cBAT, we also measure non-musical cognitive skills via the Peabody Picture Vocabulary Test (PPVT-4; Dunn & Dunn, 2007) to assess children's receptive vocabulary, and the Digit Span subtest of the Wechsler

Intelligence Scale for Children (WISC-IV; Wechsler, 2003) to assess short-term memory and working memory.

As such, the expanded cBATT allows for investigation of how beat synchronization tapping relates to perceptual sensitivity, and also measures the effect of musical metric complexity on children's tapping performance. Finally, previous work with the cBAT has investigated perceptual sensitivity in musically untrained 5-year-old children. This study expands previous work by examining the performance of both 5- and 7-year-old participants, in order to capture changes in performance at a point in development when children's motor coordination for other sensorimotor tasks is rapidly changing.

We expected that, as in previous work (Einarson & Trainor 2015, 2016), both 5- and 7-year-old North American children would more accurately detect beat misalignment in the context of simple metre than complex metre music, although performance was likely to be better overall for older children. Additionally, we predicted children would be more accurate when synchronizing their tapping with music in simple metre than in complex metre, as has been observed in North American adults (Snyder et al., 2006). Finally, given that tapping variability and perceptual sensitivity are correlated in adults (Iversen & Patel, 2008) we predicted that children with who were more perceptually sensitive to the musical beat overall would subsequently be more less variable when synchronizing their tapping to that beat.

Methods

Participants

88 children took part in the study, including 48 5-year-old children (24 female, M_{age} = 5 years, 6 months, SD = 1.6 months) and 40 7-year-old children (20 female, M_{age} = 7 years, 6 months, SD = 2.3 months). Participants were not enrolled in formal music lessons at the time of testing, and had no previous experience with formal instrumental training. Participants were randomly assigned to one of two experimental conditions in the perception task, phase error (n_5 = 24, 12 female; n_7 = 21, 10 female) or tempo error (n_5= 24, 12 female; n_7 = 19, 10 female). All children in the final sample had normal hearing and were in good health as reported by their parents on a background questionnaire. Annual family income was measured on a six-point scale (1=<$30,000, 6=>$150,000; Canadian dollars, data missing for twelve children). For both 5- and 7-year-old children the median family income was between $90,000 and $120,000 per year, with no significant difference in variability between groups ($p < .001$). Parent education was also measured on a six-point scale (1=no high school diploma, 6=graduate or professional degree; data missing for two children). For children in both groups the median formal education was a completed college diploma or certificate for both the mother and father.

An additional 11 5-year-olds and 2 7-year-olds were excluded from the sample for the following reasons: diagnosed developmental delays (n = 4), equipment problems (n = 4), failure to complete all tasks (n = 4), and having a parent who was a professional musician (*n* = 1)**.** All participants were recruited from the McMaster Infant Studies Group database, and all protocols were approved by the McMaster Research Ethics Board.

Stimuli

Each child was tested during a single session lasting approximately 45 minutes. The perception portion of the cBATT was administered in two separate blocks, where one block consisted of simple metre stimuli and the other of complex metre stimuli; block order was counterbalanced across children. Otherwise, all subjects completed the same sequence of tasks: Block 1 of the cBATT beat perception task, forward and backward Digit Span task, Block 2 of the cBATT beat perception task, the beat synchronization portion of the cBATT and, finally, the PPVT.

1. Complex Beat Alignment and Tapping Test. There were two components to the complex Beat Alignment and Tapping Test (cBATT). The first assessed perceptual sensitivity to beat alignment using an audiovisual judgment task, and the second assessed beat production ability using a tapping synchronization task.

1a. Beat perception task

The stimuli for the beat perception portion of the cBATT were the same as those described in Einarson & Trainor (2015; 2016) and consisted of videos of 12 pairs of hand puppets drumming along to 12 musical excerpts chosen from a variety of genres. Excerpts were organized in pairs that were matched according to instrumentation, timbre, tempo, and overall musical style. One musical excerpt in each of the six pairs had simple metric structure (in this case, 4/4 time signatures), and the other had complex metric structure (5/4 or 7/4 time signatures).

Excerpts were each combined with an audio file of isochronous woodblock tap so that the woodblock taps were either *correctly aligned* with the beat of the song, or made one of two misalignment errors. For *phase errors*, the superimposed beat was either 25% too early or 25% too late relative to the beat of the music, whereas for *tempo* errors it was either 10% too fast or 10% too slow. These audio files were combined with matching videos, so that a puppet's drumming gestures always corresponded to the sound of the woodblock taps.

Presentation was blocked so that all the simple metre excerpts were presented together and all the complex metre excerpts were presented together. Order of block presentation was balanced between children. One simple metre excerpt and one complex metre excerpt were used as practice trials preceding each block, and the other 10 excerpts were used as test trials. Pairs of puppets were consistently associated with particular excerpts, but we created several versions of the task across which the puppets were balanced for order of presentation, error type, and error frequency within each pair and within a given block.

Each test trial was made up of two videos of a given musical excerpt, one where the puppet's drumming was correctly aligned and the other with a puppet that committed a beat misalignment error. Error type (phase or tempo) was a between-subjects variable so that children saw only one type of misalignment error, but error direction (fast/slow or early/late) was a within-subjects manipulation, so that each child had to judge both types of mistakes. The creation of these stimuli for the cBAT perception task is described in more detail in Einarson & Trainor (2016).

1b. Beat production task

The production component of the cBAT had three types of trials, each of which required the participant to tap with the hand of their choosing on a Roland V-drum PDX-8 dual trigger electronic drum pad. In the first part of the production task, the child tapped a steady beat on the drum at a self-selected pace for 30s to assess spontaneous motor tempo (SMT). The second part of the production task had three trials, and in each trial the child was asked to synchronize his or her drumming with an isochronous sequence of metronome beeps lasting 20s. The inter-onset intervals (IOIs) of the three metronome trials were 400 ms, 550 ms, and 700 ms, and order of presentation of the three different speeds was randomized across subjects. The third part of the beat production task had six trials where the child synchronized their tapping to a subset of the musical excerpts used in the beat perception video task. Two different versions of this task were created to keep it from becoming too long for young children, and each version used three of the six simple excerpts and three of the six complex excerpts from the perception task stimulus set. Order of presentation of the six songs in each version of the task was randomized across subjects. The child was asked to synchronize his or her drumming to the beat of each excerpt, “just like the puppets did”.

Parts two and three of the production task required the child to synchronize his or her drumming with an external auditory stimulus (metronome beeps and musical excerpts, respectively). In order to determine where the child’s taps occurred in relation to the beat of the stimulus being presented, the audio file of each metronome or song contained a second audio track with tone bursts at the location of each beat. The track with embedded tone bursts was inaudible, but served as a means to record electronic triggers at the location of each beat in the stimulus. The timing of each beat (i.e. trigger) in the stimulus was recorded in one input channel and the timing of each tap by the participant was recorded in a second channel to facilitate analysis of children’s performance.

2. **Digit Span Test.** All participants completed both parts of the digit span subtest of the Wechsler Intelligence Scale for Children, 4th edition (WISC-IV; Wechsler, 2003) to assess short-term and working memory. In the digits forward task the child is required to repeat back a string of digits uttered by the experimenter, beginning with a two-digit string, and increasing by one digit on every second trial. Testing stops when the child fails to correctly repeat both strings of a given length. The digits backward task begins with two practice trials, but otherwise follows the same procedure except that it requires the child to repeat the digits in the reverse order from the experimenter.

3. **Peabody Picture Vocabulary Test.** All participants completed the Peabody Picture Vocabulary Test, 4th edition (PPVT-IV; Dunn & Dunn, 2007), which is a standardized measure of children's receptive vocabulary and considered a proxy assessment for verbal intelligence. In it, the experimenter says a word and the child must choose the appropriate picture from a set of four by pointing or speaking. Vocabulary items gradually increase in difficulty, and testing is terminated when the child incorrectly identifies eight or more of the words in a twelve-item set. Raw scores are standardized according to the subject's age, and normed as described in the Examiner's Manual.

4. **Parental Questionnaire.** While the child was being tested, parents completed a questionnaire covering their child's health, language experience, handedness, extracurricular activities, and formal or informal music experience. Demographic information regarding parental education and income was also requested, although these questions were answered by only a subset of parents.

Procedure

The perception task videos were controlled by the experimenter on a 21.5-inch Apple iMac Core i5 using *iTunes* (Version 11.0.2). This computer was connected to an external Samsung SyncMaster 24-inch widescreen monitor where the videos were presented to each child. Audio was presented through two M-Audio Studiophile AV speakers that were situated on either side of the Samsung monitor.

Each block of the cBATT perception task consisted of one practice trial followed by five test trials. At the beginning of the perception task, the experimenter began by explaining to the child that he or she was about to watch two puppets drumming along to the same song, and that the child was going to be a judge who had to determine which puppet would be a better drummer for a band. The experimenter showed the child the two puppets that would be presented in the videos for the practice trial, and identified them by name (for example, "This is my friend the bunny, and this is my friend the dog"). After the child viewed the pair of videos, the experimenter placed the two actual puppets in front of the child on the table, and asked the child to place a ribbon on the puppet who should win the prize. The practice trial at the beginning of each block was repeated until the participant correctly identified the puppet whose drumming was correctly aligned to the music. Test trials were not repeated, and children received no feedback regarding their choice.

Like the practice trial, each of the five test trials consisted of a pair of two videos. In one video, the puppet drummed along to the beat of a particular musical excerpt (the standard). In the other video the puppet's drumming was either out of phase or out of tempo relative to the excerpt. Error type (phase or tempo misalignment) was a between-subjects variable, and within each error condition the error types were balanced so that each error type (fast and slow tempo shift errors or early and late phase shift errors) occurred in equal proportion. Order of video presentation was also balanced across pairs of videos, so that half of the drumming errors were presented first in the pair, and half were presented second.

After completing the first block of the cBATT perception task, there was a short break to conduct both the forward and backward digit span measures. The second block of the cBATT perception task (one practice trial and five test trials) was administered the same way as the first block. The experimenter then requested the child move to an adjacent table to complete the cBATT synchronization task.

The child was seated in front of a 19-inch Dell LCD monitor, two Altec Lansing ACS22BW computer speakers, and a Roland V-drum PDX-8 dual trigger electronic drum pad connected to an Alesis trigger iO. The tapping data were collected in Presentation 16.1 using an ATtiny 45 microcontroller programmed with Arduino software. All children were instructed to drum with a closed fist using the hand of their choice, and the experimenter asked each child to drum "nice and steady, just like the puppets did". The experimenter cued each trial of the beat production task in Presentation, advancing through the three parts of the synchronization task: the self-paced trial, three metronome trials, and six song trials. Although children did not receive explicit feedback on their performance, the experimenter provided intermittent encouragement (e.g. "keep it up!") and verbally cued the child before each tapping trial began by asking "is your drumming hand ready?".

The last task to be conducted in each testing session was the PPVT. The child had to pass two simple practice trials, during which feedback was provided, before continuing with the testing trials. Testing was complete when the PPVT ended, and all participants received a certificate of participation and a small prize at the end of their session. Each testing session was recorded using either a Samsung SMX-F40 video camera or a GoPro HERO3+.

Results

1 Complex Beat Alignment and Tapping Test (cBATT) perception results

The dependent measure of the cBATT perception task was the proportion of time the children identified the puppet that played the standard version as being the better drummer. We conducted a 2x2x2 ANOVA with age (5, 7) and error type (phase, tempo) as between-subjects factors and metre type (simple, complex) as a within-subjects factor. There was a significant main effect of age, $F(1,84) = 13.63$, $p < .001$ and a significant main effect of metre type, $F(1,84) = 12.04$, $p < .001$, but no main effect of error type ($p = .589$) and no significant interactions (see Figure 1).

Analyses at each age level indicated that 7-year-old children's judgment accuracy was significantly better for simple metre excerpts (proportion correct = .79, $SD = .21$) than for complex metre excerpts (proportion correct = .71, $SD = .25$). 5-year-old children's performance was significantly less good overall compared to older children (see Figure 1) but showed the same pattern of significantly better accuracy for simple metres (mean proportion correct = .66, *SD*

= .22) compared to complex metres (mean proportion correct = .54, *SD* = .25). For both groups of children, judgment accuracy was not significantly different for tempo errors compared to phase errors. 5-year-old children's detection of beat misalignment was significantly above chance levels for simple metre music ($p <$ .0001) but not for complex metres (p = .30), which replicates previous findings with this age group (Einarson & Trainor, 2015). 7-year-olds performed significantly above chance for both simple ($p < .0001$) and complex ($p < .0001$) excerpts.

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insert Figure 1 approximately here

Examination of individual data for the cBATT task showed that 41 of 48 5-year-olds and 29 of 40 7-year-olds selected the correct puppet for the simple metre excerpts either more often or equally often than they chose the correct puppet for excerpts in complex metres. Thus, it is clear that a small subset of our sample was not driving our observed simple-metre bias. Judgment accuracy for the simple metre stimuli was significantly correlated with judgment accuracy for the complex metre stimuli for 5-year-olds, $r = .43$, $p = .002$, but not for 7-year-olds, $r = .16$, $p = .33$.

2 Complex Beat Alignment and Tapping Test (cBATT) production results

To analyze children's performance on the cBATT synchronization task, the timing of children's taps was compared with the timing of beats presented in the stimulus. However, because of high ITI variability and periods of sustained phase misalignment typical of children (Kirschner & Tomasello, 2009), it was not possible to associate individual taps with beats in the stimulus on a one-to-one basis as is required for linear data analysis. Instead, our analysis employs circular statistical techniques, which are often used with cyclical or directional data (Fisher, 1993; 1996; Mardia & Jupp, 2000). Studies of birds (Patel, Iversen, Bregman, & Schulz, 2009), mammals (Cook, Rouse, Wilson, & Reichmuth, 2013) and non-human primates (Hattori, Tomonaga & Matsuzawa, 2013) have employed similar methods to analyze erratic or variable synchronization behaviour in subjects who do not demonstrate the robust entrainment and phase alignment of adult humans. Furthermore, previous work has employed this type of analysis with human adults' (e.g. Fujii & Schlaug, 2013), and children's synchronization tapping (Kirschner, & Tomasello, 2009; Kirschner & Ilari, 2013; Falk, Müller, & Dalla Bella, 2015).

We examined both the synchronization consistency and phase alignment of children's tapping performance. To do this, we used unit vectors plotted on a circular ("clock") scale to represent where children's taps occurred relative to the nearest target beat, where 0° at the top of the circle represents the target beat (Fisher, 1993; Zar, 1999). A tap occurring precisely on the target response is represented by a unit vector at 0°. Using the 400 ms metronome trial as an example, a tap occurring 100 ms too late would be represented by a unit vector at 90°, whereas a tap occurring 100 ms too early would be represented by a unit vector at 270°, or –90°. Thus, each individual tap response was represented by a unit vector, where the angle of the vector represented the alignment of the response. These unit vectors, each representing one tap, were then averaged within each trial (metronome sequence or song) to obtain a mean vector, which can be decomposed into two components: mean resultant length, R, and mean angular direction, θ.

