Is Earlier Better? Investigating Sensitive Periods for Musical Training in School-Aged Children

Kierla Ireland

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______________________________________ Chair
Dr. Miranda D'Amico

______________________________________ External Examiner
Dr. Reyna Gordon

______________________________________ External to Program
Dr. Christine Beckett

______________________________________ Examiner
Dr. Kristen Dunfield

______________________________________ Examiner
Dr. Rex Kline

______________________________________ Thesis Supervisor
Dr. Virginia Penhune

Approved by: ______________________________________
Dr. Andrew Chapman, Graduate Program Director

August 21, 2019 ______________________________________
Dr. André Roy
Faculty of Arts and Sciences

Abstract

Is earlier better? Investigating sensitive periods for musical training in school-aged children

Kierla Ireland, Ph.D.

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Sensitive periods for musical training have been proposed, such that starting lessons in earlier childhood predicts better rhythm and melody skills in adult musicians. The goal of this thesis was to evaluate the effects of age of start (AoS) in musically trained children. We assessed whether children with an early AoS showed advantages over those who began later, with equivalent training. An inherent psychometric challenge with children is controlling for maturation. We started with tasks developed in our lab for adults, adapted them for school-aged children, and administered them to 213 children with and without music training. We calculated age-based scores, and estimated reliability and validity (Study 1). We then used age-based scores to assess contributions of AoS, training, and cognitive abilities to performance (Study 2).

In Study 1, the children's Rhythm Synchronization Task (c-RST) and Melody Discrimination Task (c-MDT) were found to have adequate convergent validity with adult analogues. Further, musically-trained children outperformed those without training, replicating findings of a 'musician advantage' for auditory tasks. The effect of age on task performance was largest for the c-RST, which poses the highest demands on auditory-motor integration.

In Study 2, we investigated the influence of AoS on task performance at three cutoffs (AoS of 5, 6, and 7). We controlled for music training and other variables that predict musical engagement and task performance. We found a statistically significant effect of AoS and global cognitive ability, but only for the easiest task condition, Simple Melody discrimination. No AoS effects were found for the more difficult Transposed Melody discrimination, or for the c-RST, and these two were independently predicted by auditory-verbal working memory.

Taken together, our results support a multidimensional model of musical task performance in childhood that includes the interaction of developmental, training-related and cognitive factors. The knowledge gained in this thesis may facilitate the application of musical training to other cognitive domains including language. Music and language share neural substrates and develop according to similar principles. The underlying mechanisms of language and music, and potential applications of our tasks to research on transfer effects, are discussed.

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Contribution of Authors

In collaboration with my supervisor Dr. Virginia Penhune, I designed the research questions and experiments for both papers, set up the experimental paradigm, performed data collection and statistical analyses, and wrote the manuscripts. Additional contributions of other coauthors are discussed below.

Paper 1

Averil Parker helped extensively with data collection and was involved in aspects of statistical analysis. She contributed significantly to the conceptual framework for the manuscript, and wrote sections of the Introduction and Discussion. Dr. Nick Foster provided the stimuli and made himself available for consultation during the process of adapting the melody discrimination task for children. All coauthors contributed to the conceptual interpretation of the findings and provided input on the final manuscript, which was published in April 2018.

Ireland, K., Parker, A., Foster, N., & Penhune, V. (2018). Rhythm and melody tasks for school-aged children with and without musical training: Age-equivalent scores and reliability. *Frontiers in Psychology, 9*(426), 1-19. https://www.frontiersin.org/article/10.3389/fpsyg.2018.00426

Paper 2

Thanya Iyer helped extensively with data collection and statistical analysis, and was instrumental in generating matched sub-samples of early- and late-trained child musicians. She made important contributions to the writing of the Methods, Introduction and Discussion of the manuscript. All coauthors contributed to the conceptual interpretation of the findings and provided input on the final manuscript, which was published in April 2019.

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CHAPTER ONE:

GENERAL INTRODUCTION

The ability to create and enjoy music is probably uniquely human, and music is a part of all known human societies (Honing, ten Cate, Peretz, & Trehub, 2015). Music can be highly evocative, with changes in brain chemistry that correspond to peak emotional experiences (Salimpoor, Benovoy, Larcher, Dagher, & Zatorre, 2011; Salimpoor, Benovoy, Longo, Cooperstock, & Zatorre, 2009). The ability to respond to music begins in utero (Draganova, Eswaran, Murphy, Lowery, & Preissl, 2007) and infants can perceive subtle variations in pitch and rhythm (Trainor & Corrigall, 2010; Trehub & Degé, 2015). Even without formal training, most children learn basic musical abilities (Seashore, 1915; Stalinski & Schellenberg, 2012). We learn music as we learn language; that is, in childhood, through enculturation and modeling from our immediate environments (Hannon & Trehub, 2005). It is a common belief that the key to becoming a successful musician is to begin music lessons early in life. Indeed, the most highly-accomplished musicians often started lessons in childhood: Keith Jarrett, known for improvising entire performances on the piano, started before his third birthday; pianists Oscar Peterson and Lang Lang, and popular musicians Björk and Thom Yorke, all started playing music by age 7. More formally, in qualitative interviews of over 150 adult professional musicians aged 21-90, the majority had started lessons between ages 5 and 7 (Manturzewska, 1990).

Sensitive periods for musical training have been proposed, such that starting lessons early is associated with better musical task performance later in life (Bailey & Penhune, 2010; Bailey & Penhune, 2013, 2012; Skoe & Kraus, 2014; White, Hutka, Williams, & Moreno, 2013). However, there are no studies comparing the effects of early and late age of start (AoS) in children. Therefore, the goal of this thesis was to test whether children who began training early (before age seven) showed advantages over those who began later after an equivalent amount of training. An inherent psychometric challenge in the measurement of training-related effects is to distinguish these from normative, age-based changes resulting from development. To this end, we started with rhythm and melody tasks developed in our lab for adults with a range of musical training, and adapted them for school-aged children. We administered these tasks to children with and without musical training, and calculated age-based scores to control for the effect of maturation. We estimated internal-consistency reliability and external validity for the children's tasks. Finally, we used age-based scores to assess the contribution of early AoS to task performance.

Neuroplasticity and Musical Training

Neuroplasticity, or the brain's capacity to be changed by experience, underlies all human learning and development (Hebb, 1949). Neuroplastic changes can be *experience-expectant*, arising from genetically-determined maturational processes; or they can be *experience-dependent*, arising from repeated stimulation through an experience or behaviour (Galván, 2010). These processes can also interact during what are termed "sensitive periods," specific points in maturation where experience has differential effects (Knudsen, 2004; Penhune, 2011, 2019; Stalinski & Schellenberg, 2010; Trainor, 2005; White et al., 2013). Musical training is a powerful model for understanding these types of plasticity. Normal maturation, an example of experience-expectant plasticity, changes the brain's capacity to process different types of information, and this maturation occurs along multiple trajectories depending on the underlying processing requirements (Gerber, Wilks, & Erdie-lalena, 2010; Thompson, White-Schwoch, Tierney, & Kraus, 2015). Given that this is genetically determined, it follows that some people are born with variations in brain structure that may facilitate their engagement in music, their playing ability, or their motivation to continue practicing and learning (Corrigall & Schellenberg, 2015; Ullén, Hambrick, & Mosing, 2016). Playing music recruits multiple auditory, motor, memory, planning, and reward systems of the brain (Herholz & Zatorre, 2012). There is a robust body of evidence that music can produce changes in brain structure and function. Thus, musical training exemplifies experience-dependent neuroplasticity (Dalla Bella, 2016; Wan & Schlaug, 2010). A sensitive period for musical training has been posited, such that the interaction of experience-expectant and experience-dependent mechanisms in childhood produces long-lasting and functionally relevant changes in the brain and behaviour (Knudsen, 1998; Stalinski & Schellenberg, 2010; Trainor & Corrigal, 2010; White et al., 2013). Training that occurs during a developmental peak engenders structural and behavioural changes that would not occur to the same degree with training undertaken outside that period (Penhune, 2019).

Sensitive, not Critical

A sensitive period is distinct from a *critical period*, during which a particular behaviour and its neural substrates will not develop properly without specific input (Knudsen, 2004; Penhune, 2011). A prototypical example of a critical period in the visual system comes from Wiesel and Hubel (1965), who found that kittens deprived of visual input to both eyes in the first three months of life did not develop the neural representations underlying binocular vision compared to kittens deprived of visual input later in life. A critical period is thought to be genetically determined and has an abrupt onset and offset (Knudsen, 2004). By comparison, during a sensitive period the system is thought to be flexibly potentiated by experience (White et al., 2013). Most of the evidence for sensitive periods in the human auditory system comes from studies of language development. Seminal findings include a 'perceptual narrowing' near nine months of age, such that there is a decrease in the ability to process speech sounds outside of one's native language (Werker & Tees, 1984). Relatedly, ratings of accent in a second language have been found to be negatively correlated with the AoS of learning (Flege, 1991; Flege, Munro, & MacKay, 1995). In congenitally deaf children who received cochlear implants, language proficiency is better the younger the age of implantation (Nicholas & Geers, 2007). Finally, bilingual adults who started learning their second language (L2) from birth up to age 7 showed less lateralization in the left hemisphere, indicating more efficient language processing, than those who had started learning L2 between ages 8-12 (Klein, Mok, Chen, & Watkins, 2014). The above examples can be considered sensitive periods because development is differentially affected by, but not limited to, early exposure to sensory input.

Sensitive Periods for Musical Training: Empirical Foundations

The earliest hypotheses that there might be sensitive periods for musical training emerged incidentally from studies investigating neuroanatomical differences between adult musicians and non-musicians. For instance, string players (violin, cello, and guitar) were found to have a stronger representation of the fingers of the left hand in primary motor cortex when compared to non-musicians, and this was negatively correlated with the AoS of music lessons (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995). Similarly, Amunts and colleagues (1997) found a negative correlation between the extent of the region of primary motor cortex responsible for hand and finger movement, and the age at which adult musicians had begun piano lessons. Others have used a categorical approach to explore specific age cut-offs. For example, Schlaug and colleagues (1995) found greater grey matter volume in the anterior corpus callosum, important for bimanual coordination, in adult musicians compared to non-musicians. This effect was largest in those who had started before age seven. Another group of researchers (Pantev et al., 1998) found that adult musicians who had started prior to age nine had stronger auditory-evoked brain responses to piano tones than those who began after nine. Finally, in a study of adult keyboard players, Bengtsson and colleagues (2005) found that white-matter integrity in parts of the corpus callosum needed for independent finger movements and bimanual coordination was correlated with hours of practice accrued prior to age 11. Thus, early exposure to music lessons was hypothesized to interact with and enhance normal trajectories of neural development.

These early studies suggested that AoS was a potentially important factor contributing to brain plasticity in musicians. However, in all of these studies AoS was confounded with duration of training: those who started younger had trained longer, and might also have had more lessons. Years of experience is consistently related to brain structural differences in musician groups (Abdul-Kareem et al., 2011; James et al., 2014; Sluming et al., 2002); thus, this factor, and not AoS, might drive the relationship of AoS with brain structural differences. Additionally, these early studies did not investigate behavioural changes associated with neuroanatomical differences, making their functional significance hard to interpret. Therefore, researchers from our lab and others have developed behavioural paradigms to probe for sensitive period effects while controlling for years of training and other potential confounds such as years of lessons, hours of weekly practice, and other variables such as global cognitive function and auditory working memory (Penhune, 2019).

Using a matching paradigm to control for years of experience, duration of formal training, and years of lessons, early-trained (ET) adult musicians (AoS < 7) were found to have changes in functionally relevant brain structures compared to late-trained (LT) musicians (AoS >7), and performed better on tasks of sensorimotor learning, synchronization, and discrimination (Penhune, 2019). ET musicians have enhancements in grey matter in ventral premotor cortex (Bailey, Zatorre, & Penhune, 2014), white matter in corpus callosum (Steele, Bailey, Zatorre, & Penhune, 2013), and reductions in subcortical structures involved in motor control (Baer et al., 2015; Vaquero et al., 2015). In terms of behavioural task performance, ET musicians have been found to have more precise timing than their LT counterparts when reading and playing scales from sheet music (Vaquero et al., 2015). Further, in two independent samples, ET musicians outperformed LT musicians on a rhythm synchronization task (RST) in which they listened, and then tapped along to complex rhythmic patterns (Bailey & Penhune, 2010; Bailey & Penhune, 2012). In the second sample, researchers also found an ET advantage for auditory discrimination, in the ability to detect deviant notes between two short melodies (Penhune, 2018, personal communication; Figure 1.1). Finally, ET musicians also show faster learning and better reproduction of visually-presented rhythmic sequences than LT musicians, preserving that advantage even after five days of practice (Watanabe, Savion-Lemieux, & Penhune, 2007).

The Question of Cut-offs

An important consideration is determining an appropriate cut-off for early- and late-AoS. In the earliest studies, no specific cut-off ages were explored *a priori*. Considering that most children begin lessons concurrently with the start of formal education, age seven was an informed, albeit arbitrary choice for the more recent studies. This cut-off age for adults was validated by researchers in our lab, who examined the relationship between AoS and rhythm synchronization ability at different cut-offs (6, 7, 8 and 9) in a group of ET and LT musicians (n = 77). Age of start was more highly negatively correlated with performance in the ET than the LT groups at all four cut-offs, with a significant difference for the age seven cut-off. There is also evidence for developmental peaks in grey matter prior to age 8 in cortical regions associated with task performance (Gogtay, 2004; Group, 2011). These findings support the use of age seven as a boundary for early training, which has informed our own analyses.

Altogether, results from correlational studies suggest an interaction between neural development and musical training beginning before age seven, which is associated with better performance on musical tasks much later in life. However, these findings come from studies of adult professional musicians who typically have 15-20 years of intensive training and practice (Penhune, 2019). Therefore, it is unknown whether any short-term effects of musical training during an early sensitive period can be observed in childhood. Thus, one of our aims was to investigate early-training effects in children who started music lessons before and after age seven and who had 2-3 years of practice. To do this, we used the same matching paradigm as with adults, and the same melody and rhythm tasks which were adapted and normed for children. Similar to adult studies, we also investigated the validity of various AoS cut-off ages to distinguish between ET and LT children.