The mean vector length, R, captures synchronization consistency. This reflects how much variability there was in the difference between a child's tap responses relative to the beat within a particular trial, where a longer mean vector indicated high consistency of the interval between the beat of the pacing stimulus and subjects' tapping responses. The angle of the mean vector for each trial, θ, represented the average phase alignment accuracy across the excerpt, relative to the beat of the stimulus. The radius of the circle is standardized to 1; as such, perfectly aligned tapping with consistent intertap intervals would be represented by a mean vector with a length of $R = 1.0$ and an angle of $\theta = 0°$, reflecting both consistent synchronization and accurate phase alignment.

Circular statistical analyses were conducted in two stages. First, we tested whether children's tapping performance on each trial was more consistent than would be predicted by chance, performing a Rayleigh test for unimodal distribution of circular data points on each tapping trial (Fisher, 1993). If tapping performance is consistently period-matched to the stimulus, then vector length, R, will be significantly greater than a critical value and the test will yield a significant result.

Subsequent to the Rayleigh analysis, dependent measures R and θ were analyzed separately. Each value was determined for each trial for each child. Average performance on each task (metronome tapping, simple metre song tapping, complex metre song tapping) for each age group (5, 7) is shown in Table 1. Initial analyses confirmed that there was no significant difference in either R or θ between song versions of the tapping task (song subset A, song subset B) for either age group (all p's > .10), so task version was not considered as a factor in any of the analyses that follow.

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insert Table 1 approximately here

2.1 Rayleigh test

Descriptively, across all metronome speeds, and for all but one of the musical excerpts, the proportion of children whose data reached significance in Rayleigh's test ($p \leq .05$) was higher for older children than for younger children. As predicted, performance varied widely across the stimulus set in both ages, with the proportion of children whose tapping reached significance for a given trial ranging from .04 to .88 for 5-year-olds and ranging from .40 to .98 for 7-year-olds (see Table 2).

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insert Table 2 approximately here

2.2 Self-paced tapping

Self-paced tapping did not require tapping to be synchronized to an external auditory stimulus, so we employed linear analyses. Children were instructed to tap a steady beat at a self-selected speed. A one-way ANOVA comparing children's average intertap interval (ITI) found that although 7-year-old children's SMT (M = 586ms, SD = 157) was slower that that of 5-year-old children SMT (M = 544ms, SD = 138), this difference was not significant, $F(1, 86) = 1.81$, $p < .182$.

A subsequent outlier analysis was conducted due to the high variability in both age groups. When two 5-year-old children and four 7-year-old children whose average ITI was more than two standard deviations above or below the mean for their age were removed from the sample, SMT remained similar in both age groups, but variability decreased (older M = 585ms, SD = 109; younger M = 525ms, SD = 105). A one-way ANOVA on the remaining cases revealed a significant effect of age, $F(1, 80) = 6.42$, $p = .013$, as predicted.

2.3 Synchronization tapping vector length (R)

To directly compare children's *synchronization consistency* in the synchronization tasks, as assessed by mean vector length (R), we conducted a 2x3 linear ANOVA with age (5, 7) as a between-subjects factor and synchronization task type (metronome, simple song, complex song) as a within-subjects factor.

There was a significant main effect of age, $F(1,86) = 57.83$, $p < .001$, a significant main effect of task type, $F(1,86) = 43.21$, $p < .001$, and no significant interaction ($p = .17$).

Pairwise comparisons to investigate the main effect of age showed that *R* was significantly longer for 7-year-olds than 5-year-olds for all synchronization tapping, including metronome trials ($R_{met7} = .69$, $R_{met5} = .51$, $p < .001$), simple metre songs ($R_{simple7} = .42$, $R_{simple5} = .29$, $p < .001$), and complex metre songs ($R_{complex7} = .52$, $R_{complex5} = .40$, $p < .001$). Pairwise comparison to investigate the main effect of task type showed that R was significantly longer for metronome trials than either simple meters ($p < .001$) or complex metres ($p < .001$). However, unlike in the perception task, we did not see better performance for simple metre stimuli. *R* was significantly longer for music with complex metre compared to music with simple metre ($p < .001$). This difference remained significant for both 5-year-olds ($p = .001$) and 7-year-olds ($p = .011$), suggesting that, contrary to our hypothesis, children of both ages synchronized their tapping more consistently to the tempo of music with complex metric structure.

2.4 Synchronization tapping vector angle (θ)

To directly compare the children's *phase accuracy* in the synchronization tasks, reflected by mean vector angle (θ), we conducted a series of circular ANOVAs. As stated by Kirschner and Tomasello in their own work examining similar tapping synchronization with young children (2009) there is no available statistical test for circular data (comparing θ or R between conditions and age groups) analogous to the multi-way analysis of linear data. Because an initial test for the equality of the concentration of parameters in these data using the *tang.conc* function from the 'Directional' package (Tsagris, Athineou, & Sajib, 2016) in R (R Core Team, 2016) reached significance (p = 0.003), subsequent analyses used the non-equal concentration *het.circaov* function from the same package to conduct a series of one-way circular ANOVAs.

A circular ANOVA with age as a factor revealed no significant difference in mean vector angle, $F(1,87) = .08$, $p < .77$, between 5-year-olds ($M_\theta = -8.29$, $SD_\theta = 1.49$) and 7-year-olds ($M_\theta = -6.28$, $SD_\theta = 1.19$). This suggests that unlike for tempo matching consistency, phase alignment did not improve significantly with age. Thus, subsequent analyses of vector angle did not consider the two age groups separately.

A second circular ANOVA revealed a significant effect of task type on θ, $F(1,87) = 53.78$, $p < .001$. Pairwise comparisons indicated that metronome tapping ($M_\theta = -31.90$, $SD_\theta = 1.03$) was significantly less phase aligned than simple metre tapping ($M_\theta = 9.78$, $SD_\theta = 1.38$; $p < .001$) and also significantly less phase aligned than complex metre tapping ($M_\theta = 16.27$, $SD_\theta = 1.48$; $p < .001$). However, mean θ was not significantly different for simple metre compared to complex metre tapping ($p = .49$). Mean vector angle values, like the mean vector length values, did not display the bias toward simple metre music that was hypothesized based on the perceptual data (see Figure 2).

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insert Figure 2 approximately here

2.5 Synchronization tapping and acoustic characteristics of stimuli

Although we attempted to match the simple and complex metre excerpts in a given genre according to instrumentation, timbre, tempo, and overall musical style (sometimes using two tracks from the same album), songs varied greatly across our entire stimulus set in their instrumentation, timbre, and perceived beat salience. Similarly, as described above, the proportion of children's whose tapping reached significant in Rayleigh's test varied widely across individual songs. In particular, some songs with complex metre also had a very evident beat (for example, *Money*, by Pink Floyd) and we observed that synchronization was quite good in this case for both younger children (R = .64, θ = -4°, proportion with significant Rayleigh test = .88) and older children (R = .79, θ = -13°, proportion with significant Rayleigh test = .95) despite the excerpt's 7/4 complex metric structure (see Figure 2).

Recently, measures of acoustic variability in music such as spectral flux and root-mean squared (RMS) energy have been found to predict variability in tap synchronization in adults (Stupacher, Hove, & Janata, 2016). Pulse clarity and spectral flux are also correlated with periodicity in the music-induced body movement of adults (Burger, Thompson, Luck, Saarikallio, & Toiviainen, 2014). Other acoustic measures like event density are known to correlate with adults' perceptions of 'groove' in music, characterized by wanting to tap or dance along

(Madison, Gouyon, Ullen & Hörnström, 2011). We conducted a post-hoc analysis of our stimulus set to see whether particular acoustic characteristics might correlate with children's synchronization performance. Values for event density, RMS, pulse clarity, and spectral flux were obtained for each of the twelve excerpts in the tapping stimulus set using version 1.5 of the MIRtoolbox in Matlab (Lartillot & Toiviainen, 2007).

Examination of linear correlations between acoustic characteristics and 5- or 7-year-old mean vector length for each song revealed no significant correlations for either age group (all p's > .05). We conclude that event density, RMS, pulse clarity, and spectral flux of individual songs do not affect children's synchronization consistency in any obvious way.

Circular-linear correlations between mean vector angle, θ, and acoustic characteristics were carried out using the *circlin.cor* function in the 'Directional' package in R (Tsagris, et al., 2016). Correlations calculated with this function are reported as the squared correlation, r^2, between a circular variable and a linear variable. Examination of circular-linear correlations showed that θ for each of the twelve excerpts was significantly correlated with a song's spectral flux for both older ($r^2 = .58, p < .003$) and younger ($r^2 = .39, p < .02$) children, and that event density was significantly correlated for older children ($r^2 = .57, p < .003$) and marginally significantly correlated in younger children ($r^2 = .30, p < .06$). This suggests that spectral flux and event density affect children's ability to accurately phase align to the beat of the stimulus.

The relationships between tapping phase alignment accuracy and RMS or pulse clarity were less clear in our data. RMS energy was significantly correlated with θ for younger ($r^2 = .52, p < .006$) but not older children ($r^2 = .22, p < .13$). The opposite was true for pulse clarity, which was uncorrelated in younger children ($r^2 = .03, p < .756$) but marginally significantly correlated in older children ($r^2 = .31, p < .06$).

Given that we observed no significant effects of metric complexity or age on children's phase alignment accuracy in our music synchronization task, we conclude that acoustic characteristics like spectral flux and event density affect children's tapping performance more observably than metric complexity. Which features are most important at different developmental time points, and how these acoustic features interact with other characteristics like metre to affect overall performance, remains to be investigated in future work.

3 Relation between beat perception and production portions of the cBAT

Five-year-old children's overall beat perception score was strongly correlated with mean vector length for metronome synchronization trials $r = .55$, $n = 48, p < .001$. Further examination of the metronome synchronization trials revealed that mean vector length was correlated with both simple metre beat perception score alone $r = .43, p = .002$ as well as complex metre perception score alone, $r = .50, p < .001$. However, for songs, 5-year-old children's overall beat perception score did not correlate significantly with mean vector length for simple songs ($p = .44$) or complex songs ($p = .08$). Beat perceptions scores did not correlate significantly with mean vector angle for any production measures: metronome trials (p = .13), simple songs (p = .09), or complex songs (p = .76).

By comparison, 7-year-old children's overall cBAT perception score was correlated neither with mean vector length nor with mean vector angle for metronome trials, simple metre songs, or complex metre songs (all p's > .20).

4 Relation between cBAT and cognitive tasks

4.1 cBAT perception score and cognitive tasks

PPVT standard scores were not significantly correlated with overall performance on the cBATT perception task for either age group (younger: r = .16, p = .27; older: r = -.16, p = .33), or with the simple metre or the complex metre portion of the task for either group (all p's > .13). There was variability in PPVT scores for both 5-year-olds, M = 117.23, SD = 11.27, and 7-year-olds, M = 111.48, SD = 10.90, so the lack of correlation is not because all children performed equally well on the PPVT.

Forward digit span did not correlate with simple metre beat perception, complex metre beat perception, or overall beat perception score in either age group (all p's > .30), suggesting that performance on these tasks is not affected by children's short-term memory. Working memory, indexed by backward digit span, also did not correlate with simple metre beat perception, complex metre beat perception, or overall beat perception score in either age group (all p's > .30).

4.2 cBAT production score and cognitive tasks

Scores for the PPVT, forward digit span, and backward digit span were also entered into a correlation analysis with the synchronization portion of the cBATT production task. Linear Pearson correlations were conducted to assess vector length, whereas circular-linear correlations were used to assess vector angle. Circular-linear correlations were again carried out using the *circlin.cor* function in the 'Directional' package in R (Tsagris, et al., 2016).

5-year-olds' forward digit span was significantly correlated with vector length for metronome trials (r = .34, p = .02) and simple metre songs (r = .32, p = .03) but not for complex metre songs (r = .25, p = .08). 7-year-olds' forward digit span was not significantly correlated with vector length for any task (all p's > .35). Conversely, 5-year-olds' backward digit span was not significantly correlated with vector length for any task (all p's > .25) whereas 7-year-olds' backward digit span was significantly correlated with vector length for simple songs (r = .34, p = .03), but not for metronomes (r = .25, p = .13) or complex songs (r = .01, p = .93).

Metronome vector angle correlated with both forward digit span and backward digit span in younger children (r^2_{fwd} = .14, p = .001; r^2_{bkwd} = .12, p = .005) but not in older children (p = .19; p = .33;). Vector angle for simple metre songs was also significantly correlated with both forward digit span and backward digit span in younger children (r^2_{fwd} = .07, p = .047; r^2_{bkwd} = .16, p < .001), but only backward digit span was significantly correlated in older children (r^2_{fwd} = .06, p =

.12; r^2_{bkwd} = .10, p = .02). Vector angle for complex songs correlated with neither forward nor backward span in either age group (all p's > .10).

Vector length for metronome trials, simple songs, or complex songs was not significantly correlated with PPVT standard score in either age group (all p's > .12). Metronome vector angle was significantly correlated with PPVT standard score in 7-year-olds (r^2 = .12, p = .01) but not with simple metre or complex metre vector angle for 7-year-olds (all p's > .07). PPVT score was not significantly correlated with any vector angle for 5-year-olds (all p's > .30).

5 Relation between cBAT and demographic characteristics

Neither maternal education nor paternal education was significantly correlated with any of: individual children's simple or complex metre beat perception alone, overall beat perception score, metronome synchronization vector length or angle, or simple or complex metre song synchronization vector length or angle (all p's > 0.05). Household income level was also not significantly correlated with any of the cBAT perception measures or production measures (all p's > .40). None of the children in either age group had formal instrumental training; a post-hoc comparison of cBAT performance for children whose parents either did or did not have formal music training revealed no difference between groups (p = 0.98).

Discussion

This study expanded the existing complex Beat Alignment Test (cBAT) to create the Beat Alignment and Tapping Test (cBATT) by adding a beat synchronization task to the perception-only measure of beat sensitivity described previously (Einarson & Trainor, 2015; 2016). This beat synchronization task included self-paced tapping, metronome synchronization, and synchronization to the same musical excerpts used in the perception measure. Metronome stimuli taken from Iversen & Patel's original BAT (2008) were presented at three tempi. Musical excerpts were drawn from the perception portion of the cBAT and contained excerpts in both simple and complex musical metres.

Our initial predictions were threefold: first, we expected that 7-year-olds would be better at detecting beat misalignment than 5-year-olds, but that both groups of children would show enculturation to Western musical structures (i.e. simple metre) in the form of significantly better error detection. Second, we hypothesized that both groups of children would demonstrate a similar enculturation bias in the tapping synchronization task, characterized by more consistent tapping synchronization and more accurate phase alignment in the context of simple metre music compared to complex metre music. Finally, we predicted that individuals' beat perception and synchronization abilities would be correlated. Children who showed better perceptual sensitivity to beat alignment were expected to perform better on the beat synchronization task, both when tapping to the relatively impoverished metronome stimuli and also when tapping to musical excerpts.

Our first hypothesis was supported by the perceptual data, which showed that 7-year-olds performed better than 5-year-olds overall. At the same time, like

5-year-olds, 7-year-old children were significantly better at detecting beat misalignment in simple metre music compared to complex metre music, regardless of whether the misalignments were out of phase or were driven by incorrect tempo. These perceptual data also replicate previously published findings using the cBAT task with 5-year-olds (Einarson & Trainor, 2015; 2016).

Despite the fact that both 5- and 7-year-old children demonstrated an enculturated perceptual bias for simple musical metres, a similar bias was not observed in the synchronization task for children in either age group, although tapping synchronization did improve with age. Contrary to our second hypothesis, there was no significant difference in phase alignment accuracy when comparing synchronization to simple metre excerpts versus complex metre excerpts, and children's tapping synchronization was actually more consistent for complex than simple metre music. Given that children were able to perceptually extract the beat in the stimuli, as shown in the perception part of the cBATT, these unexpected production results are unlikely to represent an inability to detect the beat or metre of the music. The fact that 5-year-old children synchronized more consistently when tapping to complex metre music is especially interesting, given that their ability to detect complex metre beat misalignment in the perception portion of the cBATT was not significantly different than chance.

Although tapping performance on simple metre excerpts was not better than on complex-metre excerpts, there was variability in performance across the 12 pieces, with fairly good performance on some pieces and relatively poor performance on others. Through post-hoc examination, we explored whether acoustic characteristics of the individual excerpts were related to children's performance. Event density and spectral flux measures were both strongly significantly correlated with phase accuracy of tapping for both younger and older children. RMS energy and pulse clarity also correlated with younger and older children's phase alignment.

Although the exact role and contribution of each of these features to performance is unclear, they account for our observation that a complex metre excerpt with a clear and salient pulse (for example, Pink Floyd's *Money,* code 'MON' in Table 1: younger $R = .64$, $\theta = -4°$; older $R = .79$, $\theta = -13°$) was easier for children to synchronize with than a sparse simple metre excerpt with a less-obvious pulse (for example, the unusually named Hawaiian guitar track, *Spam Song*, code SPA in Table 1: younger $R = .10$, $\theta = 76°$; older $R = .27$, $\theta = 6°$; see Figure 2). When children were required to synchronize motorically with the beat, the salience of these acoustic cues may have overridden any effect of simple versus complex metre, in contrast to when the same set of excerpts were used in the perception task.

These data provide evidence for a developmental dissociation in beat perception and synchronization. Performance on the beat perception task is largely determined by enculturation to culturally typical metric structure, similar to what has been observed in studies of beat perception and synchronization in adults (Snyder et al., 2006), and in other perceptual domains such as language.

However, when the beat is not directly given in the form of an imposed beat track, tapping synchronization appears to be driven primarily by acoustic features such as energy and event density. It is interesting to note that several of these characteristics also correlate with ratings of musical "groove" by adult listeners (Madison et al., 2011), and that groove is characterized by wanting to move or tap along to music.

It should also be noted that both the perception and synchronization components of the cBATT task asked children to attend to the tactus level of the metrical hierarchy. As such, the relevant musical beat was isochroous for both simple metre and complex metre stimuli. This may be part of why we did not observe the hypothesized difference in tapping synchronization performance between simple and complex metre music. Future work could investigate the effect of asking subjects to synchronize their tapping to the next level of the metrical hierarchy, where the accents in complex metre music would *not* be isochronous. It is possible that any enculturation bias in tapping performance would be more obvious in this context.

Alternately, this lack of an observable difference could simply be due to poor overall tapping synchronization in both 5- and 7-year-olds. In this case we would expect to see clearer evidence of an enculturation bias in older children, whose tapping performance would be better overall. However, the results of the Rayleigh analysis suggest that the majority of children's tapping is non-random for at least a few of the musical excerpts even at age 5, and that tapping improves in all contexts by age 7. Thus, it is unlikely that the lack of difference between metre types is attributable solely to poor performance.

Auditory-motor entrainment is constrained by motor skills in a way that the purely perceptual music task is not, and the relationship between acoustic features, motor skills, and synchronization performance is one that has not been investigated in children to date. Given that 7-year-old children with Developmental Coordination Disorder (DCD) have impaired coordination and control in a gross motor timing task compared to same-age peers (Whitall, Getchell, McMenamin, Horn, Wilms-Floet, & Clark, 2006), as do children with dyslexia (Getchell, Mackenzie, & Marmon, 2010), it is reasonable to predict that children with motor timing impairments will be less good at synchronizing tapping. However, motor skill also varies widely in 'typical' children and may contribute to tapping performance in these groups in more subtle ways. Additionally, it is not known whether children with motor impairments may also have deficits in auditory timing perception; this is a question the cBATT would be well suited to investigate.

Our third hypothesis was that children's beat perception and synchronization would be positively correlated, but we did not observe this in our data. Younger children's metronome synchronization consistency was significantly correlated with both simple and complex metre beat perception, but no other aspects of tapping consistency or accuracy correlated with beat perception in children of either age. Given that the results of our synchronization task appear to be driven by particular acoustic features of music rather than higher-order structural properties like hierarchical metric structure, we conclude that the two tasks are dissociated in young children. Other work assessing beat perception and synchronization in adults has also reported a dissociation between some aspects of perception and synchronization (Fujii & Schlaug, 2013), although the stimuli in this study included only metronomes and simple metre music.

Future work should continue to investigate how children's sensorimotor synchronization is influenced by the acoustic characteristics of musical stimuli, and how the acoustic profile of music interacts with structural features like metric complexity. Some work with adults, for example, has systematically manipulated the characteristics of music used (Stupacher et al., 2016) Additionally, only 5- and 7-year-old children were part of the present investigation; given the rapid changes in other types of motor tasks that occur before age 12, data from older children may be required to illustrate the developmental trajectory of beat perception and beat synchronization (see McAuley et al., 2006, for an example).

Finally, children in our sample struggled to align the phase of their tapping accurately, despite being able to hear the beat in the perception task and being able to approximate the interbeat interval somewhat consistently. Children's performance on the musical tasks was not correlated with verbal intelligence, or short-term or working memory, suggesting the constraint is not a general cognitive one. Tasks that assess perception separately from synchronization, such as the cBATT, are important in understanding deficits in beat perception and synchronization (Vuvan & Tranchant, 2015). If children can detect the beat in the perception task and approximate the tempo in the tapping task (i.e. R), it seems likely that the phase-driven accuracy problems (i.e. θ) represent a motor constraint. Children's perceptual sensitivity to sensory input precedes their ability to imitate or produce that input across several other domains.

In conclusion, musically untrained young children show an enculturated perceptual bias for simple metre music, but a parallel bias for better tapping synchronization to culturally typical timing structures was not observed. Instead, auditory-motor entrainment seems affected by the acoustic characteristics of the individual music excerpts. Beat perception and tapping consistency both improve significantly with age, but do not seem to be robustly correlated with one another. Questions about the impact of particular audio features on tapping consistency and variability remain to be investigated, as does the issue of motor maturation and control on sensorimotor synchronization.

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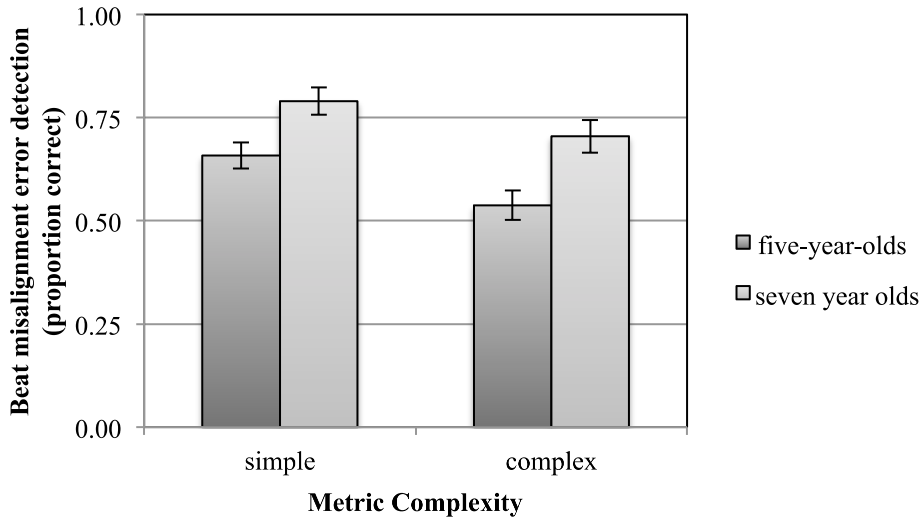

Figure 1: Perception scores from the cBATT perception task. The proportion of trials on which children chose the correctly aligned drumming is shown for 5- and 7-year-old children for simple and complex meter stimuli. Data have been collapsed across phase and tempo conditions. Error bars represent standard error.

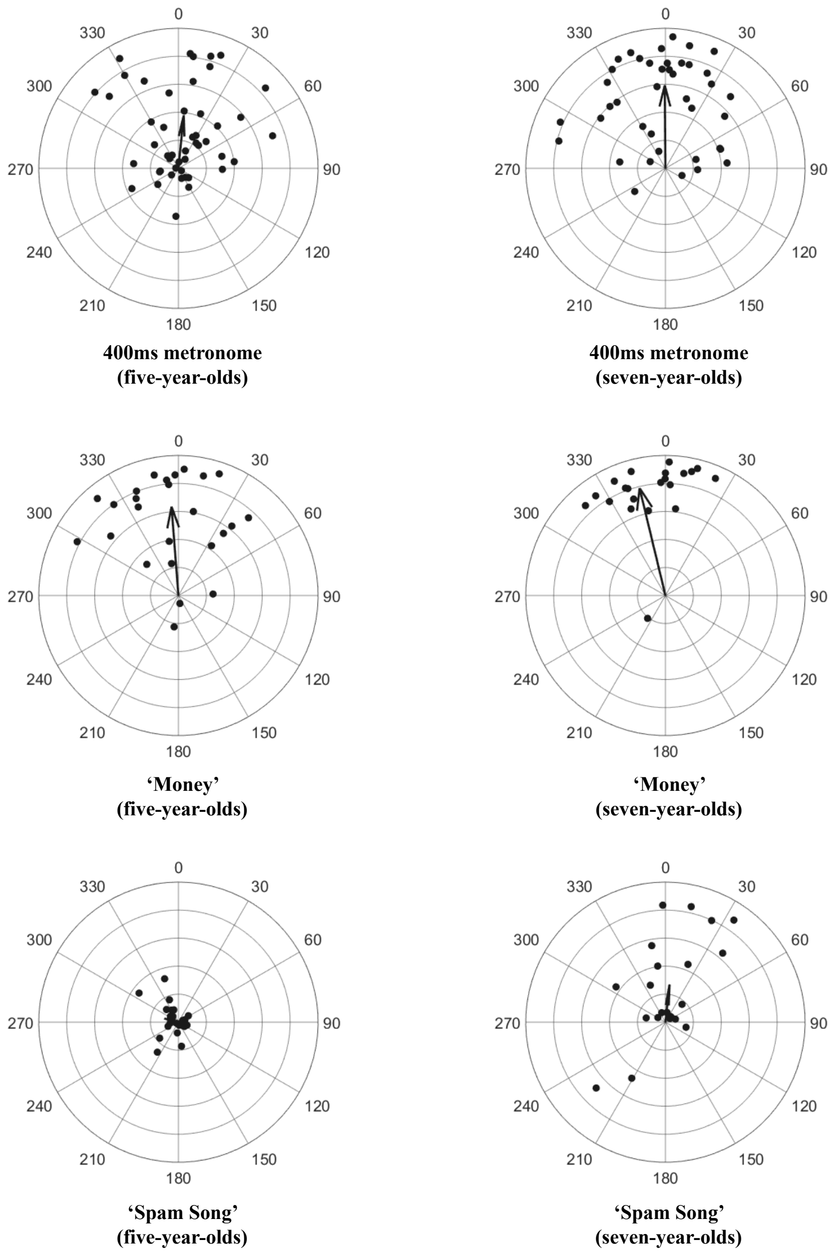

Figure 2: Synchronization consistency (vector length) and phase alignment accuracy (angular deviation from 0) for metronome conditions and two example songs for 5- and 7-year-olds. Dots represent data for individual children, and the vectors represent the average across children. 5-year-olds are shown on the left and 7-year-olds on the right. It can be seen that children synchronize fairly well to the metronome and to the song "Money", but synchronize poorly to the song "Spam Song", as indicated by the short vector length in the latter case. As well, performance is better for older children. See text for description and statistical analyses. Results for additional songs are shown in the Supplementary Material.

Table 1: Mean vector length and vector angle by task type and age

trial	type	genre	mean R 5 years	mean R 5 years	mean θ 5 years	mean θ 7 years
400ms ISI	metronome	n/a	0.38	0.59	6	0
550ms ISI	metronome	n/a	0.58	0.74	-51	-36
700ms ISI	metronome	n/a	0.56	0.72	-54	-37
AWL	simple meter	jazz	0.32	0.35	71	85
HOL	simple meter	orchestral	0.44	0.47	2	4
HSG	simple meter	rock	0.28	0.50	27	11
OWA	simple meter	pop	0.41	0.67	33	-6
SPA	simple meter	Hawaiian	0.10	0.27	-76	6
UND	simple meter	Indian	0.19	0.29	-8	-59
TFI	complex meter	jazz	0.31	0.37	146	102
MAR	complex meter	orchestral	0.52	0.62	44	41
SBH	complex meter	rock	0.19	0.32	-113	-75
MON	complex meter	pop	0.64	0.79	-4	-14
HUL	complex meter	Hawaiian	0.32	0.55	79	19
JOY	complex meter	Indian	0.39	0.49	2	3

Table 2: Proportion of participants who reached significance in Rayleigh's test

	5-year-olds	**7-year-olds**
Metronome 400ms ISI	0.56	0.85
Metronome 550ms ISI	0.81	0.98
Metronome 700ms ISI	0.79	0.93
AWL (simple meter)	0.41	0.35
HOL (simple meter)	0.64	0.65
HSG (simple meter)	0.45	0.55
HUL (complex meter)	0.25	0.80
JOY (complex meter)	0.54	0.70
MAR (complex meter)	0.86	0.85
MON (complex meter)	0.88	0.95
OWA (simple meter)	0.58	0.85
SBH (complex meter)	0.27	0.40
SPA (simple meter)	0.04	0.40
TFI (complex meter)	0.41	0.45
UND (simple meter)	0.29	0.45
Metronome Mean	0.72	0.92
Song Mean	0.45	0.62
Overall proportion significant	0.54	0.72

References

Bazile, C., Siegler, I. A., & Benguigui, N. (2013). Major changes in a rhythmic ball-bouncing task occur at age 7 years. *PloS One*, *8*(10), e74127.

Bobin-Bègue, A., Provasi, J., Marks, A., & Pouthas, V. (2006). Influence of auditory tempo on the endogenous rhythm of non-nutritive sucking. *European Review of Applied Psychology*, *56*(4), 239-245.

Burger, B., Thompson, M. R., Luck, G., Saarikallio, S. H., & Toiviainen, P. (2014). Hunting for the beat in the body: on period and phase locking in music-induced movement. *Frontiers in Human Neuroscience*, *8*, 903.

Butler, B. E., & Trainor, L. J. (2015). The musician redefined: a behavioral assessment of rhythm perception in professional club DJs. *Timing & Time Perception*, *3*(1-2), 116-132.

Cameron, D. J., Bentley, J., & Grahn, J. A. (2015). Cross-cultural influences on rhythm processing: Reproduction, discrimination, and beat tapping. *Frontiers in Psychology*, *6*: 366.