Measurement of Children's Abilities: A Research Challenge

Researchers who study children have the unique challenge of measuring training effects while concurrently controlling for maturational factors. Tests need to be sensitive enough to detect changes in training-related musical skills, and specific enough to distinguish these from the development of their underlying motor and cognitive skills (Corrigall & Schellenberg, 2015; Galván, 2010). The first tests for measuring the development of children's musical abilities were developed by Seashore (1915) and included melodic abilities such as pitch discrimination, and timing abilities such as consistency of singing speed. Gordon's Primary and Intermediate Measures of Music Audiation (PMMA and IMMA; Gordon, 1979, 1986) were initially developed to identify musical talent and determine which music classes would be most appropriate for individual children. These batteries are still the most commonly used in research, as the tasks are perceptual and thus easy to administer; moreover, there are norms for children in different age groups. However, these norms have not been updated for several decades. Thus, cohort effects related to changes in music-listening and in cognitive variables known to be related to musical abilities may make them less valid for current use (Nettelbeck & Wilson, 2004). The Montreal Battery of Evaluation of Musical Abilities (MBEMA; Peretz et al., 2013) was normed on a large sample of Canadian and Chinese children aged 6–8. It consists of melody and rhythm discrimination tasks and a musical memory task. However, given that the test was designed to identify amusia, a deficit in auditory processing, there may be ceiling effects when used with children who have intensive music training. Most recently, researchers in Brazil developed a battery of music perceptual tests for children, which was standardized on over 1,000 school-aged children (Barros et al., 2017). However, test items showed no differential functioning with age, indicating that the task may not be useful in a developmental context.

Therefore, for this thesis we aimed to develop tasks that could help delineate specific effects of musical training in children while also accounting for normal maturation. To ensure that the tasks were sensitive enough to detect differences between musically trained and untrained groups, as well as between ET and LT children, we created the children's Rhythm Synchronization Task (c-RST), and children's Melody Discrimination Tasks (c-MDT). These were based on two tasks previously used with adults with a range of musical training (RST; Chen, Penhune, & Zatorre, 2008; MDT, Foster & Zatorre, 2010b) and which had previously shown differences between ET and LT groups (Bailey & Penhune, 2010; Bailey & Penhune, 2012; Fig. 1.1). To address the challenge of accounting for maturation, we tested a large sample of children between 7 and 13 years of age, used this data to generate a set of age-based (z) scores for all children using the non-musician children as a reference group, and used these scores to compare children with early and late AoS.

Children's Musical Tasks

The children's Rhythm Synchronization Task (c-RST) is based on a task first developed for adult musicians, to compare auditory and motor neural activation while listening and tapping to rhythms (Chen et al., 2008). It was adapted for children in collaboration with the laboratory of Dr. Krista Hyde (Tryfon et al., 2017). For this task, children first listen and then tap along to an 11-note woodblock rhythm. There are six rhythms in total, and three trials per rhythm, for a total of 18 trials. There are three levels of metric regularity (low, medium, and high), indicating the number of notes of a rhythm that fall on the underlying beat. Performance is measured in terms of percent correct (the number of taps which fall in synchrony with the notes in the rhythm), and inter-tap interval (ITI) synchrony (the degree to which a child's taps match the overall temporal structure of the rhythm).

In the children's Melody Discrimination Task (c-MDT) children listen to two short, unfamiliar melodic sequences and click a mouse key to indicate whether the second was the same or different from the first. Melodies are between 1.6 and 3.5 seconds (5-11 notes) in duration, and come from the Western major scale spanning notes C4-E6. In the Simple condition, both melodies are in the same key but each 'different' melody violates the contour; thus, the child can use absolute pitch cues to detect differences. In the Transposed condition, the second melody is in a higher key; thus, the child must ignore contour and focus on relative pitch relations to detect differences.

To adapt the melody task for children, we first consulted with the developer of the adult task and referred to relevant literature on the theoretical bases of the specific underlying abilities (i.e., relative pitch and auditory discrimination; Foster & Zatorre, 2010b). We followed guidelines as instructed by experts in psychometrics and music cognition, including decreasing working memory load by reducing test length and difficulty, using stories as a procedural framework for the tasks, and estimating and reporting psychometric properties (Corrigall & Schellenberg, 2015; Kline, 2008). To decrease working memory load, we first reduced the maximum melody duration from 13 notes to 11. Next, we reduced test length from 90 trials per condition to 30, while maintaining a similar distribution of melody durations as in the adult task. We developed a short and engaging storyline that could be integrated into the existing rhythm task storyline, with a visual display using the same graphical style. To estimate suitability of this storyline for a wide age range, we carried out a qualitative pilot trial of this storyline with colleagues in a child development laboratory. After data were collected, we consulted with an expert in measurement and test design regarding the creation of an even shorter version (a "best set") for sharing with other researchers. We reported data from both the 'best set' and the original version of the c-MDT in our first publication (Ireland, Parker, Foster, & Penhune, 2018; Study 1); details about test construction as described above were reported more briefly for reasons of succinctness.

Given that this thesis aims to explore the interaction of maturation, experience and their interaction on children's melodic and rhythmic abilities, we need to know more about the development of these abilities and the auditory and motor systems that underlie them. This evidence will allow us to develop specific hypotheses for our investigations of the development of these skills in trained and untrained children (Study 1; Ireland et al., 2018) and about the differential effects of early and late AoS in child musicians (Study 2; Ireland, Iyer, & Penhune, 2019).

Auditory Development and Pitch Discrimination Ability: Experience-expectant Plasticity

Development in the human auditory system occurs early and rapidly, with a substantial increase in myelination and connectivity in the primary auditory cortex between the ages of one and five (Kral & Eggermont, 2007). Pitch discrimination – the ability to detect a difference in relative pitch between two identical melodies – develops in early childhood (Stalinski & Schellenberg, 2010; Trehub & Degé, 2015). Between ages 5 and 12, auditory processing becomes more sophisticated in terms of the auditory features that can be discriminated. Transposition discrimination, the ability to detect a difference in pitch between two melodies that are identical in contour but in different keys, requires two separate processes. First is the relative pitch discrimination ability as described above, and second is the ability to successfully hear a transposition as a form of 'musical transformation,' preserving the contour of the original melody in memory. Contour, or the pattern of ups and downs in a melody, is a highly salient feature of music (Dowling & Fujitani, 1971). Preservation of contour allows two people to sing

‘Happy Birthday’ together even when they begin on different notes. This phenomenon is conceptually similar to visual rotation; indeed, transposition discrimination is correlated with activation in the intraparietal sulcus, important for visuospatial transformation (Foster & Zatorre, 2010a). Not surprisingly given its complexity, transposition discrimination ability is still in development well into adolescence (Sutherland, Paus, & Zatorre, 2013). More globally, the long auditory maturational period is also thought to contribute to the acquisition of the complex structures of language and music (Kral & Eggermont, 2007). Through an interaction of bottom-up and top-down processing, specific auditory features in the environment are assimilated and integrated by higher-order cortical processing regions, as well as sensory and motor regions. Because different regions have different developmental trajectories (Gogtay et al., 2004), early neuroplasticity in primary auditory cortex, with later plasticity and connectivity with the whole brain, this suggests that different sensitive periods may exist for different auditory abilities (Penhune, 2011).

Motor Development and Synchronization Ability: Experience-expectant Plasticity

Motor development proceeds along a proximal to distal trajectory; thus, control of head and trunk movements occurs much earlier than control of limbs and digits, which is necessary for a child to begin music training (Altenmueller & McPherson, 2008; Gerber, Wilks, & Erdie-lalena, 2010). Synchronization – the ability to ‘track’ a regular pulse either internally or externally – is the result of two processes, one a ‘timekeeper’ and the other a ‘motor-responder’ (Wing & Kristofferson, 1973). These processes are underpinned by oscillatory activity in overlapping motor and timing networks in cortical and subcortical structures (e.g., premotor and supplementary cortex; suprachiasmatic nucleus of the hypothalamus; basal ganglia) and the cerebellum (Altenmueller & McPherson, 2008; Cohen, 2014; Dalla Bella et al., 2017). The development of synchronization ability occurs in tandem with the development of these neural structures, some of which do not reach a maturational peak until late childhood or early adolescence (Group, 2011; Monier & Droit-Volet, 2019; Raznahan et al., 2014). Therefore, although children can display a simple ‘synchronous gait’ in which the arms and legs move in opposition before age 3 (Gerber et al., 2010), they cannot tap their finger to a metronome consistently until age 4-5 (Drake, Jones, & Baruch, 2000; Drewing, Aschersleben, & Li, 2006; Monier 2019). These changes in synchronization ability are supported by two mechanisms – an overall slowing of spontaneous tempo and a decrease in tapping variability – which together allow children to adapt more flexibly to variations in speed (Monier & Droit-Volet, 2019; Thompson et al., 2015).

Longitudinal Effects of Musical Training: Experience-dependent Plasticity

We know that auditory and motor skills develop along different trajectories in childhood with maturation of the underlying neural substrates. Longitudinal studies, though few in number, provide the highest standard of evidence that enhancements in both musical abilities and task-relevant brain structures can occur after brief periods of musical training starting close to or before age seven (Habibi, Cahn, Damasio, & Damasio, 2016; Habibi, Damasio, Ilari, Veiga, et al., 2018; Hyde et al., 2009b; Putkinen, Tervaniemi, Saarikivi, Ojala, & Huotilainen, 2013). For example, 6- and 7-year-old children who received 15 months of private keyboard lessons showed increased cortical thickness in the right primary auditory cortex compared to same-aged children who received no instrumental lessons (Hyde et al., 2009a). Importantly, changes in cortical thickness were significantly correlated with children's performance on a rhythm and melody discrimination task. Children also showed enhanced connectivity in the corpus callosum, important for bimanual coordination, which was correlated with improvements on a fine-motor task (Hyde et al., 2009a). A more recent study produced similar results. Six-year-old children were assigned to group music training following the El Sistema model, team sports training, or no systemic training (Habibi, Damasio, Ilari, Sachs, et al., 2018). After one year, children in the music group outperformed the others on a task in which they synchronized drumming patterns with an adult (Ilari, Keller, Damasio, & Habibi, 2016). These same children showed enhanced connectivity in the corpus callosum and better tonal discrimination compared to the two control groups (Habibi et al., 2017). Electrophysiological evidence suggests that changes in young children's neural processing of sound occur after as little as 1-3 years of lessons. For example, auditory-evoked potentials were larger in amplitude in 4-to-5-year-old children after a year of music lessons (Shahin, Roberts, & Trainor, 2004). In another study, responses to violin tones were heightened in 4-to-6-year-old children after a year of Suzuki music lessons, when compared to children without musical training (Fujioka, Ross, Kakigi, Pantev, & Trainor, 2006). Finally, children with and without musical training were assessed every two years between 7 and 13 years old. The auditory-evoked responses of children with musical training grew larger in amplitude with time, suggesting enhanced auditory processing above and beyond normal development (Putkinen et al., 2013). Importantly, in all these studies researchers had controlled for baseline brain volume, SES, musical ability and cognitive function.

Taken together, the neural correlates of pitch discrimination undergo a developmental peak near age five. In contrast, brain structures supporting synchronization, a more complex integration of auditory and motor processes, take longer to develop, beginning around 6 years of age and peaking in late adolescence. Musical training can directly modify the neural correlates of both discrimination and synchronization through both bottom-up (sensory) and top-down (integration) processes. Thus, our first broad hypothesis was that school-aged children, having already 'passed through' an auditory-perceptual developmental peak, would perform better on the melody task than the rhythm task. Based on the evidence a logical prediction is that, controlling for age, the effect of AoS might be larger for early-trained (ET) children, who had started lessons within a possible sensitive period, compared to those who had started after this developmental peak. We also hypothesized that effects might be limited to older children for the more difficult melody transposition task, given its longer developmental trajectory. We controlled for demographic and cognitive variables that have been found to predict musical task performance, including socio-economic status (SES), working memory, and global cognitive ability (Swaminathan & Schellenberg, 2018).

Figure 1.1. Melody Discrimination Task performance in adult Early-Trained musicians, Late-Trained musicians, and Non-musicians. (V. Penhune, 2018, personal communication)

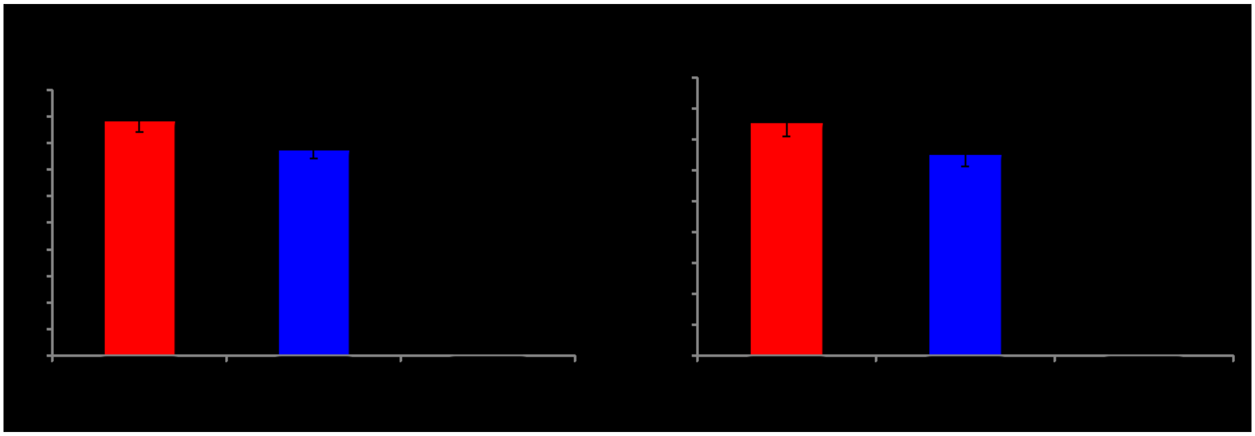
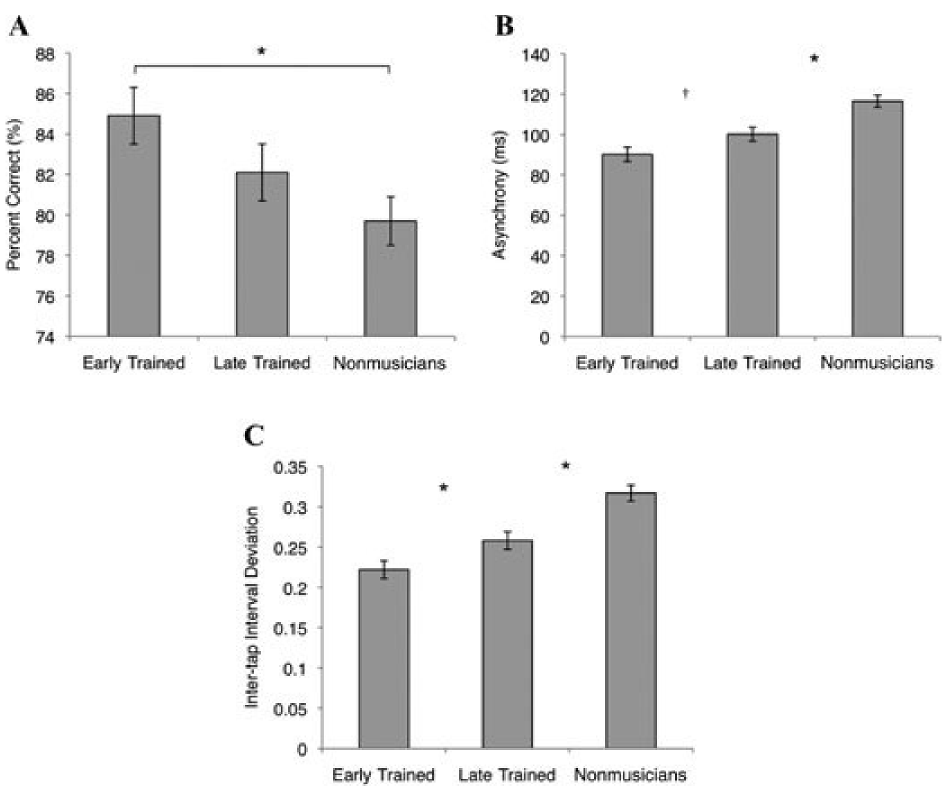


Figure 1.2. Rhythm Synchronization Task performance in adult Early-Trained musicians, Late-Trained musicians, and Non-musicians. (Bailey & Penhune, 2012).