Cameron, D. J., & Grahn, J. A. (2014). Enhanced timing abilities in percussionists generalize to rhythms without a musical beat. *Frontiers in Human Neuroscience, 8*: 1003.

Chang, H. W., & Trehub, S. E. (1977). Infants' perception of temporal grouping in auditory patterns. *Child Development*, 1666-1670.

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008). Listening to musical rhythms recruits motor regions of the brain. *Cerebral Cortex*, *18*(12), 2844-2854.

Collier, G. L., & Wright, C. E. (1995). Temporal rescaling of simple and complex ratios in rhythmic tapping. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(3), 602.

Cook, P., Rouse, A., Wilson, M., & Reichmuth, C. (2013). A California sea lion (Zalophus californianus) can keep the beat: motor entrainment to rhythmic auditory stimuli in a non vocal mimic. *Journal of Comparative Psychology*, *127*(4), 412.

Corrigall, K. A., & Trainor, L. J. (2014). Enculturation to musical pitch structure in young children: evidence from behavioral and electrophysiological methods. *Developmental Science*, *17*(1), 142-158.

DeCasper, A. J., & Spence, M. J. (1986). Prenatal maternal speech influences newborns' perception of speech sounds. *Infant Behavior and Development*, *9*(2), 133-150.

Drake, C. (1993). Reproduction of musical rhythms by children, adult musicians, and adult nonmusicians. *Perception & Psychophysics*, *53*(1), 25-33.

Drake, C., & Bertrand, D. (2001). The quest for universals in temporal processing in music. *Annals of the New York Academy of Sciences*, *930*(1), 17-27.

Drake, C., Jones, M. R., & Baruch, C. (2000). The development of rhythmic attending in auditory sequences: attunement, referent period, focal attending. *Cognition*, *77*(3), 251-288.

Drake, C., Penel, A., & Bigand, E. (2000). Tapping in time with mechanically and expressively performed music. *Music Perception: An Interdisciplinary Journal*, *18*(1), 1-23.

Drewing, K., Aschersleben, G., & Li, S.C. (2006). Sensorimotor synchronization across the life span. *International Journal of Behavioral Development*, *30*(3), 280-287.

Dunlap, K. (1910). Reaction to rhythmic stimuli with attempt to synchronize. *Psychological Review*, *17*(6), 399.

Dunn, L. M., & Dunn, D. M. (2007). *PPVT-4: Peabody Picture Vocabulary Test*. Pearson Assessments.

Eerola, T., Luck, G., & Toiviainen, P. (2006). An investigation of pre-schoolers' corporeal synchronization with music. In M. Baroni, A. R. Addessi, R. Caterina, & M. Costa (Eds.), *Proceedings of the 9th International Conference on Music Perception and Cognition (ICMPC9)* (pp. 472-476). Bologna, Italy: ICMPC.

Einarson, K. M., & Trainor, L. J. (2015). The effect of visual information on young children's perceptual sensitivity to musical beat alignment. *Timing & Time Perception*, *3*(1-2), 88-101.

Einarson, K. M., & Trainor, L. J. (2016). Hearing the beat: Young children's perceptual sensitivity to beat alignment varies according to metric structure. *Music Perception: An Interdisciplinary Journal, 34*(1), 56-70.

Falk, S., Müller, T., & Dalla Bella, S. (2015). Non-verbal sensorimotor timing deficits in children and adolescents who stutter. *Frontiers in Psychology*, *6*, 847.

Ferrel-Chapus, C., Hay, L., Olivier, I., Bard, C., & Fleury, M. (2002). Visuomanual coordination in childhood: adaptation to visual distortion. *Experimental Brain Research*, *144*(4), 506-517.

Field, T. M., & Walden, T. A. (1982). Production and discrimination of facial expressions by preschool children. *Child Development*, 1299-1311.

Fischman, M. G., Moore, J. B., & Steele, K. H. (1992). Children's one-hand catching as a function of age, gender, and ball location. *Research Quarterly for Exercise and Sport*, *63*(4), 349-355.

Fisher, N. I. (1993). *Statistical analysis of circular data*. Cambridge University Press.

Fitzpatrick, P., Schmidt, R. C., & Lockman, J. J. (1996). Dynamical patterns in the development of clapping. *Child Development*, *67*(6), 2691-2708.

Fraisse, P. (1982). Rhythm and tempo. In D. Deutsch (Ed.), *The Psychology of Music*, *1*, 149-180. New York, NY: Academic Press.

Fraisse, P., & Oléron, G. (1954). La structuration intensive des rythmes. *L'année Psychologique*, *54*(1), 35-52.

Fraisse, P., Oléron, G., & Paillard, J. (1958). Sur les repères sensoriels qui permettent de contrôler les mouvements d'accompagnement de stimuli périodiques. *L'année psychologique*, *58*(2), 321-338.

Friendly, R. H., Rendall, D., & Trainor, L. J. (2013). Plasticity after perceptual narrowing for voice perception: reinstating the ability to discriminate monkeys by their voices at 12 months of age. *Frontiers in Psychology*, *4*, 718.

Friendly, R. H., Rendall, D., & Trainor, L. J. (2014). Learning to differentiate individuals by their voices: Infants' individuation of native‐ and foreign‐species voices. *Developmental Psychobiology*, *56*(2), 228-237.

Fujii, S., & Oda, S. (2009). Effect of stick use on rapid unimanual tapping in drummers. *Perceptual and Motor Skills*, *108*(3), 962-970.

Fujii, S., & Schlaug, G. (2013). The Harvard Beat Assessment Test (H-BAT): a battery for assessing beat perception and production and their dissociation. *Frontiers in Human Neuroscience*, *7*, 771.

Fujioka, T., Trainor, L. J., Large, E. W., & Ross, B. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic beta oscillations. *The Journal of Neuroscience*, *32*(5), 1791-1802.

Gerry, D., Unrau, A., & Trainor, L. J. (2012). Active music classes in infancy enhance musical, communicative and social development. *Developmental Science*, *15*(3), 398-407.

Grahn, J. A. (2009). The role of the basal ganglia in beat perception. *Annals of the New York Academy of Sciences*, *1169*(1), 35-45.

Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience*, *19*(5), 893-906.

Greene, L. S., & Williams, H. G. (1993). Age-related differences in timing control of repetitive movement: Application of the Wing-Kristofferson model. *Research Quarterly for Exercise and Sport*, *64*(1), 32-38.

Goodwin, A., Fein, D., & Naigles, L. R. (2012). Comprehension of wh- questions precedes their production in typical development and autism spectrum disorders. *Autism Research*, *5*(2), 109-123.

Gosselin, P., Maassarani, R., Younger, A., & Perron, M. (2011). Children's deliberate control of facial action units involved in sad and happy expressions. *Journal of Nonverbal Behavior*, *35*(3), 225-242.

Hannon, E. E., Soley, G., & Ullal, S. (2012). Familiarity overrides complexity in rhythm perception: A cross-cultural comparison of American and Turkish listeners. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(3), 543.

Hannon, E. E., & Trainor, L. J. (2007). Music acquisition: effects of enculturation and formal training on development. *Trends in Cognitive Sciences*, *11*(11), 466–72.

Hannon, E. E., & Trehub, S. E. (2005a). Metrical categories in infancy and adulthood. *Psychological Science*, *16*(1), 48–55.

Hannon, E. E., & Trehub, S. E. (2005b). Tuning in to musical rhythms: infants learn more readily than adults. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(35), 12639–43.

Hannon, E. E., Vanden Bosch der Nederlanden, C. M., & Tichko, P. (2012). Effects of perceptual experience on children's and adults' perception of unfamiliar rhythms. *Annals of the New York Academy of Sciences*, *1252*(1), 92-99.

Hattori, Y., Tomonaga, M., & Matsuzawa, T. (2013). Spontaneous synchronized tapping to an auditory rhythm in a chimpanzee. *Scientific Reports*, *3*, 1566.

Hirsh-Pasek, K., & Golinkoff, R. M. (1996). *The origins of grammar: Evidence from early language comprehension*. MIT Press.

Huron, D. B. (2006). *Sweet anticipation: Music and the psychology of expectation*. MIT press.

Iversen, J.R., & Patel, A.D. (2008). The Beat Alignment Test (BAT): Surveying beat processing abilities in the general population. In K. Miyazaki, M. Adachi, Y. Hiraga, Y. Nakajima, & M. Tsuzaki (Eds.), *Proceedings of the 10th International Conference on Music Perception and Cognition (ICMPC10)* (pp. 465-468).

Jones, M. R. (1976). Time, our lost dimension: toward a new theory of perception, attention, and memory. *Psychological Review*, *83*(5), 323.

Jusczyk, P.W. (1997). Finding and remembering words: Some beginnings by English-learning infants. *Current Directions in Psychological Science*, *6*(6), 170–174.

Kelly, D. J., Quinn, P. C., Slater, A. M., Lee, K., Ge, L., & Pascalis, O. (2007). The other-race effect develops during infancy: evidence of perceptual narrowing. *Psychological Science*, *18*(12), 1084–9.

Kirschner, S., & Ilari, B. (2013). Joint drumming in Brazilian and German preschool children: cultural differences in rhythmic entrainment, but no prosocial effects. *Journal of Cross-Cultural Psychology*, 45(1), 137-166

Kirschner, S., & Tomasello, M. (2009). Joint drumming: social context facilitates synchronization in preschool children. *Journal of Experimental Child Psychology*, *102*(3), 299-314.

Lambert, J., & Bard, C. (2005). Acquisition of visuomanual skills and improvement of information processing capacities in 6-to 10-year-old children performing a 2D pointing task. *Neuroscience Letters*, *377*(1), 1-6.

Lappe, C., Trainor, L. J., Herholz, S. C., & Pantev, C. (2011). Cortical plasticity induced by short-term multimodal musical rhythm training. *PloS One*, *6*(6), e21493.

Lartillot, O., & Toiviainen, P. (2007, September). A Matlab toolbox for musical feature extraction from audio. In *International Conference on Digital Audio Effects* (pp. 237-244).

London, J. (2012). *Hearing in time: Psychological aspects of musical meter*. Oxford University Press.

Lynch, M. P., & Eilers, R. E. (1992). A study of perceptual development for musical tuning. *Perception & Psychophysics*, *52*(6), 599-608.

Madison, G., & Delignieres, D. (2009). Auditory feedback affects the long-range correlation of isochronous serial interval production: support for a closed-loop or memory model of timing. *Experimental Brain Research*, *193*(4), 519-527.

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.

Madison, G., Karampela, O., Ullén, F., & Holm, L. (2013). Effects of practice on variability in an isochronous serial interval production task: asymptotical levels of tapping variability after training are similar to those of musicians. *Acta Psychologica*, *143*(1), 119-128.

Mardia, K. V., & Jupp, P. E. (2009). *Directional statistics* (Vol. 494). England: John Wiley & Sons.

Maurer, D., & Werker, J. F. (2014). Perceptual narrowing during infancy: A comparison of language and faces. *Developmental Psychobiology*, *56*(2), 154–178.

McAuley, J. D., Jones, M. R., Holub, S., Johnston, H. M., & Miller, N. S. (2006). The time of our lives: life span development of timing and event tracking. *Journal of Experimental Psychology: General*, *135*(3), 348.

Nettl, B. (1983). *The study of ethnomusicology: Twenty-nine issues and concepts* (No. 39). University of Illinois Press.

Odom, R. D., & Lemond, C. M. (1972). Developmental differences in the perception and production of facial expressions. *Child Development*, 359-369.

Olivier, I., Ripoll, H., & Audiffren, M. (1997). Age differences in using precued information to preprogram interception of a ball. *Perceptual and Motor Skills*, *85*, 123-327.

Oller, D. K. (1980). The emergence of the sounds of speech in infancy. *Child Phonology*, *1*, 93-112.

Palmer, C., & Krumhansl, C. L. (1990). Mental representations for musical meter. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(4), 728.

Pascalis, O., de Haan, M., & Nelson, C. A. (2002). Is face processing species-specific during the first year of life? *Science*, *296*(5571), 1321-1323.

Patel, A. D., Iversen, J. R., Bregman, M. R., & Schulz, I. (2009). Experimental evidence for synchronization to a musical beat in a nonhuman animal. *Current Biology*, *19*(10), 827-830.

Phillips-Silver, J. (2009). On the meaning of movement in music, development and the brain. *Contemporary Music Review*, *28*(3), 293-314.

Povel, D. J. (1981). Internal representation of simple temporal patterns. *Journal of Experimental Psychology: Human Perception and Performance*, *7*(1), 3.

Provasi, J., & Bobin-Bègue, A. (2003). Spontaneous motor tempo and rhythmical synchronisation in 2½-and 4-year-old children. *International Journal of Behavioral Development*, *27*(3), 220-231.

R Core Team (2016). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria.

Repp, B. H. (2005). Sensorimotor synchronization: a review of the tapping literature. *Psychonomic Bulletin & Review*, *12*(6), 969-992.

Repp, B. H., & Su, Y. H. (2013). Sensorimotor synchronization: a review of recent research (2006–2012). *Psychonomic Bulletin & Review*, *20*(3), 403-452.

Rice, T. (1994). *May it fill your soul: Experiencing Bulgarian music*. Chicago, IL, USA: University of Chicago Press.

Saffran, J. R., Senghas, A., & Trueswell, J. C. (2001). The acquisition of language by children. *Proceedings of the National Academy of Sciences*, *98*(23), 12874-12875.

Saffran, J. R., Werker, J. R., & Werner, L. A. (2006). The Infant's Auditory World: Hearing, Speech, and the Beginnings of Language. In *Handbook of Child Psychology, 6th edition* (58–108). Hoboken, NJ: John Wiley & Sons.

Smoll, F. L. (1974). Development of rhythmic ability in response to selected tempos. *Perceptual and Motor Skills*, *39*(2), 767-772.

Smoll, F. L. (1975). Preferred tempo of motor performance: Individual differences in within-individual variability. *Journal of Motor Behavior*, *7*(4), 259-263.

Snyder, J. S., Hannon, E. E., Large, E. W., & Christiansen, M. H. (2006). Synchronization and continuation tapping to complex meters. *Music Perception: An Interdisciplinary Journal*, *24*(2), 135-146.

Stupacher, J., Hove, M. J., & Janata, P. (2016). Audio features underlying perceived groove and sensorimotor synchronization in music. *Music Perception: An Interdisciplinary Journal*, *33*(5), 571-589.

Trainor, L. J., & Hannon, E. E. (2013). Musical Development. In Diana Deutsch (Eds.), *The Psychology of Music* (Third ed.) (pp.423-497). London, UK: Elsevier Inc.

Trainor, L. J., & Trehub, S. E. (1992). A comparison of infants' and adults' sensitivity to western musical structure. *Journal of Experimental Psychology*. *Human Perception and Performance*, *18*(2), 394–402.

Trehub, S. E. (1976). The discrimination of foreign speech contrasts by infants and adults. *Child Development*, 466-472.

Trehub, S. E. (2000). Human processing predispositions and musical universals. In N. L. Wallin, B. Merker, & S. Brown (Eds.), *The Origins of Music* (pp. 427-448). Cambridge, MA: MIT Press.

Trehub, S. E., & Thorpe, L. A. (1989). Infants' perception of rhythm: Categorization of auditory sequences by temporal structure. *Canadian Journal of Psychology/Revue Canadienne de Psychologie*, *43*(2), 217.

Tsagris, M., Athineou, G., & Sajib, A. (2016) *Directional: Directional Statistics*. R package version 2.2. https://CRAN.R-project.org/package=Directional

van Noorden, De Bruyn, van Noorden, & Leman (in preparation). Embodied social synchronization in children's musical development.

Vanneste, V., Pouthas, J.H., & Wearden, S. (2001). Temporal control of rhythmic performance: a comparison between young and old adults. *Experimental Aging Research*, *27*(1), 83-102.

Volman, M. C. J., & Geuze, R. H. (2000). Temporal stability of rhythmic tapping "on" and "off the beat": A developmental study. *Psychological Research*, *63*(1), 62-69.

von Hofsten, C. (1980). Predictive reaching for moving objects by human infants. *Journal of Experimental Child Psychology*, *30*(3), 369-382.

Tranchant, P., & Vuvan, D. T. (2015). Current conceptual challenges in the study of rhythm processing deficits. *Frontiers in Neuroscience*, *9*: 197.

Wechsler, D. (2003). *Wechsler Intelligence Scale for Children-WISC-IV*. Psychological Corporation.

Werker, J. F., & Tees, R. C. (1999). Influences on infant speech processing: Toward a new synthesis. *Annual Reviews in Psychology*, *50*(1), 509–535.

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

Woodrow, H. (1932). The effect of rate of sequence upon the accuracy of synchronization. *Journal of Experimental Psychology*, *15*(4), 357.

Zar, J. H. (1999). *Biostatistical analysis*. Pearson Education India.

Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music: auditory–motor interactions in music perception and production. *Nature Reviews Neuroscience*, *8*(7), 547-558.

Zentner, M., & Eerola, T. (2010). Rhythmic engagement with music in infancy. *Proceedings of the National Academy of Sciences*, *107*(13), 5768-5773.

CHAPTER 5: General Discussion

Despite the universality of music as a human behaviour across the globe, the particular features of musical systems vary enormously from one culture to the next. Each culture or musical tradition has its own rules that dictate not just how pitch, timing, and timbre are manipulated in a given moment or across time, but also govern broader questions about who makes music, when, and why.

Amongst all this variability, however, anthropologists and theorists have proposed a number of characteristics to be 'musical universals' (Nettl, 2000). Examples of some of these universals include: having a discrete set of pitches, small intervals, and the use of instruments (Savage, Brown, Sakai, & Currie, 2015). However, it has been argued that music's most fundamental structural feature is its temporal organization (Hannon & Trainor, 2007). Without a steady and predictable underlying beat present it would not be possible to make music together with other people by singing or playing instruments, nor would it be possible to coordinate movements to music, as we do in dance. Humans are able to sing, play instruments, and dance together with one another because they are able to perceive, and synchronize their movements to, this beat.

Unique contributions to understanding musical beat processing

Although there is an extensive scientific literature investigating beat perception and beat synchronization in adults, this body of research has relied primarily on sensorimotor synchronization tasks like finger tapping (see Repp, 2005 and Repp & Su, 2013, for reviews). Although other non-tapping tasks have been developed using, for example, musical instruments (Loehr & Palmer, 2009; Palmer, Koopmans, Loehr, & Carter, 2009) or whole body movement (e.g. a rocking chair; Demos, Chaffin, Begosh, Daniels, & Marsh, 2011) these tasks typically do not dissociate perception and action. Instead, synchronization of a motor gesture, most commonly finger tapping, is used as an index of perceptual sensitivity. In the research presented here I designed the first behavioural timing task suitable for young children that can dissociate a child's perceptual sensitivity to complex auditory temporal information from his or her ability to synchronize motor movements to an auditory stimulus. The means to assess these two skills separately is particularly important in the case of children. Because their gross and fine motor skills have not yet achieved adult-like refinement, it is likely that the sensorimotor synchronization paradigms developed for adult research participants would provide inaccurate characterizations of children's perceptual sensitivity and potentially underestimate children's abilities. Evidence from previous studies has established that infants and toddlers exhibit spontaneous periodic motor movement like kicking and bouncing when exposed to music (Eerola, Luck, & Toiviainen, 2006; Ilari, 2015; Zentner & Eerola, 2010), suggesting that they are sensitive to the presence of an underlying pulse. However, unlike the tapping, clapping, or nodding behaviour seen in adults, their movements are typically not locked to the beat.

In order to examine children's perceptual sensitivity to the beat of music independent of their ability to synchronize motorically, we created a child-friendly version of Iversen and Patel's Beat Alignment Test (BAT) for adults (2008), called the complex Beat Alignment Test (cBAT). The perceptual task in the original BAT consists of a click track superimposed on musical excerpts; the isochronous tone either aligns with the beat of the music or is misaligned in either tempo or phase. The perceptual component of the cBAT differs from the original BAT in two respects. First, it includes musical excerpts in complex as well as simple meters. Second, it uses a child friendly task in which the child watches audiovisual clips and determines which of two puppets is better at drumming to the music. This audiovisual task does not require any motor synchronization response. In the experiment reported in Chapter 2, the click track (and puppet drumming) was either on the beat or misaligned in tempo or in phase. We found that musically untrained five-year-old children could perceive the musical beat, detecting misalignments in either the tempo or the phase of the underlying beat of the musical excerpts. The study also revealed, however, that children only demonstrated this beat sensitivity in the context of simple metre music, and their ability to detect misalignments in complex metre music was not significantly different than chance. The original audio-only BAT has been used with adults (Iversen & Patel, 2008) and some preliminary unpublished work with infants was presented at a conference (Patel, Iverson, Brandon, & Saffran, 2011), but the study in Chapter 2 with the modified cBAT was the first to assess young children's beat perception with a beat alignment task, and to compare their performance on musical excerpts with both simple and complex meters.

Given that the cBAT uses an audiovisual presentation, it was important to explore the contribution of the dynamic visual component to children's performance. The study reported in Chapter 3 not only replicated the original perceptual finding with musically untrained five year olds, but also established that removal of the dynamic puppet drumming videos (presenting a still image of the puppets on each trial instead) did not affect children's performance. Anecdotally, the experimenters collecting data in Chapter 3 reported that children who watched videos appeared to have more fun and needed less encouragement to persist in the perception task. However, there was no significant difference in the accuracy of beat alignment judgments between the two conditions. This establishes that children can base their synchronization judgments on auditory information.

Finally, Chapter 4 expanded the cBAT perception task to include a synchronization component as well. This task, renamed the complex Beat Alignment *and Tapping* Task, or cBATT, tested the same children on both the cBAT video judgment perception task and the new child-friendly tapping synchronization task to investigate the relation between auditory and motor aspects of beat processing. It was found that children's beat synchronization performance was not obviously driven by the underlying metric structure of the musical stimulus, as they were not significantly better at synchronizing with simple- compared to complex-meters excerpts. It is possible that this lack of an observable effect of metric structure was due to children's poor performance on the task overall. However, the Rayleigh test indicated that children *were* capable of synchronizing consistently to some musical contexts. The results of the synchronization task are in contrast to the results of the perception task, for which the results replicated our previous finding that children's perceptual sensitivity is affected by the metric structure category of the excerpt being presented.

Contrastively, tapping performance differed systematically across the musical excerpts, with tapping alignment much better for some than others. In addition, performance across the various excerpts was highly correlated with the same musical variables for younger and older children, suggesting that both age groups were using similar information in the music to accomplish tapping to the beat. We investigated whether synchronization was influenced by surface-level acoustic characteristics of the songs used and found highly significant correlations between tapping accuracy and a number of song-specific features like energy and pulse clarity. I posit a developmental dissociation between perception and synchronization to a beat; although beat perception seems driven by higher-level grouping principles to do with accent structure and metre, children's tapping, by comparison, seems to be affected by the low-level acoustic characteristics of the sound signal such as mean energy. The relative contributions of tempo, metric structure, energy, pulse clarity, and other features remains to be explored in future research.

Previous work has established that spontaneous motor tempo (SMT) slows through childhood (Drake & Botte, 1993; cf. Provasi & Bobin-Begue, 2003) and, consistent with this, we observed that mean ITI was significantly faster for 5-year-olds than 7-year-olds in our sample. Our observation that simple metronome tapping improved significantly with age is also consistent with the existing literature. Given that our song synchronization data did not reflect a simple metre synchronization bias, further research is needed to understand the development of children's sensorimotor synchronization ability in the context of highly complex auditory stimuli like naturalistic music, and how precisely this ability relates to perceptual sensitivity. However, the data in Chapter 4 certainly suggest that beat synchronization is not being driven by the same stimulus characteristics as beat perception, underscoring the importance of dissociating these two basic skills before exploring more nuanced characteristics of the stimuli themselves, such as metre.

A few previous studies have explored changes in beat perception and synchronization with age (Drake, Jones, & Baruch, 2000; McAuley, Jones, Holub, Johnston, & Miller, 2006) but none have isolated beat perception and motor synchronization in children. This thesis makes a unique contribution by developing, testing (Chapter 2), and replicating (Chapter 3, Chapter 4) the cBAT test, which isolates the perception of beat alignment in the context of a child-friendly method. Furthermore, the cBATT in Chapter 4 compared performance in two age groups. It represents the first attempt to understand how the perception of beat in music develops across early childhood, and how the integration of perception and motor aspects of beat might change with age.

Another characteristic of the complex Beat Alignment Task (cBAT) and the complex Beat Alignment and Tapping Task (cBATT) that is unique among existing timing tasks is the breadth of music represented within the stimulus set. The cBAT and cBATT extend previous work on music perception because the twelve songs used in the perception and production tasks encompass not only simple 4/4 metric structures, as in the original BAT, but also complex metres in 5/4 and 7/4 time. The musical stimuli differ at higher levels of the metrical hierarchy so that beats form accented groups of 4, 5, or 7 in accordance with their metric structures. However, the motor component of tapping difficulty is controlled between the simple and complex metre conditions of the task.
This is because at the lower level of the hierarchy where children attend to make perceptual judgments or synchronize their tapping, the beats are isochronously spaced for all excerpts, regardless of whether they have simple or complex structure.

The inclusion of complex metre is especially important because the majority of music cognition research is carried out within Western musical traditions in which simple metres are dominant. Although it has been proposed that all societies have music with an isochronous pulse and simple metre, (Nettl, 2000), many cultures also have music with more complex structures (Bates, 2010; Rice, 2003). Theoretically, it behooves the field to continue exploring less familiar structures if we wish to investigate the full breadth and richness of human musical experience and expertise. In addition, the inclusion of metres common and uncommon in Western music enables exploration of effects of musical familiarity and learning on beat processing.

An additional point of uniqueness is the breadth of music in the cBAT stimulus set. The excerpts were drawn from several traditional Western musical genres, including North American pop and classical orchestral music, as well as from less familiar styles, such as Indian tabla music and Hawaiian guitar. This may have made the task more demanding because even in cases where the music had a culturally typical metric structure, it did not always use familiar instrument timbres, and vice versa. In all cases, excerpts were selected from existing commercial recordings and we did not alter the acoustic profile (e.g. peak amplitude or RMS) or manipulate other defining characteristics (e.g. tempo) of the excerpts in any way. This emphasis on naturalistic musical stimuli came at the cost of experimental control, a tradeoff that is discussed further below, but this choice represents an ambitious approach to investigating both beat perception and beat synchronization in the context of real music rather than simple metronomes or synthesized MIDI stimuli.

Together, the data presented in Chapters 2 through 4 make a number of significant contributions to the time perception literature, and the cBATT assessment represents a promising new tool for the investigation of perception of temporal information and synchronization to diverse musical structures. Taken together, these results lay the foundation for subsequent investigations of how children's timing perception and timing synchronization change over the course of normal maturation, the impact of atypical motor or perceptual development on these abilities, the impact of passive exposure in diverse cultural and musical contexts, and the result of formal training in childhood. Although the data presented in this thesis deal (almost) exclusively with children, it bears repeating that even the comparably rich literature examining beat perception and synchronization in adults has largely ignored the question of metric complexity or non-Western music. Although these topics reach beyond the scope of a single dissertation, they are briefly discussed below in the context of future directions.

Limitations of the thesis research

Several of the general limitations within this thesis are a result of choices made during the design and creation of the cBAT and cBATT tasks, and as such affect all three data chapters. Although these limitations can be addressed in future work, the foundational research described here shows that the tool works well and that results using the tool are replicable.

First, the choice to use naturalistic musical stimuli for both the perception and production tasks was a deliberate one, but came at the cost of experimental control and generalizability. For example, because each musical sample was simply excerpted from an existing commercial recording, the acoustic characteristics of the stimulus set were not normalized or adjusted. As in the original BAT task (Iversen & Patel, 2008), each excerpt had a different tempo, timbre, peak amplitude, energy (i.e. RMS), and absolute duration. As described in Chapter 4, the stimulus variability posed an interpretive challenge when the synchronization data differed across excerpts. For example, the tempi of excerpts in the cBAT ranges from 88 to 172 BPM (see Table 1, Chapter 2), and it has been established that children's tapping consistency and variability vary with tempo. Children's tapping is most consistent at speeds close to their own spontaneous motor tempo (SMT), which is approximately 400 ms, equivalent to 150 beats per minute, in very young children (Provasi & Bobin-Begue, 2003) although it slows throughout childhood (Drake et al., 2000; Fraisse & Oleron, 1954). Additionally, children struggle to entrain to tempi far outside this range, although the absolute limits of their abilities have not been established. As observed by Eerola, Luck, and Toiviainen (2006), it is challenging to obtain reliable data with young children. By comparison, adults' SMT is approximately 600ms, or 100 beats per minute (Fraisse, 1974; 1982), and they are capable of synchronizing between approximately 30 and 300 bpm.

One effective solution to this dilemma was recently employed as part of the Harvard Beat Alignment Task (H-BAT; Fujii & Schlaug, 2013). After determining the tempo of each excerpt, as was done in the cBAT, the authors took the additional step of adjusting the tempi of the excerpts so that they were matched to one another. This would, for example, allow for two excerpts from the same genre to have their tempos matched, and more specifically, for the tempi to be matched within pairs to ensure that each pairing of a simple metre excerpt and a complex metre excerpt was comparable in the stimulus set. A similar type of standardization, also described in the H-BAT, involves normalizing the peak amplitudes of the stimuli. Given our hypothesis that the acoustic characteristics of different excerpts are contributing the children's tapping performance, the control afforded by modification and/or standardization of these features is potentially useful in subsequent research using the cBATT.

In addition to naturalistic music, the choice to use videos as part of the perception task was also deliberate. However, because of the nature of the timing errors (particularly the fast/slow tempo manipulations), the videos had to be created not just once at the standard tempo, but also at a variety of speeds. In order to balance the design, as described in Chapter 2, each puppet had to be filmed at more than one tempo, and drumming to more than one song. Since each musical excerpt had a different tempo and a different length, videos of one puppet drumming to a particular excerpt could not be re-used for different excerpts. This made the video creation process extremely labour intensive, and constrained the questions that could be addressed using the existing video stimuli. Thus, future studies might focus on using the still puppet images or using an avatar that could be manipulated rather than using actual filming.