CHAPTER TWO:
STUDY 1

Rhythm and melody tasks for school-aged children with and without musical training: Age-equivalent scores and reliability

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Abstract

Measuring musical abilities in childhood can be challenging. When music training and maturation occur simultaneously, it is difficult to separate the effects of specific experience from age-based changes in cognitive and motor abilities. The goal of this study was to develop age-equivalent scores for two measures of musical ability that could be reliably used with school-aged children (7-13) with and without musical training. The children's Rhythm Synchronization Task (c-RST) and the children's Melody Discrimination Task (c-MDT) were adapted from adult tasks developed and used in our laboratories. The c-RST is a motor task in which children listen and then try to synchronize their taps with the notes of a woodblock rhythm while it plays twice in a row. There are three levels of rhythmic complexity corresponding to a decrease in beat strength. The c-MDT is a perceptual task in which the child listens to two melodies and decides if the second was the same or different. Melodies are presented either in the same key or transposed upward by four semitones. We administered these tasks to 213 children in music camps (musicians, n = 130) and science camps (non-musicians, n = 83). We also assessed children's baseline motor and auditory abilities. We estimated internal-consistency reliability for both tasks, and compared children's performance to results from studies with adults. As expected, musically trained children outperformed those without music lessons, scores decreased as difficulty increased, and older children performed the best. Using non-musicians as a reference group, we generated a set of age-based norms, and used these scores to predict task performance with additional years of training. Years of lessons statistically significantly predicted performance on both tasks, over and above the effect of age. We also assessed the relation between musicians' scores on music tasks, baseline tasks, auditory working memory, and nonverbal reasoning. These tasks and the associated norms fill an important need for researchers interested in evaluating the impact of musical training in longitudinal studies, those interested in comparing the efficacy of different training methods, and for those assessing the impact of training on non-musical abilities, such as reading skills and other cognitive functions.

Introduction

Researchers, music teachers, and parents have a strong interest in understanding and assessing children's musical abilities. However, measuring these abilities in childhood can be a challenge because training and normal maturation occur simultaneously, making it difficult to disentangle the effects of music experience from cognitive and motor development (Corrigall & Schellenberg, 2015; Galván, 2010). This also makes comparisons with adult musicians problematic. Therefore, the goals of this study were to develop measures of musical ability that could be reliably used with school-aged children (7-13), and to generate a set of age-based norms for children with and without training. The resulting children's Rhythm Synchronization Task (c-RST) and children's Melody Discrimination Tasks (c-MDT) were based on two tasks previously used with adults (RST; Chen, Penhune et al., 2008; MDT, Foster & Zatorre, 2010a). For both tasks, we assessed whether children's patterns of performance would be similar to adults across levels of difficulty, whether performance would be better for children with music training, and whether scores would increase with age. Using the age-normed scores derived from the non-musician sample, we also assessed the contributions of years of music training to performance, and the possible relationships between music and cognitive abilities, including auditory working memory.

Musical ability is defined as the innate potential to perceive, understand, and learn music (Law & Zentner, 2012; Schellenberg & Weiss, 2013). It is assumed that, like other innate capacities, musical abilities are normally distributed in the population (Schellenberg & Weiss, 2013), and that even without musical training these abilities develop with age (Stalinski & Schellenberg, 2012). In the first year, infants can discriminate between simple rhythm patterns and meters (Hannon & Johnson, 2005). Producing synchronized movement takes longer to master. Children as young as four can tap to a beat, and this ability improves between 4 and 11 years old (Drake et al., 2000). Existing evidence shows that by age 7 children can reproduce very short rhythms (Drake, 1993; Drake et al., 2000; Repp & Su, 2013). Children become more sensitive to the metrical structures of their culture with exposure to music (Corrigall & Schellenberg, 2015), and by adulthood are better at detecting changes in rhythms with a metrical structure specific to their culture (Hannon & Trehub, 2005). Basic melody discrimination is in place very early in life. Even before birth, near-term fetuses can detect a change in pitch of roughly an octave (Lecanuet, Graniere-Deferre, Jacquet, & DeCasper, 2000). By 2 months old infants can discriminate between semitones, and they can process transposed songs, a more cognitively demanding task, by early childhood (Plantinga & Trainor, 2005, 2009). The brain's response to auditory stimuli has a relatively long developmental timeframe, continuing to mature until 18–20 years old (Ponton, Eggermont, Khosla, Kwong, & Don, 2002). As children move through the school years they are more sensitive to aspects of music specific to their culture (Corrigall & Schellenberg, 2015). Implicit knowledge of key membership is acquired first, followed by implicit knowledge of harmony (Lynch, Eilers et al., 1990; Schellenberg, Bigand et al., 2005; Trainor & Trehub, 1994). Explicit knowledge of key membership and harmony begins around 6 years old and continues to develop until 11 years old (Costa-Giomi, 1999a).

School-aged children with musical training – even as little as one to three years – have been found to score higher on musical tasks than those with no training. Longitudinal and quasi-experimental studies provide the most compelling evidence for the effects of musical training on musical abilities. Six-year-olds who received 15 months of keyboard lessons improved on a combined melodic and rhythmic discrimination score compared to controls (Hyde et al., 2009a). In a sample of children aged 7-8, rhythm and tonal discrimination improved significantly more after 18 months of musical training than after science training (Roden et al., 2014). In another study, children were followed from ages 7-13; those with music training showed better detection of deviant musical stimuli, as measured with the mismatch negativity ERP response (Putkinen et al., 2013). Most recently, children aged 6-8 were given group music lessons, group soccer training, or no training for two years (Habibi et al., 2016). The musically trained children were the most accurate at discriminating changes in pitch.

The earliest tests for measuring children's musical ability included both perceptual tasks such as discriminating among pitches or timbres, and motor tasks such as controlling tempo while singing (Seashore, 1915). Subsequent batteries have focused more on perceptual tasks, perhaps due to the difficulty of administering and evaluating children's musical performance objectively. The most recent and well-known batteries of music perception with age-equivalent scores for school-aged children are the *Primary* and *Intermediate Measures of Music Audiation* (PMMA and IMMA; Gordon, 1979, 1986). The PMMA and IMMA are commonly used in research, given that there are norms for children in different age groups. However, these norms have not been updated for three to four decades. Thus, cohort effects related to changes in music-listening and in cognitive variables known to be related to musical abilities may make these norms less valid for current use (Nettelbeck & Wilson, 2004). More recent test batteries include the Montreal Battery of Evaluation of Musical Abilities (MBEMA; Peretz, Gosselin et al., 2013), which was administered to a large sample of Canadian and Chinese children aged 6-8. Like the PMMA and IMMA, the MBEMA consists of perceptual discrimination tasks (contour, scale, interval, and rhythm), with an added memory task. Although scores are reported for children with up to two years of musical training, the test was designed to identify amusia (an auditory-processing deficit), and as such may not be sensitive enough to detect differences in ability between children with and without training, or changes with age. Most recently, researchers developed a battery of tests of music perception, standardized on over 1,000 Brazilian schoolchildren aged 7-13 (Barros et al., 2017). Unfortunately, test scores showed no improvements with age, indicating that the task is unlikely to be useful in a developmental context. In addition, no musically-trained children were included in the sample. In sum, children's musical abilities change with age, and are influenced by musical training. It also appears that the developmental trajectories of rhythm reproduction and melody discrimination are different, with melodic abilities developing earlier. Further, current tests of musical abilities in children are limited in their utility for examining the effects of development and training. Given the increased interest in assessing musical skills in childhood, an important goal of this study is to provide the community with reliable tests with up-to-date norms.

Cognitive abilities such as working memory and nonverbal reasoning change with age, and are associated with both musical training and with musical aptitude (Schellenberg & Weiss, 2013; Swaminathan et al., 2016). Even after very little training, children score higher on age-equivalent measures of immediate and short-term working memory (Bergman Nutley, Darki, & Klingberg, 2014; Roden, Grube, Bongard, & Kreutz, 2014). In a well-known longitudinal study, children's scores on tests of global cognitive function increased after 36 weeks of music lessons, when compared to art lessons or no lessons (Schellenberg, 2004). In addition, there is evidence of associations between musical and language abilities (Gordon et al., 2015; Patel, 2012). For instance, melody perception and language comprehension are correlated by age 5 (Sallat & Jentschke, 2015), and young children's ability to detect large deviations of pitch in speech were found to improve after only 8 weeks of music lessons (Moreno & Besson, 2006). By age 6, children's rhythmic perceptual abilities are predictive of their ability to produce complex grammatical structures (Gordon et al., 2016). In children with lower SES, small amounts of music lessons may have a protective effect on literacy skills, compared to control subjects (Slater et al., 2014). Given the complex overlap between musical, cognitive, and language skills, and their relation to music training, in the current study we administered tests of auditory working memory and global cognitive function.

The tests of musical ability developed for the current study are based on adult tasks. Both tasks were abbreviated and simplified to be more engaging and have a shorter administration time. The children's Rhythm Synchronization Task (c-RST; Figure 1) and children's Melody Discrimination Task (c-MDT: Figure 2) were adapted following guidelines advanced by Corrigall & Schellenberg (2015), including adding a storyline, reducing test duration, and providing feedback.

The Rhythm Synchronization Task (RST) is a computer-based task that assesses the ability to tap in synchrony to a series of rhythms that vary in metrical complexity. It is based on an adult task initially developed for brain imaging and then modified for behavioural studies (Chen et al., 2008). Adult professional musicians scored higher than non-musicians on the RST (Bailey & Penhune, 2010, 2012; Karpati et al., 2016). Moreover, irrespective of training, scores decreased as metric regularity (indicated by the presence of a steady pulse) decreased (Bailey & Penhune, 2010; Chen et al., 2008; Matthews et al., 2016). The RST was recently adapted for children, with the purpose of comparing typically developing children and those with autism spectrum disorder (Tryfon et al., 2017).

The Melody Discrimination Task (MDT) is a computer-based task that assesses the ability to discriminate between two melodies that differ by one note either in the same key or transposed. Adult musicians outperformed non-musicians on this task (Foster & Zatorre, 2010a; Karpati et al., 2016) and scores are related to length of musical training (Foster & Zatorre, 2010b). Moreover, neuroimaging results found that transposition discrimination – the ability to recognize deviant pitches irrespective of the key in which they are presented – may be anatomically distinct from other discrimination abilities (Foster et al., 2013; Foster & Zatorre, 2010a, 2010b). For the current study this task was shortened, and a storyline added, for use with children. Items were selected for optimal reliability and difficulty.

The goal of the present study is to assess the influence of age and musical training on children's musical abilities using the RST and MDT. Given that children's rhythmic and melodic abilities have different developmental trajectories, we measure melody and rhythm separately, and provide standardized scores for each age group. We use age-equivalent scores to investigate the effects of musical training on task performance. Finally, we assess the relation between musical training and cognitive abilities in musically trained children.

Method

Participants

We tested 213 children aged 7 to 13 years in music and science camps in Montréal, Ottawa, and Waterloo, Canada. Children were categorized as musicians (n = 130) or non-musicians (n = 83) based on a parent questionnaire adapted in our lab (Survey of Musical Interests; Desrochers et al., 2006). The term musician was operationalized as a child who had at least 2.5 years of consecutive music lessons (M = 5.06 years, SD = 1.58, range 2.74 – 10.00). Music lessons were operationalized as extra-curricular, weekly, one-on-one sessions of at least 30 minutes in duration and taught by an expert. Child musicians also practiced for at least half an hour a week (M = 3.16 hours, SD = 2.49, range = 0.50 - 14.00). Music practice could be structured (using a book or specific exercises) or unstructured (free playing), as long as it occurred outside of lessons and on the same instrument. The term non-musician was operationalized as a child with no more than 2.5 years of consecutive lessons (M = 0.43, SD = 0.74, range 0.00-2.30). We assessed children's SES by estimating maternal years of education. As in the original questionnaire, mothers reported their highest level of education on an ordinal scale. We converted this to an approximate interval scale with the following estimates: high school = 12 years; college diploma = 14 years; baccalaureate degree = 16 years; master's degree = 18 years; doctorate or medical professional degree = 22 years.

Demographic and practice-related characteristics for all children by musicianship and age group are in given in Table 2.1. Parents provided written consent and children provided verbal assent before participating. Children were given a gift card and a small toy as thanks for their participation. The study was approved by Concordia University's Human Research Ethics Board.

Rhythm Synchronization Task

The child version of the RST (c-RST; Figs 2.1 & 2.2.) differs from the adult task in several ways (Tryfon et al., 2017). First, to make it more engaging, a storyline and corresponding graphics were generated. Next, task difficulty was reduced by removing the most difficult ('non-metric') rhythm level, and replacing it with an easy ('strongly metric') level. As with the adult task, a single trial of the c-RST consists of two phases: (1) 'Listen' and (2) 'Tap in Synchrony.' A giraffe with headphones is displayed on the computer screen. During the Listen phase, the giraffe's headphones are highlighted, indicating that the child should listen to the rhythm without tapping. During the Tap in Synchrony phase, the giraffe's hoof is highlighted, indicating that the child should tap along in synchrony with each note of the rhythm using the index finger of the right hand on a computer mouse. The c-RST has three levels of rhythmic complexity that vary in difficulty from easiest to hardest: Strongly Metric, Medium Metric, and Weakly Metric. There are two rhythms per difficulty level, for a total of six rhythms which are presented in counterbalanced order. Rhythms consist of 11 woodblock notes spanning an interval of 4 to 6 seconds. Each of the six rhythm trials is played three times in a row, for a total of 18 trials. Before starting the test, children complete five practice trials at the Strongly Metric level, with feedback from the experimenter. The rhythms used for the practice trials are not those used in the main task. Performance on the RST is measured in two outcomes: (1) proportion correct, or the child's ability to tap within the 'scoring window' (as explained below); and (2) percent inter-tap interval (ITI) synchrony, or the child's ability to reproduce the temporal structure of a rhythm. The proportion correct is calculated as the proportion of taps that fall within the scoring window (i.e., half the ISI before and after the stimulus). The ITI synchrony is calculated as the ratio of the child's response intervals (r) to the stimulus time intervals (t), with the following formula: Score $= 1 - \text{abs}(r - t)/t$. For both proportion correct and ITI synchrony, proportions are multiplied by 100 to generate a percentage.