As an aside, readers should note that the meticulous and labour intensive nature of the stimulus creation was underscored in this work by the fact that the videos in question were created not once, but *three* times over the course of this research. The first set of videos, created in 2011, showed puppets that tapped the drum with an *alternating* right-left-right-left pattern. When the initial study was presented, a colleague pointed out that although it was isochronous, this 'alternating' visual representation of the drumming was implicitly binary and could potentially result in depressed performance in the complex metre condition of the perception task. Based on this valid concern, the videos were created a second time in 2012 with a *simultaneous* bimanual drumming gesture, where both hands tapped the drum together instead of in alternation. However, changes in video technology and camera settings resulted in an inadvertent error where the second set of footage was mildly blurry. Finally, the videos were created a third time in 720p that same year, again depicting the simultaneous bimanual drumming. These final videos also underwent post-production processing to adjust the colour saturation and brightness, so that these values were matched across all 72 videos clips in the stimulus set. It is this third set of high resolution, more controlled videos that were used in Chapters 2, 3, and 4.

As demonstrated in Chapter 3, the dynamic visual component of the stimuli in the perception task (i.e. the aforementioned videos) did not significantly alter children's performance on the task compared to static images. The original intention of the videos was to the make the somewhat abstract audio-only BAT judgment task more concrete so it could be used with young children. If a static image of the puppet would suffice, this would allow more easily for the creation of numerous permutations of stimuli. Not only could the tempo or acoustic profile of music be adjusted as needed, but also a wider variety of excerpts could be used, including more excerpts from the genres already present, excerpts from other genres, with other metres, with other acoustic characteristics, etc. One obvious example is ternary metric structures, such as 3/4 time, which were represented in Iversen & Patel's original BAT task, but are not included in the cBAT(T).

The potential to adjust the task as described above raises a third limitation of the existing cBAT(T) that, unlike the naturalistic stimuli and dynamic video, is not specific to the design of the task itself but instead is a fundamental one related to timing manipulation. Because of the difficulties described above in creating cBAT(T) videos, the studies outlined in this thesis examine only four timing manipulations, namely 'too slow' and 'too fast' (+/- 10% of excerpt IBI), or 'too early' and 'too late' (+/- 25% of excerpt IBI), as detailed in Chapter 2. However, with the use of still images as show to work effectively in Chapter 3, it would be interesting for future work to use different degrees of tempo and phase misalignment as well as to explore the impact of other types of manipulations on beat perception and production.

There is also a general issue concerning the relationship between phase and tempo. Although the data in this thesis have been presented as though the phase and tempo shifts are entirely different types of temporal manipulations, the first to alignment and the other to speed, they are actually more difficult to separate. In particular, a tempo misalignment, where the beat is too fast or slow, also necessarily has misaligned phase. The difference in this case is that the magnitude of the resultant phase misalignment is not fixed; rather, the phase error varies cyclically, increasing, peaking on the offbeat, decreasing, and then returning to correct alignment before cycling again.

A fourth limitation of the research presented here is that, in its present form, the cBATT is not able to distinguish between the contributions of metre, tempo, pulse clarity, or other characteristics to children's tapping performance. This is largely due to the limitations already discussed above, including the fact that tempo and duration varied across the naturalistic excerpts; as well, beat saliency or pulse clarity fluctuated both within and between songs. Our post-hoc analyses confirmed that acoustic characteristics measured using the MIR toolbox (Lartillot & Toiviainen, 2007) were highly significantly correlated with tapping performance, specifically tap accuracy (as indexed by mean vector angle). It seems possible that the effects of these correlated acoustic characteristics, including energy, event density, and others, may be confounded with the effects of some additional factors, such as tempo or syncopation. Manipulating the characteristics of the musical stimulus set in the ways described above may not only increase experimental control, but would be an effective step towards disambiguating these possible factors.

Related to this fourth limitation are technical challenges related to creating the hardware necessary to administer the tapping task. Many researchers who have been studying tapping synchronization in adults for years or decades use hardware that, although effective, is no longer available for purchase (Justin London, 2011, personal communication). Our custom-built microcomputer interface box met our needs by allowing the Roland electronic drum to interface with the computer, and was highly effective, offering good consistency with very little delay or jitter in the signal. However, it was also vulnerable to damage and among other injuries was once stepped on by a child, damaged beyond repair, and had to be recreated. Aside from the demands on time, a more robust device would be desirable if other research teams wish to use the cBATT in the future.

A second technical limitation that was difficult to resolve was related directly to the electronic drum hardware. In pilot testing, experimenters struggled to get children to tap the drum in a way that was consistently detectable by the drum's sensor. Analysis of pilot data suggested that children's tapping was either too far from the sensor, or was not forceful enough to be detected. In order to increase the drum's ability to detect a wider variety of tap responses, we disabled the drum's ability to record amplitude information (i.e. the forcefulness of a given tap) in order to maximally increase its sensitivity (i.e. the drum's ability to detect when a tap occurred). I combined this change with an expanded training protocol for each participant prior to the synchronization task. Although these adjustments did improve tap detection, the drum still occasionally missed taps. In the absence of an improvement to the hardware itself, future studies might consider adapting the task. This could include adjusting the device sensitivity settings further or perhaps modifying task demands for the children, for example, by allowing children to use a stick or mallet, the taps of which might be more easily detected.

A final limitation is that it should be noted that the potential contribution of extra-musical abilities in children to their cBAT(T) performance is an area requiring further investigation. This thesis attempted to account for the contribution of non-musical cognitive skills (specifically, verbal intelligence and memory) to children's ability to complete the musical cBAT(T) tasks. For example, preceding work on the topic of young children's metre perception, synchronization, and sequence replication underscored the important contribution of children's memory to their ability to complete complex tasks (Einarson & Trainor, 2011; 2012), and memory has been found to correlate with musical task performance in young children (Anvari, Trainor, Woodside, & Levy, 2002; Kraus, Strait, & Parbery-Clark, 2012). A modest correlation between memory and beat perception was observed in Chapter 2, but not replicated in data from the other chapters using different cohorts of children. The impact of children's motor skills on their ability to perceive and synchronize with temporal information is a particularly interesting question that has not been addressed to date, and merits attention in future work.

To summarize, there are a number of ways in which the stimulus set, task design, and experimental apparatus might be altered to continue investigating the questions explored in this thesis. These include control and standardization of the acoustic profiles of the audio stimuli, use of static rather than dynamic visuals, a wider range of tempo and phase misalignments, a broader sample of musical excerpts (including within the existing metre types and genres, as well as potential additional categories like ternary metres), improvements to the drum hardware and drum-computer interface, and finally, consideration of other non-musical abilities. Accordingly, relevant suggestions for future investigation are outlined below.

Directions for future research

Chapters 2, 3, and 4 characterize five- and seven-year-old children's sensitivity to beat alignment when music has 4/4, 5/4, or 7/4 metric structure. The characteristics of the musical excerpts used in the task were outlined in Table 1 of Chapter 2. Given the unresolved questions about the role of metre, tempo, genre, and acoustic characteristics, future research on the topics outlined in this section would be well-served by considering the stimulus variability in the existing cBAT(T) task. As discussed in the preceding section, solutions could include adjusting tempi and duration, or normalizing and matching acoustic characteristics like pulse clarity. As mentioned above, use of static images for the perception task in place of dynamic videos would allow for numerous permutations of the stimuli when varying the magnitude of phase and tempo misalignments. Static images would also enable expansion of the musical stimulus set to include additional excerpts within a particular metre or genre that is already represented in the cBAT(T), or facilitate the inclusion of new stimuli that increase breadth, such as ternary metres or additional genres.

Aside from issues directly related to the design of the cBAT(T) task itself, there are a number of promising avenues for future investigation that follow from the work described in this thesis. First, we did not observe a significant difference in the *accuracy* of song synchronization tapping for five-year-old compared to seven-year-old children. This is discordant with prior research suggesting that by age seven children's synchronization tapping is approaching adult levels (McAuley et al, 2006), since older children in our study were not statistically more accurate than younger children. Results of the Rayleigh test indicate that both groups of children show highly variable and inaccurate tapping in at least some of the musical contexts in our stimulus set. However, there was a significant improvement between 5 and 7 years of age in metronome tapping and in song tapping *consistency*, a result that is consistent with previous work. Although their stimulus set is different from the cBAT(T), Iverson and Patel (2008) also reported significant variability in adult tapping behaviour among individuals using the original BAT task. Future research should examine sources of individual variability in performance for adults, as well as for children at different ages.

Each of the studies in the current thesis assessed musically untrained five-year-olds, and the addition of seven-year-olds in Chapter 4 is a first step toward investigating changes in beat perception and synchronization across childhood. In the future, it would be beneficial to extend this work using other age groups; unpublished and pilot data from our research group suggest both four- and eight-year-old children can also successfully complete the cBAT. Work with a wider age range would establish baseline levels of ability for typically developing children of different ages, which, with few exceptions (McAuley et al., 2000; Drake et al., 1990), are largely absent from the beat perception and synchronization literature. Moreover, this would also illustrate the developmental progression of perception and synchronization abilities with age, both independently and in relation to one another. For example, little is known about children's processing of musical information at different levels of the metrical hierarchy (e.g. at the level of the isochronous beat versus the level of metric groupings). In a developmental study of a non-musical rhythmic task, namely, ball-bouncing, Bazile and colleagues (2013) claim that there is a sensitive period in the development of perceptual-motor coordination occurring after the age of 8, with significant qualitative and quantitative changes including the emergence of faster, more accurate and more consistent motor coordination. If this is the case, an upward extension of the cBATT task beyond age 7 is likely to be particularly informative.

Related to the question of age and maturation is a second potential source of such individual differences. Motor skills almost certainly contribute to the ability to entrain motor movements to an auditory stimulus. However, it is not clear the degree to which poor synchronization performance might be attributable to motor deficits, as opposed to perceptual ones. Tranchant and Vuvan (2015) suggest that a measure like BAT is uniquely suited to pinpoint the locus of timing deficits in such cases. The developmental progression of gross and fine motor skill attainment can vary greatly across children, resulting in variation in children's absolute level of skill at a given chronological age. Children's varying individual timelines for motor maturation may be a powerful contributor to variability in tapping performance at any given age. Additionally, future work should assess children's gross or fine motor skills in order to control for the contribution of physical abilities not only to the beat synchronization task, but also to determine whether and to what extent children's auditory beat perception is tied to motor activity as it is in adults (for example, Grahn & Brett, 2007; Zatorre, Chen, & Penhune, 2007).

We have conducted a first investigation of this topic using the cBATT with 48 children between the ages of 4 and 8 and including an assessment of motor skills as a covariate. In addition to replicating the pattern of perceptual results described in this thesis, motor skills scores significantly correlated with children's tapping synchronization performance. In addition, overall performance on the beat perception task was significantly related to children's motor skills as assessed by the Motor Assessment Battery for Children, or M-ABC (Einarson & Trainor, in preparation).

If children who have poor motor skills struggle with not only the synchronization task but are, in fact, also less good at beat perception, this raises another potential avenue for future research. The data of Einarson & Trainor (in preparation) suggest that motor skills influence not only motor entrainment, but also perceptual entrainment. If research demonstrates that children with motor impairments are also struggling with unrecognized perceptual impairments, this research may eventually be relevant for the diagnosis and/or treatment of conditions such as Developmental Coordination Disorder (DCD; see Whitall et al., 2008).

Although children's data suggest a relationship between synchronization and perception deficits, there are reasons to believe the relationship may look different in adulthood. The cBATT's ability to investigate these two skills separately has potential to inform the recent "explosion" (Tranchant & Vuvan, 2015) of scientific interest in rhythm and time processing, and particularly in timing deficits. Recent work has identified an adult case of so-called 'beat deafness', thought to be analogous to tone deafness (Palmer, Lidji, & Peretz, 2014; Philips-Silver, Toiviainen, Gosselin, Piche, Nozaradan, Palmer, & Peretz, 2011) and another group has proposed a condition dubbed dysrhythmia, where participants with intact beat perception also exhibit impaired ability to synchronize tapping (Launay, Grube, & Stewart, 2014). The BAT and cBATT tasks provide a useful means of assessing beat perception (as opposed to other timing-based tasks like duration sensitivity or the ability to detect manipulations to rhythm sequences, since these tasks can also be completed using strategies that are not specific to beat-based timing information, such as change detection). Dissociating beat sensitivity from beat synchronization, as the cBAT does, provides a potential means to localize the source of the observed beat synchronization deficit in these clinical cases. This question is particularly interesting given data suggesting perception and action deficits may be linked in childhood (Einarson & Trainor, in preparation) but dissociated in adulthood, or at least in adult clinical cases (Philips-Silver et al., 2011; Launay et al., 2014).

Finally, it should be acknowledged that throughout Chapters 2, 3, and 4 I have attributed the observed perceptual bias for simple metre music to passive enculturation and perceptual specialization. This is consistent with research showing that perceptual specialization for culturally typical musical metres emerges in Western infants during the same age window in development when specialization for other types of native stimuli like phonemes, faces, and voices, also occurs (Hannon & Trehub, 2005a; 2005b; Kelly et al., 2005; Maurer & Werker, 2014; Soley & Hannon, 2010; Werker & Tees, 2005). Additionally, in some of the few cross-cultural studies to date, adults from cultures where simple metres are widespread have been shown to have biases for simple metres, but adults from Bulgaria and Turkey, where complex metres are common, have not (Hannon & Trehub, 2005a; Kalender, Trehub, & Schellenberg, 2013).

However, a study published this year demonstrated that Turkish adults did *not* detect changes in complex metre music at rates that were significantly different from American adults (Yates, Justus, Atalay, Mert, & Trehub, 2016). Only Turkish adults trained in Turkish classical or folk music showed the type of equal sensitivity to both simple and complex metre types that has previously been attributed to *all* members of that musical culture (Kalender et al., 2013). The authors conclude that broad familiarity with a variety of metric structure types is more important to task performance in the context of unfamiliar music than enculturation to a particular metre type. This fascinating result underscores the need for further investigations to disambiguate the effects of passive enculturation from formal training. More importantly for the field of timing research as a whole, it highlights the necessity of considering a broad range of temporal structures before making claims about which abilities are universal or about how abilities develop as a function of experience and exposure. For example, although the data in this thesis have reflected what I have claimed is an enculturated perceptual bias, no work to date has compared Western and non-Western children in a cross-cultural study.

Returning to the issue of passive enculturation and formal training, a final question of interest for future investigations is the effect of formal music instruction on children's perceptual sensitivity, synchronization ability, and degree of enculturation. For example, not only can musical experience in infancy hasten the enculturation process (Gerry, Unrau, & Trainor, 2012), but trained percussionists (Manning & Schutz, 2016) and disk jockeys (Butler & Trainor, 2015) have significantly better sensitivity to fine-grained timing information than do non-musicians, and sensitivity to timing information seems to be influenced by type of music training as well (Yates et al., 2016). However, despite the general public's persistent fascination with scientific investigations of music training in childhood, it remains a challenge to establish the effects of training in the absence of baseline measures of timing abilities in untrained children. The data in this thesis offer that type of baseline measure for use in future studies of timing perception in musically trained children.

Summary and final conclusions

To conclude, the evidence presented in this thesis extends previous studies investigating children's timing perception by examining beat perception and sensorimotor synchronization using two distinct tasks, and with a single stimulus set incorporating both simple and complex metre music into both of those tasks. The complex Beat Alignment Task (cBAT) as described in both the published data in Chapters 2 and 3 and the unpublished complex Beat Alignment and Tapping Task (cBATT) data in Chapters 4 and 5 is suitable for children across a range of ages and abilities, and includes a diverse array of music drawn from several musical cultures and genres. Thus, it fills several unique gaps in the existing literature.

Other tasks have been designed to screen for musical impairments or deficiencies (MBEA; Peretz et al., 2003), to evaluate musical aptitude (PROMS; Law & Zentner, 2012) or musical sophistication (MSI; Müllensiefen, Gingras, Musil, & Stewart, 2014) or to assess beat perception and synchronization in adult subjects (BAT; Iversen & Patel, 2008; H-BAT, Fujii & Schlaug, 2013). However, the only other task designed to assess children's ability, the Montreal Battery for the Evaluation of Musical Aptitude (MBEMA; Peretz, Gosselin, Caron-Caplette, Trehub, & Beland, 2013) does so exclusively in the context of 'Western' tonality and timing, does not assess metre, and additionally, cannot be used with children under the age of 10.

In summary, we find that musically untrained children show a perceptual bias for simple metre music at age five, likely an effect of enculturation, and that this bias persists at age seven despite overall improvements in performance. Children's level of sensitivity was not significantly different between the phase and tempo misalignments (25% and 10% of IBI, respectively) used in the cBAT task, and perceptual sensitivity was neither enhanced nor impaired by the presence of concordant dynamic visual stimuli as opposed to static images. Overall perceptual sensitivity did not correlate with verbal intelligence, as indexed by receptive vocabulary, nor did it correlate in any strong or consistent way with children's memory; thus, the music task was not simply tapping into general cognitive ability. In the cBATT sensorimotor synchronization task, children were significantly better at synchronizing to the comparatively impoverished metronome stimuli, and were much less consistent and more variable when tapping to music, regardless of metre type. Tapping performance seemed to be driven by acoustic characteristics of the music, rather than metric complexity; this remains to be explored in future work.

Collectively, these three studies comprise a meaningful contribution to the beat perception and synchronization literature, and to the field of developmental music cognition more broadly. They demonstrate that although beat perception and synchronization abilities develop slowly and are refined over the course of many years, even young children with no formal training can demonstrate sophisticated sensitivity and make evaluative judgments. This work underscores the importance of examining how associated abilities like perception, synchronization, motor skills, and cognitive abilities develop in tandem through childhood. Given the universality of music, and of isochronous pulse structures across human musical cultures, this research also highlights the importance of examining diverse structures beyond those found in Western music.

General References

Ammirante, P., Patel, A. D., & Russo, F. A. (2016). Synchronizing to auditory and tactile metronomes: a test of the auditory-motor enhancement hypothesis. *Psychonomic bulletin & review*, *23*(6), 1882-1890.

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing, and early reading ability in preschool children. *Journal of Experimental Child Psychology*, *83*(2), 111-130.

Aschersleben, G. (2002). Temporal control of movements in sensorimotor synchronization. *Brain and Cognition*, *48*(1), 66-79.

Bates, E. (2010). Mixing for parlak and bowing for a büyük ses: the aesthetics of arranged traditional music in Turkey. *Ethnomusicology*, *54*(1), 81-105.

Bazile, C., Siegler, I. A., & Benguigui, N. (2013). Major changes in a rhythmic ball-bouncing task occur at age 7 years. *PloS One*, *8*(10), e74127.

Bobin-Bègue, A., Provasi, J., Marks, A., & Pouthas, V. (2006). Influence of auditory tempo on the endogenous rhythm of non-nutritive sucking. *European Review of Applied Psychology*, *56*(4), 239-245.

Butler, B and Trainor, LJ (2015). The Musician Redefined: A Behavioral Assessment of Rhythm Perception in Professional Club DJs. *Timing & Time Perception*, 3(1-2), 116-132.

Cameron, D. J., Bentley, J., & Grahn, J. A. (2015). Cross-cultural influences on rhythm processing: Reproduction, discrimination, and beat tapping. *Frontiers in Psychology*, *6*: 366.

Cameron, D. J., & Grahn, J. A. (2014a). Neuroscientific investigations of musical rhythm. *Acoustics Australia*, *24*(2), 111-16.

Cameron, D. J., & Grahn, J. A. (2014b). Enhanced timing abilities in percussionists generalize to rhythms without a musical beat. *Frontiers in Human Neuroscience, 8*: 1003.

Chang, H. W., & Trehub, S. E. (1977). Infants' perception of temporal grouping in auditory patterns. *Child Development*, 1666-1670.

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008). Listening to musical rhythms recruits motor regions of the brain. *Cerebral Cortex*, *18*(12), 2844-2854.

Cook, P., Rouse, A., Wilson, M., & Reichmuth, C. (2013). A California sea lion (Zalophus californianus) can keep the beat: motor entrainment to rhythmic auditory stimuli in a non vocal mimic. *Journal of Comparative Psychology, 127*(4), 412.

Corrigall, K. A., & Trainor, L. J. (2014). Enculturation to musical pitch structure in young children: evidence from behavioral and electrophysiological methods. *Developmental Science*, *17*(1), 142-158.

Curtin, S., & Werker, J. F. (2007). The perceptual foundations of phonological development. In M. G. Gaskell (Ed.), *The Oxford Handbook of Psycholinguistics*. Oxford, UK: Oxford University Press.

Dalla Bella, S., Farrugia, N., Benoit, C. E., Begel, V., Verga, L., Harding, E., & Kotz, S. A. (2016). BAASTA: Battery for the assessment of auditory sensorimotor and timing abilities. *Behavior Research Methods*, 1-18.

Demos, A. P., Chaffin, R., Begosh, K. T., Daniels, J. R., & Marsh, K. L. (2012). Rocking to the Beat: Effects of Music and Partner's Movements on Spontaneous Interpersonal Coordination. *Journal of Experimental Psychology: General, 141*(1), 49-53.

Drake, C. (1993). Reproduction of musical rhythms by children, adult musicians, and adult nonmusicians. *Perception & Psychophysics*, *53*(1), 25-33.

Drake, C., & Bertrand, D. (2001). The quest for universals in temporal processing in music. *Annals of the New York Academy of Sciences*, *930*(1), 17-27.

Drake, C., & Botte, M.C. (1993). Tempo sensitivity in auditory sequences: Evidence for a multiple-look model. *Perception & Psychophysics*, *54*, 277–286.

Drake, C., & El Heni, J. B. (2003). Synchronizing with music: Intercultural differences. *Annals of the New York Academy of Sciences*, *999*(1), 429-437.

Drake, C., Jones, M. R., & Baruch, C. (2000). The development of rhythmic attending in auditory sequences: attunement, referent period, focal attending. *Cognition*, *77*(3), 251-288.

Drake, C., Penel, A., & Bigand, E. (2000). Tapping in time with mechanically and expressively performed music. *Music Perception: An Interdisciplinary Journal*, *18*(1), 1-23.

Drewing, K., Aschersleben, G., & Li, S.C. (2006). Sensorimotor synchronization across the life span. *International Journal of Behavioral Development*, *30*(3), 280-287.

Dunlap, K. (1910). Reaction to rhythmic stimuli with attempt to synchronize. *Psychological Review*, *17*(6), 399.

Eerola, T., Luck, G., & Toiviainen, P. (2006). An investigation of pre-schoolers' corporeal synchronization with music. In M. Baroni, A. R. Addessi, R. Caterina, & M. Costa (Eds.), *Proceedings of the 9th International Conference on Music Perception and Cognition (ICMPC9)* (pp. 472-476). Bologna, Italy: ICMPC.

Einarson, K. M., & Trainor, L. J. (2011, June). *Perception and production of rhythms in 5-year-old children: Specialization for simple versus complex metres*. Poster presented at Neuroscience and Music IV: Learning and Memory Conference, Edinburgh, Scotland.

Einarson, K. M., & Trainor, L. J. (2012). Young children's musical enculturation: Developing a test of young children's metre processing skills. In *Proceedings of the 12th International Conference on Music Perception and Cognition*, Thessaloniki, Greece (p. 274).

Einarson, K. M., & Trainor, L. J. (2015). The effect of visual information on young children's perceptual sensitivity to musical beat alignment. *Timing & Time Perception*, *3*(1-2), 88-101.

Einarson, K. M., & Trainor, L. J. (2016). Hearing the beat: Young children's perceptual sensitivity to beat alignment varies according to metric structure. *Music Perception: An Interdisciplinary Journal, 34*(1), 56-70.

Einarson, K. M., & Trainor, L. J. (in preparation). Young children's ability to perceive and synchronize to the beat in music is related to motor skills.

Ferrel-Chapus, C., Hay, L., Olivier, I., Bard, C., & Fleury, M. (2002). Visuomanual coordination in childhood: adaptation to visual distortion. *Experimental Brain Research*, *144*(4), 506-517.

Fitzpatrick, P., Schmidt, R. C., & Lockman, J. J. (1996). Dynamical patterns in the development of clapping. *Child Development*, *67*(6), 2691-2708.

Folland, N. A., Butler, B. E., Smith, N. A., & Trainor, L. J. (2012). Processing simultaneous auditory objects: infants' ability to detect mistuning in harmonic complexes. *The Journal of the Acoustical Society of America*, *131*(1), 993-997.

Fraisse, P. (1982). Rhythm and tempo. In D. Deutsch (Ed.), *The Psychology of Music*, *1*, 149-180. New York, NY: Academic Press.

Fraisse, P., & Oléron, G. (1954). La structuration intensive des rythmes. *L'année Psychologique*, *54*(1), 35-52.

Fraisse, P., Oléron, G., & Paillard, J. (1958). Sur les repères sensoriels qui permettent de contrôler les mouvements d'accompagnement de stimuli périodiques [On the sensory data that enable control of movements that accompany periodic stimuli]. *L'Année Psychologique*, 58, 322-338.

Friendly, R. H., Rendall, D., & Trainor, L. J. (2013). Plasticity after perceptual narrowing for voice perception: reinstating the ability to discriminate monkeys by their voices at 12 months of age. *Frontiers in Psychology*, *4*, 718.

Friendly, R. H., Rendall, D., & Trainor, L. J. (2014). Learning to differentiate individuals by their voices: Infants' individuation of native‐ and foreign‐species voices. *Developmental Psychobiology*, *56*(2), 228-237.

Fujii, S., & Schlaug, G. (2013). The Harvard Beat Assessment Test (H-BAT): a battery for assessing beat perception and production and their dissociation. *Frontiers in Human Neuroscience*, *7*, 771.

Fujioka, T., Trainor, L. J., Large, E. W., & Ross, B. (2012). Internalized timing of isochronous sounds is represented in neuromagnetic beta oscillations. *The Journal of Neuroscience*, *32*(5), 1791-1802.

Gerry, D. W., Faux, A. L., & Trainor, L. J. (2010). Effects of Kindermusik training on infants' rhythmic enculturation. *Developmental Science*, *13*(3), 545-551.

Gerry, D., Unrau, A., & Trainor, L. J. (2012). Active music classes in infancy enhance musical, communicative and social development. *Developmental Science*, *15*(3), 398-407.

Getchell, N., Mackenzie, S. J., & Marmon, A.R. (2010). Short term auditory pacing changes dual motor task coordination in children with and without dyslexia. *Adapted Physical Activity Quarterly, 27,* 32–46.

Gibbon, J. (1977). Scalar expectancy theory and Weber's law in animal timing. *Psychological Review*, *84*(3), 279.

Gordon, E. E. (1986). *Manual for the Primary Measures of Music Audiation and the Intermediate Measures of Music Audiation: Music Aptitude Tests for Kindergarten and First, Second, Third, and Fourth Grade Children*. GIA Publications, Incorporated.

Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience*, *19*(5), 893-906.

Hannon, E. E., & Johnson, S. P. (2005). Infants use meter to categorize rhythms and melodies: Implications for musical structure learning. *Cognitive Psychology*, *50*(4), 354-377.

Hannon, E. E., Soley, G., & Levine, R. S. (2011). Constraints on infants' musical rhythm perception: Effects of interval ratio complexity and enculturation. *Developmental Science*, *14*(4), 865-872.

Hannon, E. E., Soley, G., & Ullal, S. (2012). Familiarity overrides complexity in rhythm perception: A cross-cultural comparison of American and Turkish listeners. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(3), 543.

Hannon, E. E., & Trainor, L. J. (2007). Music acquisition: effects of enculturation and formal training on development. *Trends in Cognitive Sciences*, *11*(11), 466–72.

Hannon, E. E., & Trehub, S. E. (2005a). Metrical categories in infancy and adulthood. *Psychological Science*, *16*(1), 48–55.

Hannon, E. E., & Trehub, S. E. (2005b). Tuning in to musical rhythms: infants learn more readily than adults. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(35), 12639–43.

Hannon, E. E., Vanden Bosch der Nederlanden, C. M., & Tichko, P. (2012). Effects of perceptual experience on children's and adults' perception of unfamiliar rhythms. *Annals of the New York Academy of Sciences*, *1252*, 92–99.

Hattori, Y., Tomonaga, M., & Matsuzawa, T. (2013). Spontaneous synchronized tapping to an auditory rhythm in a chimpanzee. *Scientific Reports*, 3, 1566.

Huron, D. B. (2006). *Sweet anticipation: Music and the psychology of expectation*. MIT press.

Ilari, B. (2015). Rhythmic Engagement With Music in Early Childhood A Replication and Extension. *Journal of Research in Music Education*, *62*(4), 332-343.

Iversen, J.R., & Patel, A.D. (2008). The Beat Alignment Test (BAT): Surveying beat processing abilities in the general population. In K. Miyazaki, M. Adachi, Y. Hiraga, Y. Nakajima, & M. Tsuzaki (Eds.), *Proceedings of the 10th International Conference on Music Perception and Cognition (ICMPC10)* (pp. 465-468).

Jones, M. R. (1976). Time, our lost dimension: toward a new theory of perception, attention, and memory. *Psychological Review*, *83*(5), 323.

Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review*, *96*(3), 459.

Kalender, B., Trehub, S. E., & Schellenberg, E. G. (2013). Cross-cultural differences in meter perception. *Psychological Research*, *77*, 196–203.

Kang R., Nimmons G.L., Drennan W., Longnion J., Ruffin C., et al. (2009) *Development and validation of the University of Washington Clinical Assessment of Music Perception Test*. Ear and Hearing *30*(4), 411–418.

Kelly, D. J., Liu, S., Lee, K., Quinn, P. C., Pascalis, O., Slater, A. M., & Ge, L. (2009). Development of the other-race effect during infancy: Evidence toward universality?. *Journal of Experimental Child Psychology*, *104*(1), 105-114.

Kelly, D. J., Quinn, P. C., Slater, A. M., Lee, K., Ge, L., & Pascalis, O. (2007). The other-race effect develops during infancy: evidence of perceptual narrowing. *Psychological Science*, *18*(12), 1084–9.