Tapping and Continuation Task

The Tapping and Continuation Task was included as a test of basic synchronization and timing. This task has been frequently used in both adults and children (Aschersleben, 2002; Balasubramaniam et al., 2009; Dalla Bella et al., 2017; Matthews et al., 2016; Tryfon et al., 2017; Whitall et al., 2008; Wing & Daffertshofer, 2004). For this task, children tap along with an isochronous rhythm of woodblock notes for 15 seconds (paced tapping), and are instructed to continue tapping at the same tempo for 15 seconds once the rhythm stops (non-paced tapping). The tapping task runs for 6 trials at the same tempo (inter-stimulus interval [ISI] of 500 ms). Performance is measured in terms of tapping variability; only the non-paced trials are scored. The ITIs and their respective standard deviations are averaged across all 6 trials for non-paced tapping. The average SD is then divided by the average ITI to generate a coefficient of variation (i.e., the child's tapping variability relative to his or her own performance).

Melody Discrimination Task

For each trial of the MDT, participants listen to two melodies of equal duration separated by a 1.2-s silence, and then indicate whether the second melody is the same or different than the first. There are two conditions: Simple and Transposed. In the Simple condition, both melodies are in the same key. In the "different" trials, the pitch of a single note in the second melody is shifted up or down by between one and five semitones, while preserving the contour of the first melody. The participant thus must compare individual pitches to detect the deviant note. In the Transposed condition, all the notes in the second melody are transposed upward by four semitones (a major third). In the "different" trials a single note is shifted up or down by one semitone, while preserving the contour of the first melody. Thus, the participant must use relative pitch to perceive the deviant note within a transposed model. All melodies in the MDT were composed of low-pass- filtered isochronous harmonic tones (320 ms each, corresponding to a tempo of 93.75 bpm) from the Western major scale, using tones taken from the two octaves between C4-E6. All major scales are represented except B, F-sharp, and C-sharp; minor scales include E, A, and E-flat.

The child version of the MDT (c-MDT; Figs 2.2 & 2.3) differs from the adult version in several ways. The adult version comprises 180 melodies (90 simple and 90 transposed), which range from 5 to 13 notes per melody. This was considered too long for testing with children so 60 items were selected (30 simple and 30 transposed) based on a reduced range of notes for lower difficulty (5–11 notes per melody). After this set of 60 items was administered to all children, we calculated item-level statistics *post-hoc* in order to retain a "best set" of data with the following criteria: (1) KR-20, or Cronbach's alpha for dichotomous items, of at least 0.50; (2) point-biserial correlation, or the degree to which items correlate with the total score for each condition, of at least 0.10; (3) item difficulty above chance; and (4) administration time under 20 min, including instructions and practice. The resulting best set is composed of 40 melodies, 20 per condition, with 5–11 notes per melody. The results reported in the current paper are for this best set. Raw score means and standard deviations for the 60-item set are provided for comparison in the Appendix.

The Simple and Transposed conditions each have 20 trials, with an equal number of "same" and "different" trials per condition. Each condition is presented as two blocks of 10 trials with a break in between. The 20 trials are presented in random order within conditions, but the order of conditions is always the same (Simple, Transposed) to preserve the storyline. In the corresponding graphical display, children see a teacher elephant who "sings" a melody which is then repeated by either the "echoing elephant who sings it perfectly" or the "forgetful monkey who always makes a little mistake."

In the graphical display for the Transposed condition, children are again shown the teacher elephant who sings the melody, which is repeated by the "baby elephant" or the "baby monkey" who "sing in a much higher voice" (i.e., in a transposed key); they are instructed to ignore this difference and instead listen for the "little mistake."

Syllable Sequence Discrimination Task

The Syllable Sequence Discrimination Task (SSDT) was designed as a baseline task for the MDT that would place similar demands on auditory working memory ability. In the c-SSDT the child hears two sequences of 5–8 non-word syllables, spoken in a monotone with F0 held constant, and judges whether they are the same or different. Syllables were generated using permutations of 7 consonants [f, k, n, p, r, s, y] and 4 vowel sounds [a, i, o, u], which were then selected for minimal semantic association (Foster and Zatorre, 2010a). The c-SSDT contains the following 13 phonemes: fah, foh, foo, kah, koh, nah, poh, rah, ree, roh, roo, sah, yah. Sequence lengths (5–8 syllables) were selected to match the adult version of the task. In the graphical display adapted for this task, the elephant and monkey are shown wearing robot helmets and are said to be "copying robot sounds," with the same response cue as in the c-MDT ("echoing elephant" or "forgetful monkey").

For both the c-MDT and c-SSDT, children are familiarized through four practice trials, two with feedback from the experimenter and two without feedback. After all trials of both tasks, the word 'correct' or 'incorrect' is displayed for one second. Experimenters are seated so as not see children's responses or feedback. Discrimination is scored as the percentage of correct responses. The child's responses are scored as 0 (incorrect) or 1 (correct), generating a proportion which is then multiplied by 100.

Cognitive Tasks

To assess cognitive abilities that might be related to performance on the music tasks we administered the Digit Span (DS), Letter-Number Sequencing (LNS), and Matrix Reasoning (MR) subtests from the Wechsler Intelligence Scale for Children, fourth edition (WISC-IV; Wechsler, 2003). Digit Span is a measure of immediate auditory memory, in which the child repeats strings of digits forward or backward. Letter-Number Sequencing (LNS) is a measure of auditory working memory and manipulation, in which the child hears a string of letters and numbers and must repeat them back in numerical and alphabetical order, respectively. Matrix Reasoning (MR) is a measure of nonverbal reasoning, and is considered to be a reliable estimate of general intellectual ability (Brody, 1992; Raven, J., Raven, J. C., and Court, 1998). For this task, the child must identify the missing portion of an incomplete visual matrix from one of five response options.

All subtests were administered according to standardized procedures. Raw scores were converted to scaled scores based on age-based norms for all three subtests. The population-based mean for subtest scaled scores on the WISC-IV is 10, with a standard deviation of 3 (Wechsler, 2003).

General Procedure

Testing took place over a 1-h session. Participants were given short breaks between tasks to enhance motivation. Computer- based tasks were administered on a laptop computer running Presentation software (Neurobehavioral Systems, http://www. neurobs.com/). Auditory tasks were presented binaurally via Sony MDRZX100B headphones adjusted to a comfortable sound level. Musical tasks were administered before cognitive tasks, with musical task order (either c-RST or c-MDT first) counterbalanced across participants. Cognitive tasks were administered in the order in which they appear in the original WISC-IV battery.

All programs for administration and scoring, as well as a user manual with norms, will be made available upon request to the first author.

Results

Sample Characteristics: Child Musicians and Non-Musicians

Data for group differences in the sample are presented in Table 2.2. We first conducted a chi-square analysis to determine whether the number of boys and girls differed between musicians and non-musicians. There were significantly more female musicians than males, and significantly more male non-musicians than females [χ^2 (1) = 5.89, *p* = .015]. Subsequently we carried out ANOVAs with musicianship and gender as between-subjects factors. For Simple melodies there was a significant musicianship-by-gender interaction [F (1, 209) = 5.53, *p* = .02, partial η^2 = .03)], such that male musicians outperformed male non-musicians by a greater margin (20%) than girls (12%). However, this effect is small in magnitude, and there were no musicianship-by-gender interactions for any other outcome variables of interest (C-RST or MDT). Thus, gender was not added as a covariate for group difference analyses.

We conducted independent two-sample *t*-tests, and calculated Hedge's *g* effect sizes, to examine the degree to which musicians and non-musicians differed in SES (estimated years of maternal education), cognitive variables including auditory working memory (Digit Span, Letter-Number Sequencing) and general intellectual ability (Matrix Reasoning), or performance on baseline tasks (Tapping Variability, Syllable Sequence Discrimination). Cognitive data were lost for four children but as they represent fewer than 2% of the sample these scores were not replaced (Kline, 2011). Twelve musicians' mothers and 10 non-musicians' mothers did not answer the question about maternal education.

There were no statistically significant differences in SES [t(189) = 0.43, p = .67, g = 0.06] or auditory working memory [Digit Span t(207) = 1.79, p = .08, g = 0.25; Letter-Number Sequencing t(207) = 0.75, p = .45, g = 0.10]. Although statistically different, both groups scored in the Average range for general intellectual ability [Matrix Reasoning t(207) = 2.28, p = .023, g = 0.32.] By contrast, musicians performed significantly better on both baseline tasks [Tapping Variability t(211) = -3.86, $p < .001$, g = 0.54; Syllable Sequence Discrimination t(211) = 3.49, p = .001, g = 0.48]. Therefore, these were included as covariates for the regression analyses.

Reliability

To examine internal-consistency reliability, we used Cronbach's alpha for the c-RST, which estimates the mean of all possible split-half reliabilities, and KR-20 for the c-MDT, equivalent to Cronbach's alpha for dichotomous variables. Reliability estimates were derived for musicians and non-musicians separately. Scores on the c-RST were found to be adequately reliable for musicians ($\alpha = .64$) but slightly less so for non-musicians ($\alpha = .60$). Score reliability is higher on the c-MDT and, similar to the c-RST, is higher for musicians (KR-20 = .86) than for non-musicians (KR-20 = .75).

Effects of Musicianship, Task and Age

To examine the degree to which performance on the c-RST and c-MDT varied between musicians and non-musicians, across levels of each task (e.g., rhythmic complexity and melody type), and between children of different age groups, we carried out mixed-design ANOVAs with musicianship and age as between-subjects factors, and task level as a repeated measure. Outcome variables for the c-RST were proportion correct and ITI synchrony; the outcome for the c-MDT was percent correct. Partial eta-squared effect sizes were calculated, and post-hoc analyses were carried out with Bonferroni corrections for multiple comparisons.

For the c-RST (proportion correct and ITI synchrony), the assumption of sphericity was violated such that the variances of the differences between levels of rhythmic complexity were not homogeneous (Mauchly's $W = .94$, $p = .002$ for both). Thus, degrees of freedom for all effects were corrected using Greenhouse-Geisser estimates ($\hat{\varepsilon} = .94$ for proportion correct and .95 for ITI synchrony).

For the c-RST – proportion correct, there was a marginally significant effect of musicianship [F (1, 201) = 3.65, $p = .058$, partial $\eta^2 = .02$], and significant main effects of rhythmic complexity [F (1.89, 379.64) = 205.24, $p < .001$, partial $\eta^2 = .51$] and age group [F (5, 201) = 5.24, $p < .001$, partial $\eta^2 = .12$]. Overall, children's scored taps decreased in a stepwise fashion from Strongly Metric to Medium Metric (p < .001), and from Medium Metric to Weakly Metric rhythms (p = .004). Post-hoc comparisons revealed that the oldest children outperformed the youngest but there were no stepwise changes between age groups. There was a significant interaction between rhythmic complexity and age [F (9.44, 379.64) = 4.48, $p < .001$, partial $\eta^2 = .10$]. Decomposition of this interaction revealed that children's scored taps increased significantly more with age for Strongly Metric rhythms than for the more difficult rhythms.

For the c-RST – ITI synchrony, there were significant main effects of musicianship [F (1, 201) = 9.39, p = .002, partial η^2 = .05], rhythmic complexity [F (1.89, 379.71) = 250.95, p < .001, partial η^2 = .56], and age group [F (5, 201) = 12.13, p < .001, partial η^2 = .23]. Overall, musicians outperformed non-musicians and synchronization ability decreased in a stepwise fashion from Strongly Metric to Medium Metric (p < .001), and from Medium Metric to Weakly Metric rhythms (p = .005). Post-hoc comparisons revealed that the oldest children tapped more in synchrony than the youngest, but there were no stepwise changes between age groups. There was also a significant age-group-by-complexity interaction [F (9.45, 379.71) = 2.27, p = .016, partial η^2 = .05], such that scores differed the most with age for Strongly Metric rhythms.

For the c-MDT, significant main effects were found for musicianship [F (1, 198) = 76.01, p < .001, η^2 = .28], melody type [F (1, 198) = 141.31, p < .001, η^2 = .42], and age group [F (5, 198) = 5.90, p = .001, η^2 = .13]. No significant interaction effects were found. Overall, musicians scored higher than non-musicians and children's scores were higher for Simple melodies than Transposed melodies. Post-hoc comparisons revealed that, overall, the oldest children performed best, but there were no significant stepwise increases between age groups.

Age-equivalent Scores

Given the main effects of age group for both the c-RST and c-MDT, we created age-equivalent (z-) scores for children on each task. Means and standard deviations are based on non-musicians (n = 83), who serve as the reference group with very little or no musical experience. Raw score means and standard deviations for musicians and non-musicians are presented in Table 2.3, and z-score conversions are provided in Table 2.4. Based on these, researchers using the c-RST or c-MDT with new groups of children can compare performance to either the trained or untrained sample.

To examine the contribution of years of training to performance on the c-RST and c-MDT, we conducted hierarchical multiple regressions for all children with at least one year of lessons (n = 151; Tables 2.5-2.8). Outcome variables were z-scores for the c-RST (proportion correct and ITI synchrony) and c-MDT (Simple and Transposed melodies). The predictor variable for all three analyses was duration of lessons in years. Scores for the two baseline variables (Tapping Variability and Syllable Sequence Discrimination) were entered at the first step, since these were statistically significantly better in musicians.

For the c-RST – proportion correct, the regression model with only baseline variables accounted for 4.9% of the variance and was statistically significant (adjusted $R^2 = .05$, $p = .009$). Additional years of training accounted for no additional variance (adjusted $R^2 = .04$, $p = .884$).

For the c-RST – ITI synchrony, baseline variables accounted for 2.2% of the variance and the regression model was not statistically significant (adjusted $R^2 = .02$, $p = .071$). When years of lessons were added, these accounted for 4.2% additional variance and the model was significant (adjusted $R^2 = .06$; $p = .011$). Specifically, a one-year increase in lessons contributed to an increase of .22 standard deviations in ITI synchrony z-scores ($\beta = .22$, $p = .011$). This is equivalent to a raw-score increase of 1.5% in children without musical training.