Kelly, D. J., Quinn, P. C., Slater, A. M., Lee, K., Gibson, A., Smith, M., Liezhong, G. & Pascalis, O. (2005). Three-month-olds, but not newborns, prefer own-race faces. *Developmental Science, 8*(6), F31-F36.

Kirschner, S., & Ilari, B. (2013). Joint drumming in Brazilian and German preschool children: cultural differences in rhythmic entrainment, but no prosocial effects. *Journal of Cross-Cultural Psychology*, *45*(1), 137-166.

Kirschner, S., & Tomasello, M. (2009). Joint drumming: social context facilitates synchronization in preschool children. *Journal of Experimental Child Psychology, 102*(3), 299-314.

Kraus, N., Strait, D. L., & Parbery‐Clark, A. (2012). Cognitive factors shape brain networks for auditory skills: spotlight on auditory working memory. *Annals of the New York Academy of Sciences*, *1252*(1), 100-107.

Kuhl, P. K. (2004). Early language acquisition: Cracking the speech code. *Nature Reviews Neuroscience, 5*, 831-843.

Kuhl, P. K. (2008). Linking infant speech perception to language acquisition: Phonetic learning predicts language growth. In P. McCardle, J. Colombo & L. Freund (Eds.), *Infant pathways to language: Methods, models, and research directions* (pp. 213-243). New York: Erlbaum.

Kuhl, P. K., Conboy, B. T., Padden, D., Nelson, T., & Pruitt, J. (2005). Early speech perception and later language development: Implications for the "critical period". *Language Learning and Development*, *1*(3-4), 237-264.

Kuhl, P. K., Stevens, E., Hayashi, A., Deguchi, T., Kiritani, S., & Iverson, P. (2006). Infants show a facilitation effect for native language phonetic perception between 6 and 12 months. *Developmental Science*, *9*(2), F13-F21.

Kuhl, P. K., Tsao, F. M., & Liu, H. M. (2003). Foreign-language experience in infancy: Effects of short-term exposure and social interaction on phonetic learning. *Proceedings of the National Academy of Sciences*, *100*(15), 9096-9101.

Lambert, J., & Bard, C. (2005). Acquisition of visuomanual skills and improvement of information processing capacities in 6-to 10-year-old children performing a 2D pointing task. *Neuroscience Letters*, *377*(1), 1-6.

Large, E.W. (2000). On synchronizing movements to music. *Human Movement Science*, 19, 527–566.

Large, E. W., & Gray, P. M. (2015). Spontaneous tempo and rhythmic entrainment in a bonobo (Pan paniscus). *Journal of Comparative Psychology*, *129*(4), 317.

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*, *106*(1), 119.

Large, E. W., & Palmer, C. (2002). Perceiving temporal regularity in music. *Cognitive Science*, 26(1), 1-37.

Lartillot O., Toiviainen P (2007) MIR in Matlab (II): A toolbox for musical feature extraction from audio. In *Proceedings of the 8th International Conference on Music Information Retrieval*, Eds Dixon S, Bainbridge D, Typke R (Österreichische Computer Gesellschaft, Vienna, Austria), pp. 127–130.

Lartillot, O., & Toiviainen, P. (2007, September). A Matlab toolbox for musical feature extraction from audio. In *International Conference on Digital Audio Effects*, pp. 237-244.

Launay, J., Grube, M., & Stewart, L. (2014). Dysrhythmia: a specific congenital rhythm perception deficit. *Frontiers in Psychology*, *5*, 18.

Law, L. N., & Zentner, M. (2012). Assessing musical abilities objectively: Construction and validation of the Profile of Music Perception Skills. *PloS One*, *7*(12), e52508.

Lerdahl, F., & Jackendoff, R. (1983). An overview of hierarchical structure in music. *Music Perception: An Interdisciplinary Journal*, *1*(2), 229-252.

Lewkowicz, D. J., & Ghazanfar, A. A. (2009). The emergence of multisensory systems through perceptual narrowing. *Trends in Cognitive Sciences*, *13*(11), 470-478.

Loehr, J. D., & Palmer, C. (2009). Sequential and biomechanical factors constrain timing and motion in tapping. *Journal of Motor Behavior*, *41*(2), 128-136.

London, J. (2012). *Hearing in time: Psychological aspects of musical meter*. Oxford University Press.

Lynch, M. P., & Eilers, R. E. (1992). A study of perceptual development for musical tuning. *Perception & Psychophysics*, *52*(6), 599-608.

Lynch, M. P., Eilers, R. E., Oller, D. K., & Urbano, R. C. (1990). Innateness, experience, and music perception. *Psychological Science*, *1*(4), 272-276.

Manning, F. C., & Schutz, M. (2013). “Moving to the beat” improves timing perception. *Psychonomic Bulletin & Review, 20,* 1133-1139.

Manning, F. C., & Schutz, M. (2015). Movement enhances perceived timing in the absence of auditory feedback. *Timing & Time Perception, 3,* (3-12).

Manning, F. C., & Schutz, M. (2016). Trained to keep a beat: Movement-related enhancements to timing perception in percussionists and non-percussionists. *Psychological Research, 80*(4), 532-542.

Maurer, D., & Werker, J. F. (2014). Perceptual narrowing during infancy: A comparison of language and faces. *Developmental Psychobiology*, *56*, 154–178.

McAuley, J. D., Jones, M. R., Holub, S., Johnston, H. M., & Miller, N. S. (2006). The time of our lives: life span development of timing and event tracking. *Journal of Experimental Psychology: General*, *135*(3), 348–67.

Müllensiefen, D., Gingras, B., Musil, J., & Stewart, L. (2014). The musicality of non-musicians: an index for assessing musical sophistication in the general population. *PloS One*, *9*(2), e89642.

Nelson, D. G. K., Jusczyk, P. W., Mandel, D. R., Myers, J., Turk, A., & Gerken, L. (1995). The head-turn preference procedure for testing auditory perception. *Infant Behavior and Development, 18*(1), 111-116.

Nettl, B. (1983). *The study of ethnomusicology: Twenty-nine issues and concepts* (No. 39). University of Illinois Press.

Nettl, B. (2000). An ethnomusicologist contemplates musical universals. In N. L. Wallin, B. Merker, & S. Brown (Eds.), *The origins of music* (pp. 464–472). Cambridge, MA: MIT Press.

Palmer, C., Koopmans, E., Loehr, J. D., & Carter, C. (2009). Movement-related feedback and temporal accuracy in clarinet performance. *Music Perception: An Interdisciplinary Journal*, *26*(5), 439-449.

Palmer, C., & Krumhansl, C. L. (1990). Mental representations for musical meter. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(4), 728.

Palmer, C., Lidji, P., & Peretz, I. (2014). Losing the beat: deficits in temporal coordination. *Philosophical Transactions of the Royal Society B*, *369*(1658), 20130405.

Patel, A. D., Iversen, J. R., Brandon, M., & Saffran, J. (2011). Do infants perceive the beat in music? A new perceptual test. Abstract in *Proceedings of the 2011 Biennial Meeting of the Society for Music Perception and Cognition (SMPC 2011)*. Rochester, NY: SMPC.

Patel, A. D., Iversen, J. R., Bregman, M. R., & Schulz, I. (2009). Experimental evidence for synchronization to a musical beat in a nonhuman animal. *Current Biology*, *19*(10), 827-830.

Patel, A. D., Iversen, J. R., Chen, Y., & Repp, B. H. (2005). The influence of metricality and modality on synchronization with a beat. *Experimental Brain Research*, *163*(2), 226-238.

Peretz, I., Champod, A. S., & Hyde, K. (2003). Varieties of musical disorders: The Montreal Battery of Evaluation of Amusia. *Annals of the New York Academy of Sciences*, *999*(1), 58-75.

Peretz, I., Gosselin, N., Nan, Y., Caron-Caplette, E., Trehub, S. E., & Béland, R. (2013). A novel tool for evaluating children's musical abilities across age and culture. *Frontiers in Systems Neuroscience*, *7*, 30.

Peters, M. (1989). The relationship between variability of intertap intervals and interval duration. *Psychological Research*, *51*(1), 38-42.

Phillips-Silver, J., Toiviainen, P., Gosselin, N., Piché, O., Nozaradan, S., Palmer, C., & Peretz, I. (2011). Born to dance but beat deaf: a new form of congenital amusia. *Neuropsychologia*, *49*(5), 961-969.

Phillips-Silver, J., & Trainor, L. J. (2005). Feeling the beat: movement influences infant rhythm perception. *Science*, *308*(5727), 1430-1430.

Phillips-Silver, J., & Trainor, L. J. (2007). Hearing what the body feels: Auditory encoding of rhythmic movement. *Cognition*, *105*(3), 533-546.

Povel, D. J. (1981). Internal representation of simple temporal patterns. *Journal of Experimental Psychology: Human Perception and Performance*, *7*(1), 3.

Povel, D. J., & Essens, P. (1985). Perception of temporal patterns. *Music Perception: An Interdisciplinary Journal*, *2*(4), 411-440.

Provasi, J., & Bobin-Bègue, A. (2003). Spontaneous motor tempo and rhythmical synchronisation in 2½-and 4-year-old children. *International Journal of Behavioral Development*, *27*(3), 220-231.

Repp, B. H. (2005). Sensorimotor synchronization: a review of the tapping literature. *Psychonomic Bulletin & Review*, *12*(6), 969-992.

Repp, B. H., London, J., & Keller, P. E. (2013). Systematic distortions in musicians' reproduction of cyclic three-interval rhythms. *Music Perception: An Interdisciplinary Journal*, *30*(3), 291-305.

Repp, B. H., & Su, Y. H. (2013). Sensorimotor synchronization: a review of recent research (2006–2012). *Psychonomic Bulletin & Review*, *20*(3), 403-452.

Rice, T. (1994). *May it fill your soul: Experiencing Bulgarian music*. Chicago, IL, USA: University of Chicago Press.

Saffran, J. R., Loman, M. M., & Robertson, R. R. (2000). Infant memory for musical experiences. *Cognition,* 77(1), B15-B23.

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

Schachner, A., Brady, T. F., Pepperberg, I. M., & Hauser, M. D. (2009). Spontaneous motor entrainment to music in multiple vocal mimicking species. *Current Biology*, *19*(10), 831-836.

Scott, L. S., Pascalis, O., & Nelson, C. A. (2007). A domain-general theory of the development of perceptual discrimination. *Current Directions in Psychological Science*, *16*(4), 197-201.

Simpson, E. A., Varga, K., Frick, J. E., & Fragaszy, D. (2010). Infants experience perceptual narrowing for nonprimate faces. *Infancy, 16*(3), 318-328.

Slater, J., Tierney, A., & Kraus, N. (2013). At-risk elementary school children with one year of classroom music instruction are better at keeping a beat. *PLoS One*, *8*(10), e77250.

Snyder, J. S., Hannon, E. E., Large, E. W., & Christiansen, M. H. (2006). Synchronization and continuation tapping to complex meters. *Music Perception: An Interdisciplinary Journal*, *24*(2), 135-146.

Soley, G., & Hannon, E. E. (2010). Infants prefer the musical meter of their own culture: A cross-cultural comparison. *Developmental Psychology*, *46*, 286–292.

Sowiński, J., & Dalla Bella, S. (2013). Poor synchronization to the beat may result from deficient auditory-motor mapping. *Neuropsychologia*, *51*(10), 1952-1963.

Su, Y. H., & Pöppel, E. (2012). Body movement enhances the extraction of temporal structures in auditory sequences. *Psychological Research*, *76*(3), 373-382.

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*, *31*(10), 3805-3812.

Torre, K., & Balasubramaniam, R. (2009). Two different processes for sensorimotor synchronization in continuous and discontinuous rhythmic movements. *Experimental Brain Research*, *199*(2), 157-166.

Trainor, L. J., & Trehub, S. E. (1992). A comparison of infants' and adults' sensitivity to western musical structure. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(2), 394–402.

Trainor, L. J., Wu, L., & Tsang, C. D. (2004). Long‐term memory for music: Infants remember tempo and timbre. *Developmental Science*, *7*(3), 289-296.

Tranchant, P., & Vuvan, D. T. (2015). Current conceptual challenges in the study of rhythm processing deficits. *Frontiers in Neuroscience*, *9*.

Trehub, S. E. (1976). The discrimination of foreign speech contrasts by infants and adults. *Child Development*, 466-472.

Ullal-Gupta S, Hannon EE, Snyder JS (2014) Tapping to a Slow Tempo in the Presence of Simple and Complex Meters Reveals Experience-Specific Biases for Processing Music. *PLoS ONE 9*(7): e102962.

van Ulzen, N. R., Lamoth, C. J., Daffertshofer, A., Semin, G. R., and Beek, P. J. (2008). Characteristics of instructed and uninstructed interpersonal coordination while walking side-by-side. *Neuroscience Letters, 432*, 88–93.

Vorberg, D., & Wing, A. (1996). Modeling variability and dependence in timing. *Handbook of Perception and Action*, *2*, 181-262.

Vuust, P., Wallentin, M., Mouridsen, K., Østergaard, L., & Roepstorff, A. (2011). Tapping polyrhythms in music activates language areas. *Neuroscience Letters*, *494*(3), 211-216.

Werker, J. F., & Lalonde, C. E. (1988). Cross-language speech perception: Initial capabilities and developmental change. *Developmental Psychology*, *24*(5), 672.

Werker, J. F., & Tees, R. C. (1999). Influences on infant speech processing: Toward a new synthesis. *Annual Reviews in Psychology*, *50*(1), 509–535.

Werker, J. F., & Tees, R. C. (2005). Speech perception as a window for understanding plasticity and commitment in language systems of the brain. *Developmental Psychobiology*, *46*, 233–251.

Whitall, J., Chang, T. Y., Horn, C. L., Jung-Potter, J., McMenamin, S., Wilms-Floet, A., & Clark, J. E. (2008). Auditory-motor coupling of bilateral finger tapping in children with and without DCD compared to adults. *Human Movement Science*, *27*(6), 914-931.

Whitall, J., Getchell, N., McMenamin, S., Horn, C., Wilms-Floet, A., & Clark, J. E. (2006). Perception–action coupling in children with and without DCD: Frequency locking between task-relevant auditory signals and motor responses in a dual-motor task. *Child Care, Health, and Development, 32*, 679–692.

Wiltermuth, S. S., & Heath, C. (2009). Synchrony and cooperation. *Psychological Science*, *20*(1), 1-5.

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

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

Woodrow, H. (1932). The effect of rate of sequence upon the accuracy of synchronization. *Journal of Experimental Psychology*, *15*(4), 357.

Yates, C. M., Justus, T., Atalay, N. B., Mert, N., & Trehub, S. E. (2016). Effects of musical training and culture on meter perception. *Psychology of Music*. Advance online publication. doi: 10.1177/0305735616657407

Zacks, J. M., & Tversky, B. (2001). Event structure in perception and conception. *Psychological Bulletin, 127*(1), 3.

Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music: auditory–motor interactions in music perception and production. *Nature Reviews Neuroscience*, *8*(7), 547-558.

Zentner, M., & Eerola, T. (2010). Rhythmic engagement with music in infancy. *Proceedings of the National Academy of Sciences*, *107*(13), 5768-5773.