For the c-MDT – Simple melodies, the model with only baseline variables was statistically significant (adjusted $R^2 = .04$, $p = .013$), and additional years of training accounted for 5.2% additional variance (adjusted $R^2 = .09$, $p = .004$). Specifically, a one-year increase in lessons contributed to an increase of .24 standard deviations in Simple melody z-scores ($\beta = .24$, $p = .004$). This is equivalent to a raw-score increase of 2.5% in children without musical training.

For the c-MDT – Transposed melodies, the model with only baseline variables was statistically significant (adjusted $R^2 = .03$, $p = .037$). Additional years of training accounted for 10.6% additional variance (adjusted $R^2 = .13$, $p < .001$). Specifically, a one-year increase in lessons contributed to an increase of .34 standard deviations in Transposed melody z-scores ($\beta = .34$, $p < .001$). This is equivalent to a raw-score increase of 2.9% in children without musical training.

Relation Between Musical and Cognitive Abilities

To examine the relation between musical, baseline, and cognitive task performance in musicians, we calculated bivariate correlations between z-scores for c-RST (proportion correct and ITI synchrony) and c-MDT, scaled scores on Digit Span, Letter-Number Sequencing, and Matrix Reasoning, and raw scores for baseline tasks (Tapping Variability and Syllable Sequences). Given the ample prior evidence that musical training and cognitive variables are positively correlated, bivariate correlations are reported at the one-tailed level of significance. Correlation data are presented in Table 2.9.

The c-RST – proportion correct was significantly correlated with DS [r (130) = .22, p = .007)], but not LNS [r (130) = .13, p = .068)] or MR [r (130) = .04, p = .318)]. The c-RST – ITI synchrony was significantly correlated with all three cognitive tasks, namely DS [r (130) = .40, p < .001)], LNS [r (130) = .33, p < .001)], and MR [r (130) = .16, p = .033)]. The c-MDT – Simple Melodies was significantly correlated with DS [r (130) = .16, p = .039] but not LNS [r (130) = .11, p = .113] or MR [r (130) = .12, p = .095)]. The c-MDT – Transposed Melodies was marginally correlated with DS [r (130) = .14, p = .059] and with LNS [r (130) = .15, p = .049)], and significantly correlated with MR [r (130) = .20, p = .01)]. Tapping Variability correlated with DS [r (130) = -.15, p = .05] and MR [r (130) = -.19, p = .014)], but not with LNS [r (130) = .07, p = .215]. Finally, Syllable Sequences correlated significantly with all cognitive variables [DS: r (130) = .33, p < .001; LNS: r (130) = .22, p = .007; MR: r (130) = .24, p = .003)].

Discussion

In the present study, we evaluated two tests of musical ability that were developed for school-age children (7-13 years of age), and present normative data for groups with and without training. Our findings show that the c-RST and c-MDT are acceptably reliable, and that they are sensitive enough to demonstrate differences in performance between children with and without musical training, replicating findings from previous studies using the same tasks in adults. Older children performed better than younger children, but with no discernible stepwise increases between age groups. Within-task performance also mirrored adult patterns, with scores decreasing across levels of metrical complexity for the rhythm task and better scores for the Simple compared to the Transposed conditions in the melody task. Using z-scores derived from the untrained sample, we found that music lessons significantly predicted task performance over and above baseline tasks. Finally, we found that, for musically-trained children, performance on musical and baseline tasks was highly correlated with most cognitive abilities tested.

When the c-RST and c-MDT were evaluated for internal consistency, both were found to be adequately reliable. However, reliability for the c-RST was lower than for the c-MDT, likely due to the smaller number of trials. We also found that reliability for both tasks was lower for children without musical training. These issues could be addressed by using psychometric techniques based in item response theory. For instance, future iterations of these tasks might include items that adapt to individual differences in ability, such that correct responding leads to more difficult items and vice-versa (Harrison, Collins, & Müllensiefen, 2017; Kline, 2011).

Finally, because these tasks do not assess all aspects of musical skill, we recommend that they be used in combination with other complimentary measures.

In this child sample, musicians outperformed non-musicians on both musical tasks, consistent with findings from previous studies in adult musicians using the same tasks (Bailey & Penhune, 2010; Chen et al., 2008; Foster & Zatorre, 2010a; Karpati et al, 2016; Matthews et al., 2016). Moreover, the results are consistent with studies comparing children with and without training on other musical tasks (Habibi et al., 2016; Hyde et al., 2009; Moreno et al., 2009; Roden et al., 2014). We also found the expected within-task effects in our child sample, such that raw scores decreased as task demands increased. For the c-RST, scores were lower as metric regularity (i.e., beat strength) decreased, consistent with previous studies using the RST with adults (Bailey & Penhune, 2010; Matthews et al. 2016). For the c-MDT, all children were better at detecting deviant melodies when presented in the same key rather than a transposed key, which is similar to previous studies with adults (Foster & Zatorre, 2010b, 2010a). As predicted, the oldest children scored highest on both the c-RST and the c-MDT. This is supported by a previous finding using the c-RST (Tryfon et al., 2017), and by more general findings that children's rhythmic and melodic abilities improve with age and exposure to the music of their own culture (Stalinski & Schellenberg, 2012; Trainor & Corrigall, 2010).

Using z-scores derived from children without musical training, we were able to successfully predict increases in musical task performance from additional years of lessons, over and above the influence of baseline variables. For the c-RST, musical training predicted rhythm synchronization ability, over and above the influence of age. However, even with a minimum of three years of lessons, child musicians score at the level of non-musician adults (Bailey & Penhune, 2012). The neural substrates of auditory-motor integration develop across childhood, as demonstrated by cross-sectional studies showing that synchronization ability differs significantly between age groups in childhood, and is on par with adult ability by late adolescence (Drake et al., 2000; Drewing et al., 2006; Savion-Lemieux et al., 2009). Thus, to perform at adult levels on the c-RST, it appears that children need to both be older and have adequate musical training.

We also found that musically-trained children had better performance on the baseline Tapping and Continuation Task than those without music lessons. This is consistent with adult studies using similar tasks (Baer et al., 2015; Repp, 2010). However, this apparent advantage for musicians appears only at ages 9 and 11 in our sample. This pattern is very similar to a much earlier study in which children with musical experience had lower tapping variability than non-musicians, but only at 8 and 10 years old; there was no difference for the youngest or oldest age groups (Drake et al., 2000). According to Dynamic Attending Theory, the neural oscillations underlying auditory-motor synchronization stabilize as children get older (Drake et al., 2000). These bottom-up timing abilities, which are based in oscillatory entrainment and increase naturally as children get older, may be temporarily enhanced by musical experience in early or middle childhood. This experience-dependent boost in middle childhood may then decline as the underlying mechanisms mature through adolescence, for both musicians and non-musicians. Adult professional musicians, in turn, have the lowest tapping variability as a function of extended practice, the benefits of which extend far beyond the changes due to maturation.

In contrast to rhythm synchronization, musical training predicted improvement in melody discrimination ability, for both simple and transposed melodies. Transposition was especially sensitive to musical training, with the highest effect size for additional years of training on task performance. This is consistent with previous research showing that simple discrimination ability stabilizes in childhood (Stalinski & Schellenberg, 2012) whereas, without musical training, development of transposition discrimination is limited, with adolescents and adults performing at close-to-chance levels on this task (Foster & Zatorre, 2010b; Sutherland et al., 2013). Thus, the ability to detect changes in pitch within a transposed model may only develop fully in musically trained individuals. Quite unexpectedly, child musicians performed better on the baseline Syllable Sequence Discrimination Task (c-SSDT) than children without musical training. This is at odds with previous studies with adults where musically trained and untrained participants performed equally (Foster & Zatorre, 2010b; Karpati et al., 2016). However, this finding is consistent with a possible transfer effect from music training to language-related skills that may be specific to childhood. In addition to enhancing bottom-up (sensory) discrimination thresholds, musical training also affects multiple top-down cognitive processes that may contribute to enhancing performance on non-musical tasks, or far-transfer effects (Moreno & Bidelman, 2014; Patel, 2012). One such effect is improved phonological awareness, which is the first stage of learning to read and involves segmenting components of speech as they occur in time (Moritz, Yampolsky, Papadelis, Thomson, & Wolf, 2013). The c-SSDT requires listening to a pair of syllable sequences and identifying whether one syllable has changed. This may tap into skills related to phonological awareness. Indeed, brief musical training has been found to increase linguistic abilities in young children (Moreno & Besson, 2006; Moreno et al., 2009). Moreover, children at risk of language delays who received 1 year of music lessons showed no decline in basic literacy skills relative to control subjects (Slater et al., 2014).

Finally, we found that musicians' z-scores for both musical and baseline tasks were correlated to nearly all cognitive variables. Correlations between rhythm synchronization and tapping with cognitive performance are consistent with other studies of far-transfer demonstrating a relationship between rhythm and language skills in children. For example, children with specific language impairments score poorly on rhythmic production tasks (Gordon et al., 2016) and tapping variability in adolescents is negatively correlated with reading skill (Tierney & Kraus, 2013). On the c-MDT we observed an interesting contrast such that performance for Simple melodies was correlated with scores on the Digit Span test, whereas performance for Transposed melodies was correlated with scores on Letter-Number Sequencing. This is likely because Digit Span requires only immediate auditory memory and attention, whereas Letter-Number Sequencing requires mental manipulation and thus imposes a heavier demand on working memory and executive control. This lends additional behavioural evidence to the hypothesis that transposition is distinct from other discrimination abilities (Foster et al., 2013; Foster & Zatorre, 2010a; Sutherland et al., 2013). Moreover, when considered with our regression results, this suggests that transposition relates to higher-order cognitive abilities that are especially sensitive to the impact of musical training in childhood. Finally, musicians' scores on the c-SSDT were correlated with all cognitive abilities tested, again consistent with evidence of far transfer effects from music lessons to phonological awareness (Moreno et al., 2011; Moritz et al., 2013).

Conclusions

In conclusion, this study demonstrates that we have been successful in developing norms for two reliable and valid tests of musical skill for school-age children that are sensitive to the effects of training. These tasks and the associated norms fill an important need for researchers trying to assess the impact of music training in childhood. We hope that they will be important tools for researchers interested in evaluating the impact of musical training in longitudinal studies, those interested in comparing the efficacy of different training methods, and for those assessing the impact of training on non-musical abilities, such as reading skills and other cognitive functions.

Table 2.1

Demographic and Practice Characteristics of the Sample (N = 213), by Musicianship and Age Group

MUSICIANS (n = 130)	**7 n = 11 (6F)**	**8 n = 18 (13F)**	**9 n = 23 (15F)**	**10 n = 24 (12F)**	**11 n = 30 (16F)**	**13 n = 24 (18F)**
Age (years)	7.59	8.46	9.50	10.46	11.69	13.00
	(0.41)	(0.26)	(0.33)	(0.28)	(0.40)	(0.49)
Maternal education (years)	17.27	18.53	18.29	18.17	17.00	16.94
	(2.87)	(2.77)	(2.31)	(2.33)	(2.61)	(2.24)
Age of start (years)	4.13	4.44	4.71	5.29	5.71	7.69
	(0.70)	(0.64)	(1.23)	(1.31)	(1.43)	(1.43)
Music lessons (years)	3.42	4.01	4.67	5.04	5.93	5.27
	(0.73)	(0.66)	(1.29)	(1.31)	(1.55)	(1.45)
Weekly practice (hours)	2.52	3.17	2.83	3.24	3.56	2.32
	(2.15)	(1.79)	(1.59)	(1.73)	(3.06)	(2.26)
NON-MUSICIANS (n = 83)	**7 n = 15 (5F)**	**8 n = 14 (6F)**	**9 n = 16 (7F)**	**10 n = 13 (7F)**	**11 n = 13 (7F)**	**13 n = 12 (5F)**
Age (years)	7.09	8..51	9.46	10.46	11.66	13.65
	(0.45)	(0.36)	(0.29)	(0.22)	(0.45)	(0.57)
Maternal education (years)	17.60	17.66	18.40	16.22	18.15	15.56
	(2.16)	(2.70)	(2.33)	(1.28)	(2.51)	(0.75)

Table 2.2

Group Differences between Musicians and Non-Musicians on Demographic, Baseline and Cognitive Tasks

Measure	**Musicians (SD)**	**Non-musicians (SD)**	***t (df)***	***p***	***g***
Maternal education (years)	17.54 (2.44)	17.34 (2.28)	0.59 (211)	.558	0.08
Digit Span (scaled score)	11.45 (3.08)	10.68 (2.94)	1.79 (207)	.076	0.26
Letter-Number Sequencing (scaled score)	11.68 (1.92)	11.47 (2.18)	0.75 (207)	.454	0.10
Matrix Reasoning (scaled score)	12.44 (2.62)	11.53 (2.84)	2.35 (207)	.020	0.33
Tapping & Continuation Task: Tapping Variability	0.10 (0.05)	0.13 (0.05)	3.49 (211)	.001	0.49
Syllable Sequence Discrimination Task: Percent Correct	0.82 (0.12)	0.76 (0.13)	-4.83 (211)	<.001	0.68

Table 2.3

Raw Score Means and Standard Deviations for Music and Baseline Tasks, by Musicianship and Age Group

MUSICIANS	**7** **n = 11** **(6F)**	**8** **n = 18** **(13F)**	**9** **n = 23** **(15F)**	**10** **n = 24** **(12F)**	**11** **n = 30** **(16F)**	**13** **n = 24** **(18F)**
RST: Proportion correct						
Strongly Metric	83.18	86.17	89.26	89.50	92.80	92.96
	(6.10)	(7.13)	(6.37)	(7.22)	(4.66)	(5.86)
Medium Metric	75.18	76.50	80.30	79.83	82.80	80.67
	(5.67)	(5.18)	(6.76)	(7.53)	(6.73)	(6.66)
Weakly Metric	74.64	77.17	79.52	78.00	81.73	76.83
	(5.45)	(6.19)	(3.80)	(8.02)	(4.68)	(7.23)
RST: ITI Synchrony						
Strongly Metric	70.82	73.94	77.48	80.54	82.77	83.96
	(11.33)	(9.94)	(9.64)	(7.33)	(8.08)	(4.86)
Medium Metric	60.18	59.78	57.74	63.33	67.67	67.33
	(7.85)	(9.68)	(6.39)	(9.41)	(6.73)	(6.03)
Weakly Metric	57.36	53.61	62.74	60.75	64.83	63.79
	(8.82)	(11.48)	(9.09)	(9.56)	(7.21)	(6.05)
TCT: Tapping Variability	14.06	11.49	11.08	10.33	7.88	8.85
	(4.76)	(5.82)	(5.57)	(5.19)	(2.23)	(2.72)
MDT: Percent Correct						
Simple Melodies	70.45	75.83	78.26	80.63	86.33	80.00
	(19.03)	(14.17)	(12.02)	(12.19)	(8.90)	(12.07)
Transposed Melodies	56.82	60.56	70.30	62.29	72.67	70.50
	(12.51)	(13.71)	(13.41)	(16.75)	(10.89)	(15.99)
SSDT: Percent Correct	72.73	81.39	78.57	81.04	86.83	85.83
	(14.03)	(14.33)	(13.11)	(12.94)	(8.25)	(10.07)

NON-MUSICIANS	**7** **n = 15** **(5F)**	**8** **n = 14** **(6F)**	**9** **n = 16** **(7F)**	**10** **n = 13** **(7F)**	**11** **n = 13** **(7F)**	**13** **n = 12** **(5F)**
RST: Proportion correct						
Strongly Metric	80.07	85.00	86.00	84.62	87.54	94.75
	(10.14)	(9.51)	(8.22)	(10.12)	(6.98)	(3.49)
Medium Metric	78.20	77.00	78.81	77.69	81.15	79.50
	(6.33)	(5.04)	(9.20)	(5.59)	(3.51)	(6.54)
Weakly Metric	77.53	77.07	76.69	75.85	77.62	75.92
	(8.41)	(8.15)	(8.78)	(6.67)	(7.62)	(7.45)
RST: ITI Synchrony						
Strongly Metric	68.73	68.79	76.31	75.15	81.69	86.83
	(10.26)	(26.31)	(10.00)	(8.87)	(5.50)	(3.54)
Medium Metric	56.87	56.07	63.87	58.23	60.38	66.08
	(4.91)	(7.47)	(7.73)	(8.70)	(8.39)	(9.61)
Weakly Metric	54.13	52.36	58.69	58.85	60.46	54.17
	(16.73)	(12.00)	(12.47)	(8.66)	(10.46)	(15.63)
TCT: Tapping Variability	16. 35	13.11	15.28	12.32	11.48	9.39
	(4.44)	(4.81)	(8.82)	(5.39)	(2.32)	(4.33)
MDT: Percent Correct						
Simple Melodies	55.67	68.21	60.31	65.08	70.38	72.50
	(11.16)	(13.24)	(9.03)	(15.14)	(14.64)	(17.39)
Transposed Melodies	48.33	52.50	51.88	51.00	56.92	58.17
	(8.59)	(12.37)	(7.93)	(12.67)	(12.00)	(10.15)
SSDT: Percent Correct	72.67	67.50	76.56	81.77	81.54	77.33
	(14.50)	(9.95)	(11.79)	(14.69)	(9.87)	(10.31)

Table 2.4

Raw Score to Age-Equivalent (Z-) Score Conversion Table for Music Task Outcome Variables, by Musicianship

MUSICIANS

z	RST % correct (Strong)	RST % correct (Medium)	RST % correct (Weak)	RST % ITI synch (Strong)	RST % ITI synch (Medium)	RST % ITI synch (Weak)	TCT tapping variability	MDT % correct (Simple)	MDT % correct (Transposed)	SSDT % correct	z
+3.0	100.00	96.69	92.45	92.00	83.07	81.00	4.12	100.00	95.00	100.00	**+3.0**
+2.5	98.76	94.76	89.00	92.00	80.38	78.52	4.30	100.00	95.00	100.00	**+2.5**
+2.0	97.14	91.00	88.00	89.14	77.00	74.14	4.97	100.00	90.00	100.00	**+2.0**
+1.5	97.00	86.00	85.00	87.00	71.04	70.04	5.37	95.00	85.00	95.00	**+1.5**
+1.0	95.00	83.00	82.00	85.00	68.00	67.00	6.59	90.00	75.00	90.00	**+1.0**
+0.5	91.00	80.00	79.00	82.00	64.00	63.00	7.59	80.00	67.00	85.00	**+0.5**
0	88.00	77.00	76.00	78.00	60.00	58.00	9.23	75.00	60.00	75.00	**0**
-0.5	83.00	74.00	73.00	70.00	54.96	51.96	10.12	69.80	50.00	70.00	**-0.5**
-1.0	76.00	68.00	65.00	60.00	49.00	45.00	13.35	60.00	44.30	60.00	**-1.0**
-1.5	70.62	63.48	62.10	54.24	44.00	39.10	19.08	46.20	38.10	45.00	**-1.5**
-2.0	70.00	58.93	56.24	53.00	41.24	35.31	28.40	36.55	35.00	45.00	**-2.0**
-2.5	70.00	58.00	55.00	53.00	40.00	35.00	29.62	35.00	35.00	45.00	**-2.5**
-3.0	-	-	-	-	-	-	-	-	-	-	**-3.0**

NON-MUSICIANS

z	RST % scored (Strong)	RST % scored (Medium)	RST % scored (Weak)	RST % ITI synch (Strong)	RST % ITI synch (Medium)	RST % ITI synch (Weak)	TCT % tapping variability	MDT % correct (Simple)	MDT % correct (Transposed)	SSDT % correct	z
+3.0	-	-	-	-	-	-	-	-	-	-	**+3.0**
+2.5	-	-	-	-	-	-	-	-	-	-	**+2.5**
+2.0	98.64	90.60	92.00	92.32	81.64	76.64	4.28	96.60	75.00	100.00	**+2.0**
+1.5	98.00	88.00	88.96	89.00	74.96	73.96	4.28	85.00	70.00	95.00	**+1.5**
+1.0	95.00	83.00	85.00	87.00	69.00	69.56	5.14	80.00	65.00	90.00	**+1.0**
+0.5	92.00	82.00	79.12	82.24	64.00	63.00	7.04	75.00	60.00	85.00	**+0.5**
0	88.00	79.00	77.00	79.00	60.00	59.00	8.67	65.00	50.00	75.00	**0**
-0.5	82.00	77.00	74.00	73.88	55.00	51.00	11.14	55.00	45.00	70.00	**-0.5**
-1.0	77.00	73.00	68.32	64.00	52.00	43.44	13.11	50.00	45.00	62.20	**-1.0**
-1.5	70.00	65.20	64.04	59.04	49.04	35.04	15.28	40.04	33.08	55.00	**-1.5**
-2.0	60.72	59.76	57.04	28.56	43.44	19.52	16.35	40.00	30.00	48.40	**-2.0**
-2.5	58.00	55.00	55.00	-	38.00	10.00	19.69	40.00	30.00	45.00	**-2.5**
-3.0	58.00	55.00	55.00	-	38.00	10.00	29.63	40.00	30.00	45.00	**-3.0**

Table 2.5

Summary of Hierarchical Regression Analysis for Variables Predicting Age-Equivalent Scores on the c-RST (Proportion correct)

	B	**SE *B***	***β***	***t***	***p***
Step 1					
Constant	0.38	0.16		2.35	.020
TCT: Tapping Variability	-1.57	1.43	-.09	-1.10	.271
SSDT: % correct (z)	0.19	0.07	.23	2.82	.005
Step 2					
Constant	0.41	0.26		1.56	.121
TCT: Tapping Variability	-1.64	1.49	-.09	-1.10	.275
SSDT: % correct (z)	0.19	0.07	.22	2.78	.006
Lessons (years)	-0.01	0.04	-.01	-.15	.884

Note: N = 151 (children with >= 1 year of music lessons). R^2 = .06, adj. R^2 = .05, $F(2, 148)$ = 4.83, p = .009 for Step 1; R^2 = .06, adj. R^2 = .04, $F(1, 147)$ = 0.02, p = .884 for Step 2.

Table 2.6

Summary of Hierarchical Regression Analysis for Variables Predicting Age-Equivalent Scores on the c-RST (ITI Synchrony)

	B	**SE *B***	***β***	***t***	***p***
Step 1					
Constant	0.45	0.14		3.17	.002
TCT: Tapping Variability	-2.25	1.27	-.14	-1.78	.078
SSDT: % correct (z)	0.08	0.06	.11	1.37	.174
Step 2					
Constant	-0.01	.23		-0.04	.967
TCT: Tapping Variability	-1.29	1.30	-.08	-1.00	.322
SSDT: % correct (z)	0.10	0.06	.13	1.65	.101
Lessons (years)	0.08	0.03	.22	2.59	.011

Note: N = 151 (children with >= 1 year of music lessons). R^2 = .04, adj. R^2 = .02, $F(2, 148)$ = 2.69, p = .071 for Step 1; R^2 = .08, adj. R^2 = .06, $F(1, 147)$ = 6.70, p = .011 for Step 2.

Table 2.7

Summary of Hierarchical Regression Analysis for Variables Predicting Age-Equivalent Scores on the c-MDT (Simple Melodies)

	B	**SE *B***	***β***	***t***	***p***
Step 1					
Constant	1.03	0.21		4.89	<.001
TCT: Tapping Variability	-0.50	1.87	-.02	-0.26	.792
SSDT: % correct (z)	0.26	0.09	.24	2.95	.004
Step 2					
Constant	0.26	0.33		0.79	.428
TCT: Tapping Variability	1.10	1.91	.05	0.58	.564
SSDT: % correct (z)	0.29	0.09	.26	3.31	.001
Lessons (years)	0.13	0.05	.24	2.93	.004

Note: N = 151 (children with >= 1 year of music lessons). R^2 = .06, adj. R^2 = .04, $F(2, 148)$ = 4.45, p = .013 for Step 1; R^2 = .11, adj R^2 = .09, $F(1, 147)$ = 8.60, p = .004 for Step 2.

Table 2.8

Summary of Hierarchical Regression Analysis for Variables Predicting Age-Equivalent Scores on the c-MDT (Transposed Melodies)

	B	SE *B*	*β*	*t*	*p*
Step 1					
Constant	1.52	0.30		5.15	<.001
TCT: Tapping Variability	-3.23	2.64	-.10	-1.23	.222
SSDT: % correct	0.27	.013	.18	2.20	.029
Step 2					
Constant	0.00	0.45		0.00	.999
TCT: Tapping Variability	-.05	2.60	.00	-0.02	.984
SSDT: % correct (z)	0.33	0.12	.21	2.75	.007
Lessons (years)	0.26	0.06	.34	4.28	<.001

Note: N = 151 (children with >= 1 year of music lessons). R^2 = .04, adj. R^2 = .03, $F(2, 148)$ = 3.37, p = .037 for Step 1; R^2 = .15, adj R^2 = .13, $F(1, 147)$ = 18.28, p < .001 for Step 2.

Table 2.9

Zero-Order Correlations, Means and Standard Deviations for Music Task, Baseline, and Cognitive Variables in Musicians

Measure	1	2	3	4	5	6	7	8	9	M	SD
1. RST: Proportion correct (z)	1.00	.38***	-.12	.15*	.19*	.21**	.22**	.13	.04	0.18	0.84
2. RST: ITI synchrony (z)		1.00	-.13	.05	.05	.16*	.40***	.33***	0.16*	0.28	0.72
3. TCT: tapping variability			1.00	-.01	-.09	-.10	-.14	-.06	-.17*	0.10	0.05
4. MDT: Percent correct (Simple; z)				1.00	.44***	.29***	.16*	.11	.12	1.09	1.09
5. MDT: Percent correct (Transposed; z)					1.00	.25**	.14	.15*	.20**	1.39	1.48
6. SSDT: Percent correct (z)						1.00	.33***	.22**	.24**	0.00	0.98
7. Digit Span							1.00	.47***	.28***	11.45	3.08
8. Letter-Number Sequencing								1.00	.40***	11.68	1.92
9. Matrix Reasoning									1.00	12.44	2.62

Note: Correlations are reported at the one-tailed level of significance. * = $p < .05$; ** = $p < .01$; *** $p < .001$

Figure 2.1. Examples of stimuli used in the c-RST. Strongly Metric, Medium Metric and Weakly Metric refer to the regularity of the underlying pulse (Strongly Metric = easiest). Figure adapted from Tryfon et al. (2017).

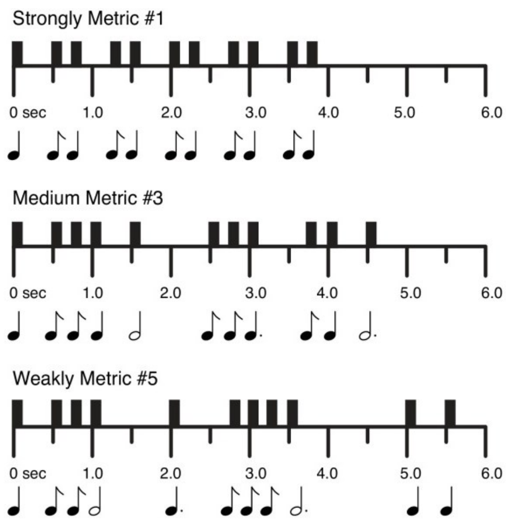


Figure 2.2. Graphical display for the c-RST. Image is presented in full colour within the actual task.

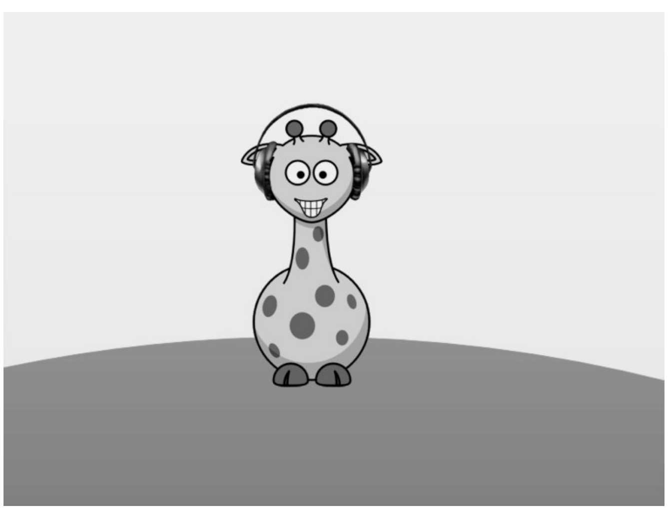


Figure 2.3. Examples of stimuli from the c-MDT Simple Melody condition (L) and Transposed Melody condition (R). Children listen to two melodies and decide whether the second was the same or different. Arrows represent the ‘different’ note. Figure adapted from Karpati et al. (2016).

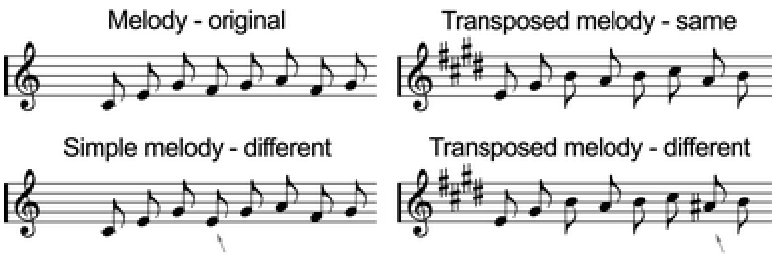
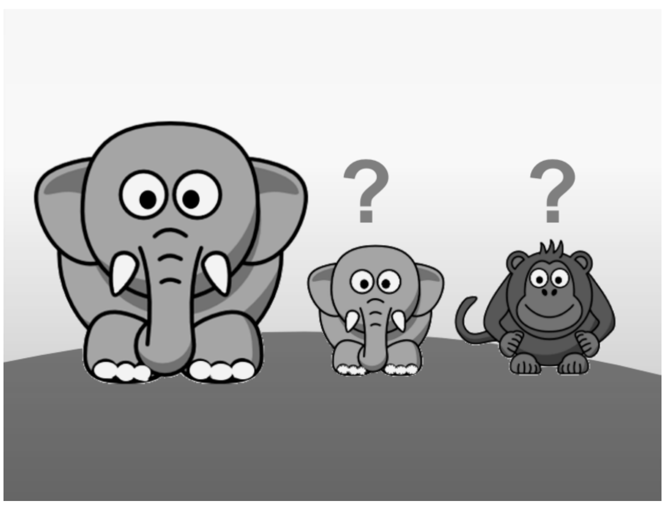


Figure 2.4. Graphical display of response probe for the c-MDT. Image is presented in full colour within the actual task. Small animals represent ‘same’ and ‘different’ response choices.



CHAPTER THREE:
STUDY 2

Contributions of age of start, cognitive abilities and practice to musical task performance in childhood.

Ireland, K., Iyer, T. A., & Penhune, V. B. (2019). Contributions of age of start, cognitive abilities and practice to musical task performance in childhood. *PloS one*, *14*(4), e0216119. https://doi.org/10.1371/journal.pone.0216119

Abstract

Studies with adult musicians show that beginning lessons before age seven is associated with better performance on musical tasks and enhancement in auditory and motor brain regions. It is hypothesized that early training interacts with periods of heightened neural development to promote greater plasticity and better learning and performance later in life. For this study, we assessed whether the effects of early training can be observed in childhood. We also evaluated the degree to which such effects are related to training, or whether early training has different effects on particular musical skills depending on their cognitive, perceptual or motor requirements. We compared groups of child musicians who had started lessons earlier or later on age-normed tests of rhythm synchronization and melody discrimination. We also matched for age, years of experience, working memory and global cognitive ability. Results showed that children who started early performed better on simple melody discrimination and that scores on this task were predicted by both age of start (AoS) and cognitive ability. There was no effect of AoS for the more complex rhythm or transposed melody tasks, but these scores were significantly predicted by working memory ability, and for transposed melodies, by hours of weekly practice. These findings provide evidence that earlier AoS for music training in childhood results in enhancement of specific musical skills. Integrating these results with those for adult musicians, we hypothesize that early training has an immediate impact on simple melody discrimination skills that develop early, while more complex abilities, like synchronization and transposition require both further maturation and additional training.

Introduction

Studies in adults show that musicians who begin training before age seven show enhancements in behaviour and brain structure compared with those who begin later (Baer et al., 2015; Bailey & Penhune, 2010; Bailey et al., 2014; Bailey & Penhune, 2012; Schlaug et al., 1995; Steele et al., 2013). Based on this evidence, it is hypothesized that training during specific periods of brain maturation in childhood leads to greater plasticity and thus to better learning and performance in the long term. However, many studies demonstrating the impact of early training are in adults with more than 10 years of experience; thus, it is unclear whether early training has immediate effects in childhood, or whether those effects require additional maturation and/or long-term practice to develop. Further, early training may have different effects on specific musical skills depending on their cognitive, perceptual or motor requirements. Therefore, in this study we compared performance on tests of musical ability in groups of children who began lessons earlier or later but who were matched for years of experience and other relevant training and cognitive factors. In addition to standard matched-group comparisons we also used regression to assess the differential contribution of cognitive measures and training.

Early researchers suggesting that the age of start (AoS) of musical training might modulate brain plasticity had compared the surface area of the corpus callosum in musicians and non-musicians (Schlaug et al., 1995). They found that overall the anterior corpus callosum was larger in musicians, but that this effect was greater for those who began training before age seven. No specific rationale for this cut-off was given, either based on the trajectories of brain maturation or music training. Most importantly, there was no control for the normally high correlation between AoS and years of experience, with earlier AoS related to greater experience. Subsequently, a series of studies from our lab and others have examined the impact of early training on behavior and the brain using samples of early-trained (< 7; ET) and late-trained (>7; LT) musicians matched for years of experience, years of formal training, and hours of current practice. Behaviourally, ET musicians have been found to have more accurate performance on complex sensorimotor synchronization tasks than LT musicians, using both visual-motor and auditory-motor paradigms (Bailey & Penhune, 2010; Bailey & Penhune, 2012; Steele et al., 2013; Watanabe et al., 2007). In the visual-motor domain, ET musicians outperformed LT musicians on a timed motor sequence task (TMST) for which they were trained to reproduce sequences of visually-presented ‘rhythms’ on a piano keyboard. The advantage for ET musicians was observed in training periods as short as two days (Steele et al., 2013) or five days (Watanabe et al., 2007). In another sample, ET musicians had more precise timing than LT musicians during a task that required reading and playing scales from sheet music (Vaquero et al., 2015). In the auditory-motor domain, ET musicians outperformed LT musicians on a rhythm synchronization task (RST) in which they listened, and then tapped along to each note of rhythms that varied in metrical complexity (Bailey & Penhune, 2010). This finding was replicated in a second sample of ET and LT musicians with the same complex rhythmic task (Bailey & Penhune, 2012). By contrast, in another sample of ET and LT musicians, no differences were found for a simple synchronization and continuation task (Baer et al., 2015). Taken together, these results suggest that early training has greater long-term effects on more complex rhythmic tasks.

Longitudinal and quasi-experimental studies provide the strongest evidence that music training in childhood can produce changes in brain structure above and beyond normal maturation, and that these changes often correspond to improvements on musical tasks. Importantly, in these studies all children were found to be equivalent prior to music training in terms of brain structure, SES and cognitive abilities. In one study, six-year-old children were given 15 months of private keyboard lessons, and compared to a control group with only school-based music classes (Hyde et al., 2009b). Those with private lessons showed enhancements in motor regions which were correlated with improvements on a melody and rhythm discrimination task. They also showed enhanced white-matter connectivity which correlated with improvements on a fine-motor sequencing task. Another group which followed children aged 6-18 for two years found a positive association between musical training and the rate of cortical thickness maturation in motor regions (Hudziak et al., 2014). Very recently, six-year-old children were assigned to group music training following the El Sistema model, team sports training, or no systemic training (Habibi, Damasio, Ilari, Sachs, et al., 2018). After one year, children in the music group showed better performance on a task in which they synchronized drumming patterns with an adult (Ilari et al., 2016). After two years, children in the music group showed enhanced connectivity in the corpus callosum and better tonal discrimination compared to the two control groups (Habibi et al., 2017). Electrophysiological evidence suggests that changes in young children’s neural processing of sound occur after as little as one to three years of lessons. For example, auditory-evoked potentials were larger in amplitude in four- to five-year-old children after one year of music lessons (Shahin et al., 2004). In another study, responses to violin tones were heightened in children aged 4-6 after one year of Suzuki music lessons when compared to children without musical training (Fujioka et al., 2006). Finally, children with and without musical training were assessed every two years from age 7-13. The auditory-evoked responses of children with musical training grew larger in amplitude with time, suggesting enhanced auditory processing above and beyond normal development (Putkinen et al., 2013).

As described above, no specific rationale has been developed for the age of seven cut-off used in previous work. One study from our lab attempted to validate this cut-off by examining the relationship between AoS and rhythm synchronization performance for different age cut-offs (6, 7, 8 and 9) in a large sample of adult ET and LT musicians (Bailey & Penhune, 2013). For all cut-offs, AoS was more highly correlated with performance in the ET than the LT groups, with a significant difference for the age seven cut-off. These findings support the use of age seven as a boundary for early training, but they also indicate that it is not a hard cut-off.

Taken together, these findings indicate training may enhance the developmental trajectory for musical skills through interaction with normal maturation and plasticity in auditory and motor regions of the brain. Longitudinal studies with children show that one to three years of music lessons in childhood can lead to improvements in synchronization and pitch discrimination which are related to changes in the underlying neural substrates. Cross-sectional studies with adults show that, even when controlling for lifetime musical training, having started before age seven was associated with better sensorimotor musical abilities later in life. A non-linear relationship has been proposed between AoS and task performance, with better performance associated with early AoS up to age nine (Bailey & Penhune, 2013). Therefore, the purpose of this study was to investigate the relative contributions of AoS, music lessons, and music practice to musical task performance in childhood. A large sample of children aged 6-14 with music training were tested on Melody Discrimination and Rhythm Synchronization tasks developed in our lab (Ireland et al., 2018; Tryfon et al., 2017). Demographic and training information as well as measures of cognitive abilities were also collected. Based on previous studies in adults, we first examined group differences between ET and LT child musicians at a range of AoS cut-offs (5, 6 and 7) using age-equivalent z-scores. These groups were matched for years of lessons, cognitive and demographic variables. In a second step we assessed the relationship between AoS and performance between groups across these cut-offs. Finally, we used hierarchical regression to assess the individual contributions of AoS, cognitive and training variables to task performance.

Method

Participants

We tested 130 child musicians (age range: 6.50-14.08 years) from music day camps in Montréal, Ottawa, and Waterloo, Canada. We operationalized the term "musician" as a child fulfilling the following criteria: a) having at least 2.5 consecutive years of weekly, one-on-one music lessons on the same instrument (*M* = 5.06 years, *SD* = 1.58, range 2.58 – 10.00); (b) attending music lessons at time of recruitment; and (c) practicing music at least half an hour per week outside of lessons and on the same instrument (*M* = 3.16 hours, *SD* = 2.49, range 0.50 – 14.00). Children were eligible if they answered 'yes' to having at least one private music lesson per week. We did not inquire about duration of private lessons, or about group lessons. Music practice could be structured (using a book or specific exercises) or unstructured (free playing). Practice-related and demographic data were collected from parents on a questionnaire adapted in our lab (Survey of Musical Interests; Desrochers, Comeau, Jardaneh, & Green-Demers, 2006). We estimated SES using maternal years of education (*M* = 17.54 years, *SD* = 2.44, range 12.00 – 22.00). Mothers reported their highest level of education on an ordinal scale, and we converted this to an approximate interval scale with the following estimates: high school = 12 years; college diploma = 14 years; baccalaureate degree = 16 years; master's degree = 18 years; doctorate or medical professional degree = 22 years. Parents provided written consent and children provided verbal assent before participating. Children were given a gift card and a small toy as thanks for their participation. The study was approved by Concordia University's Human Research Ethics Board.

Musical Tasks

For the children's Melody Discrimination Task (c-MDT), children listen to two melodies of equal duration separated by a 1.2-second silence, and then indicate whether the second melody is the same or different (Figs 3.1 & 3.2). There are two conditions, Simple and Transposed, each with 20 trials (10 same and 10 different). In the Simple condition, both melodies are in the same key and in the "different" trials the pitch of a single note in the second melody is shifted up or down by up to five semitones. The child thus must compare individual pitches to detect the deviant note. In the Transposed condition, all the notes in the second melody are transposed upward by four semitones (a major third) and in the "different" trials a single note is shifted up or down by one semitone. Thus, since the melodic contour is preserved, the child must use relative pitch to perceive the deviant note. Melodies are composed of low-pass-filtered harmonic tones (320 ms) from the Western major scale (range: C4-E6). The 20 trials are presented in random order within conditions, but the order of conditions is always the same (Simple, Transposed) to preserve the storyline. Before starting each condition (Simple or Transposed), children are familiarized through four practice trials, two with feedback from the experimenter and two without feedback. The procedure for adapting the c-MDT from the adult version was recently published (Ireland et al., 2018). After all trials, the word 'correct' or 'incorrect' is displayed for one second. During experimental trials, experimenters are seated so as not see children's responses or feedback. Performance on the c-MDT is scored as the percentage of correct responses. The child's responses are scored as 0 (incorrect) or 1 (correct), generating a proportion which is then multiplied by 100. Given the evidence of transposition ability being anatomically distinct from other auditory discrimination abilities, Simple and Transposed melodies are always reported separately.

For the children's Rhythm Synchronization Task (c-RST), children listen and then try to tap along to each note of a rhythm while it plays, using the index finger on a computer mouse (Figs 3.3 & 3.4). Rhythms consist of 11 woodblock notes spanning an interval of 4 to 6 seconds. The c-RST has two rhythms at each of three levels of complexity (low, medium, high), for a total of six rhythms, which are presented in a counterbalanced order. Low complexity rhythms are repetitive and have a strong beat, whereas high complexity includes syncopated rhythms, which do not emphasize the beat. In a larger sample of children with and without musical training, ITI synchrony decreased consistently with increasing rhythmic complexity (Ireland et al., 2018)]. Thus, for this study, we used the average of all three complexity levels. A single trial of the c-RST consists of a 'Listen' phase and a 'Tap in Synchrony' phase, and each rhythm is presented for three consecutive trials (i.e., Listen-Tap; Listen-Tap; Listen-Tap). Before starting the test, children complete five practice trials at the low complexity level, with feedback from the experimenter. The rhythms used for the practice trials are not those used in the main task. Performance on the RST is measured in inter-tap interval (ITI) synchrony, or the child's ability to reproduce the temporal structure of a rhythm. It is calculated as the ratio of the child's response intervals (r) to the stimulus time intervals (t), with the following formula: Score = 1–abs(r–t)/t. This proportion is multiplied by 100 to generate a percentage, with scores closer to 100 indicating better synchrony.

Cognitive Tasks

We administered three subtests from the Wechsler Intelligence Scale for Children, fourth edition (WISC-IV; Wechsler, 2003): Digit Span (DS), Letter-Number Sequencing (LNS), and Matrix Reasoning (MR). Digit Span is a measure of immediate auditory memory, in which the child repeats strings of digits forward or backward. Letter-Number Sequencing (LNS) is a measure of auditory working memory, in which the child hears a string of letters and numbers and must repeat them back in numerical and alphabetical order, respectively. Together, DS and LNS comprise the Working Memory Index and are reported as such herein. Matrix Reasoning (MR) is a measure of nonverbal reasoning, and is considered to be a reliable estimate of general intellectual ability (Brody, 1992; Raven, J., Raven, J. C., & Court, 1998). For this task, the child must identify the missing portion of an incomplete visual matrix from one of five response options. All subtests were administered according to standardized procedures. Raw scores were converted to scaled scores based on age-based norms.

General Procedure

Testing took place over a one-hour session. Participants were given short breaks between tasks to enhance motivation and prevent fatigue. Computer-based tasks were administered on a laptop computer running Presentation software (Neurobehavioral Systems, http://www.neurobs.com/). Task order was counterbalanced across participants. Auditory tasks were presented binaurally via Sony MDRZX100B headphones pre-adjusted to a comfortable sound level. Cognitive tasks were administered in the order in which they appear in the original WISC-IV battery.

Results

Examining Group Differences Between ET and LT Child Musicians

We first examined average group differences between ET and LT children by creating three sub-samples based on AoS: age five (N = 110), age six (N = 96) and age seven (N = 52), with equal numbers of ET and LT musicians in each group. Children who had started prior to the cut-off were categorized as ET; those who had started at or after the cut-off were categorized as

LT. To create matched samples at each AoS cutoff (age 5, 6 and 7) we first selected the group of ET children. Then, we matched an LT counterpart that resembled the ET child as closely as possible (+/- up to one-half of a standard deviation) on the following variables: years of music lessons, gender, Matrix Reasoning, Working Memory Index, Maternal Education and hours of weekly practice. For example, if an ET child had a WMI of 24, where $M = 20$ and $SD = 6$, we selected an LT counterpart with a WMI in the range of 21-27. Demographic, training-related, and cognitive characteristics of ET and LT musicians in the three sub-samples are presented in Tables 3.1-3.3.

For the c-RST we predicted that ET children would score higher than LT at an AoS cut-off of age seven, as in previous findings with adult musicians. There are no published studies of the c-MDT comparing ET and LT musicians, given that the task was created by the author; however, we previously found that Simple Melody scores were higher than Transposed Melodies at all ages (Ireland et al., 2018)]. Moreover, the neural correlates of transposition ability have been found to develop later in life (Sutherland et al., 2013). Thus, we hypothesized that any AoS effects would be limited to Simple Melodies.

We conducted a one-way analysis of variance (ANOVA) with group (ET or LT) as the two-level factor, at each AoS cut-off (5, 6, and 7) on the age-normed z-scores for each child for each outcome measure (c-MDT: Simple and Transposed Melodies; c-RST: ITI Synchrony; Figs 3.5 & 3.6). All assumptions for one-way ANOVA were met, including univariate normality, independence of observations, and homogeneity of variance (Kline, 2004). There were no group differences at the first cut-off (ET $< 5 \leq$ LT) for any outcome (Simple Melodies: $F(1, 108) = 0.39$, $p = .537$, partial $\eta^2 = .004$; Transposed Melodies: $F(1, 108) = 0.41$, $p = .523$, partial $\eta^2 = .004$; ITI Synchrony: $F(1, 108) = 0.39$, $p = .389$, partial $\eta^2 = .007$). . At the second cut-off (ET $< 6 \leq$ LT), ET musicians outperformed LT for Simple [$F(1, 94) = 9.56$, $p = .003$, partial $\eta^2 = .092$] but not Transposed melody discrimination [$F(1, 94) = 0.69$, $p = .407$, partial $\eta^2 = .007$]. Groups did not differ in ITI Synchrony [$F(1, 94) = 0.13$, $p = .719$, partial $\eta^2 = .001$]. Similarly, at the oldest cut-off (ET $< 7 \leq$ LT), ET outperformed LT for Simple [$F(1, 50) = 4.29$, $p = .043$, partial $\eta^2 = .079$] but not Transposed melody discrimination [$F(1, 50) = 0.41$, $p = .524$, partial $\eta^2 = .008$] and there were no differences in ITI Synchrony [$F(1, 50) = 0.61$, $p = .439$, partial $\eta^2 = .012$].

Examining ET-LT Cut-offs

To explore the validity of AoS cut-offs, we calculated the correlations between AoS and z-score for ET and LT groups for each task and at each cut-off. We then compared correlation coefficients between groups using Fisher's z Transformation and z-test (Meng, Rosenthal, & Rubin, 1992). In addition, we calculated slopes using regression models and compared them using *t*-test analyses. In a previous study examining ET-LT cut-offs of 6, 7, 8, and 9 in adult musicians, younger age of start predicted better performance on the Rhythm Synchronization Task at all four cut-offs. Furthermore, correlations and slopes differed the most between ET and LT musicians when age seven was used to divide the groups (Bailey & Penhune, 2013). This was taken as suggestive of an AoS effect for age seven. If such an effect is observable in childhood, we predict that younger age of start will correlate with better c-RST performance at all three cut-offs. Moreover, we expect that correlations and slopes will differ the most between ET and LT children at age seven for the c-RST.

Overall, there were no statistically significant differences in correlations or slopes at any cut-off. However, several patterns of correlations emerged in LT groups which corresponded to our hypotheses. For Simple Melodies, younger AoS predicted better performance at the youngest cut-off, age five [$r(53) = -.25$, $p = .069$]. For Transposed Melodies, task performance was not correlated with AoS at any cut-off. For rhythm synchronization, younger AoS predicted higher z-scores at the oldest cut-off, age seven [$r(24) = -.48$, $p = .013$].

Examining AoS as a Predictor

Lastly, we conducted a hierarchical polynomial regression analysis (Cohen, Cohen, West, & Aiken, 1983) to examine the contributions of AoS, music lessons and practice, and cognitive abilities, as well as any non-linear relationships, to musical task performance. In contrast to the previous analyses in which we matched children in ET and LT groups, for this analysis we used the full dataset ($N = 130$), limiting the range of potential contributing factors while minimizing data loss. To do this, we converted raw values to standardized values, or used standard scores, for all predictors (age of start, years of lessons, hours of weekly practice, SES, WMI, MR). We removed all cases with an absolute value exceeding 2.50 SD on any of these predictors. This limited range resulted in the removal of 16 cases, for a total sample size of 114. As with the matched-subjects approach, we used age-based (z) scores for all musical tasks to control for differences due to maturation.

For each musical task, predictors besides AoS that were statistically significantly correlated with the outcome were added at step 1 as control variables (c-RST: WMI r = .28; c-MDT Simple: MR [r = .20]; c-MDT Transposed: WMI [r = .20], weekly practice [r = .25]). Our predictor of interest, the linear variable 'age of start' (AoS), was added at step 2. The power terms 'AoS^2' and 'AoS^3' were added at steps 3 and 4, to examine quadratic and cubic relations, respectively. To reduce multicollinearity with its power terms, we centered the variable AoS at its mean for each age group; this centered variable was used as the basis for all regression analyses (Kline, 2011).

For Simple Melodies, a linear regression model with only Matrix Reasoning accounted for 4.1% of the variance (β = .20, t = 1.89, adjusted R^2 = .03, p = .031). Adding AoS contributed 3.2% independent variance to the model (β = -.18, t = -1.95, adjusted R^2 = .06, p = .054). Power terms did not add any independent variance to the model.

For Transposed Melodies, a linear regression model with only Working Memory accounted for 4.0% of the variance (β = .20, adjusted R^2 =.03, p = .034). Adding Weekly Practice Hours contributed 7.4% independent variance to the model (β = .27, adjusted R^2 = .10, p = .003). Neither AoS nor any of its power terms accounted for independent variance to the model.

For Rhythm Synchronization, a linear regression model with only Working Memory accounted for 7.7% of the variance (β = .28, t = 3.06, adjusted R^2 = .07, p = .003). Neither AoS nor any of its power terms accounted for additional variance to the model.

Discussion

The results of this study showed that children who began training before age seven performed better on a simple melody discrimination task than those who started later, after being matched for musical training, demographic and cognitive variables. Further, both AoS and a measure of global intellectual function independently predicted scores on this task. There were no group differences or effects of AoS for the more complex rhythm synchronization and transposed melody discrimination tasks, but these were statistically significantly predicted by working memory ability. Additionally, weekly practice was an independent predictor of transposed melody discrimination. These results provide clear evidence for the contributions of maturational, training and cognitive factors in predicting musical task performance.

In the present sample, simple discrimination abilities were highest in those who had started music lessons before ages six and seven. Our finding of an AoS effect for simple pitch discrimination is supported by longitudinal studies showing that even short periods of music training during childhood can improve children's discrimination of simple tones and melodies (Habibi et al., 2017; Hyde et al., 2009a), neural processing of musical sounds and pitches (Besson, Schön, Moreno, Santos, & Magne, 2007; Fujioka et al., 2006; Putkinen et al., 2013; Shahin et al., 2004), and accuracy in singing a simple melody (Hutchins, 2018). This advantage for low-level pitch processing is likely a function of early maturation in the primary auditory cortex, in which there is a massive increase in the number of synapses and in myelination between ages one and five (Kral & Eggermont, 2007; Moore, 2002; Moore & Guan, 2001; Moore & Linthicum Jr, 2007). We and others have hypothesized that music training during periods of rapid maturational change may lead to greater brain plasticity that would promote enhanced learning both immediately and over the long term (Altenmueller & Furuya, 2016; Herholz & Zatorre, 2012; Steele et al., 2013).

We also found that performance on simple pitch discrimination was related to global cognitive ability. There are several ways that cognitive and musical abilities might be related. On one hand, a global factor is posited to underlie the ability to approach and remain engaged with all cognitive tasks, resulting in positive correlations among these tasks, a phenomenon known as 'the positive manifold' (Kovacs & Conway, 2016). This general ability would also support basic music-perceptual abilities which, like other cognitive processes, are hypothesized to be innate and normally distributed (Schellenberg & Winner, 2011). On the other hand, there is direct causal evidence that musical training during middle childhood, when compared to other types of training, can increase global cognitive ability (Schellenberg, 2004). Moreover, in a large longitudinal study of neuropsychological functioning across childhood, raw scores on tasks of global intellect increased sharply between ages 6-10 and reached adult levels by age 12-13 (Waber et al., 2007). These maturational changes coincide with the time at which children in our sample are starting music lessons, and thus changes in cognitive abilities with maturation may also contribute to performance on music tasks. Altogether, our results provide evidence that music training before age seven results in specific gains in simple pitch discrimination, that are likely linked with developmental peaks in brain regions supporting basic auditory processing and with global cognitive development.

In contrast, we found no evidence that earlier start of training differentially contributed to rhythm synchronization ability. This is not consistent with results from studies with adult musicians showing that those who begin training before age seven outperform those who begin later on rhythm tasks (Bailey & Penhune, 2010; Bailey & Penhune, 2012; Vaquero et al., 2015; Watanabe et al., 2007). However, our finding is consistent with the maturation of rhythmic abilities in childhood: beat perception is in place by infancy (Hannon, Nave-Blodgett, & Nave, Van Noorden & De Bruyn, 2009; Winkler, Háden, Ladinig, Sziller, & Honing, 2009) but auditory-motor integration does not develop fully until mid- to late adolescence (Drewing et al., 2006; Savion-Lemieux et al., 2009). Moreover, rhythmic tapping tasks require basic fine-motor abilities that do not mature until late childhood (Gerber et al., 2010; Monier & Droit-Volet, 2019). Further, even with musical training, children's rhythmic abilities take time to mature. For instance, children aged 6-8 improved on a tonal discrimination task after two years of music lessons, but rhythm discrimination did not appear to change (Habibi et al., 2016). Similarly, in children receiving music lessons from ages 7-13, there were improvements in the detection of pitch errors, but not timing errors, as measured with EEG (Putkinen et al., 2013). To integrate the results of studies with child and adult musicians, we hypothesize that children must be older, have matured in terms of motor abilities, and have accrued substantial training to perform well on this task. This is supported by our previous findings using the same task with 7-13 year-old children showing continuing improvement with age, and that years of lessons contribute significantly to performance (Ireland et al., 2018). Finally, for rhythm synchronization we also found that children's scores were significantly associated with working memory ability. This supports previous findings that scores on the task were correlated with measures of working memory in children (Ireland et al., 2018) and adults (Bailey & Penhune, 2010; Bailey & Penhune, 2012).

For discrimination of transposed melodies, we also found no differences between matched ET and LT groups, and no effect of AoS. Similar to rhythm synchronization, there was a statistically significant association between working memory and task performance. These correlational findings support the possibility of a bidirectional relationship between musical training and working memory. On the one hand, playing music requires attending to and holding sequences of notes in mind, and applying the correct motor program to execute movements. These skills are supported by working memory which, like global cognitive function, develops most sharply between ages 6-10 and reaches adult levels by age 12-13 (Waber et al., 2007). On the other hand, music practice directly enhances working memory through repetition of increasingly complex sensory-motor skills. Correspondingly, children with musical training have been found to have better performance on tasks of verbal and visuospatial working memory (Bergman Nutley et al., 2014). Thus, children with a better working memory capacity may be likely to engage in music training, and by doing so may enhance this skill.

We also found that hours of weekly practice, but not AoS or duration of musical training, significantly predicted transposed melody discrimination. This is consistent with findings from studies with adults that lifetime music practice accounted for more than two-thirds of the variance in performance on the same task (Foster & Zatorre, 2010b). This task is more difficult because it requires the participant to ignore contour, a highly salient auditory feature (Dowling & Fujitani, 1971). There are two cues that help children differentiate the melodies: interval structure, or the change in pitch from one note to the next (McDermott, Keebler, Micheyl, & Oxenham, 2010), and tonal function, or the degree to which the second melody 'fits' the key of the first (Beckett, 2019, personal communication). Children learn about interval structure and key implicitly through enculturation, and explicitly through activities associated with lessons and practice such as reading and repetition of musical scales. Thus, although non-musicians may understand implicitly, musicians' explicit practice enables them to perform much better on the transposed melody task. More than the other tasks in this study, transposed discrimination seems to require active engagement with music training, and with regular weekly practice specifically.

Our findings provide new evidence in children that earlier start of music training results in better performance for simple melody discrimination, even when controlling for years of experience. This is likely a metaplastic effect where starting music training during a time of peak neurodevelopmental change produces better immediate and long-term learning. Performance for the more complex rhythm and transposition tasks did not show an effect of age of start and transposition ability was related to hours of practice. Performance for all music tasks was related to cognitive ability, indicating that cognitive skills likely both promote engagement in music and may be enhanced by training. Integrating these results with those for adult musicians, we hypothesize that early training has an immediate impact on skills like simple melody discrimination that develop early, while more complex abilities, like synchronization and transposition require both further maturation and additional training.

Table 3.1. Matched Demographic, Practice-Related and Cognitive Variables in Early-Trained (ET) and Late-Trained (LT) Musicians; ET < 5 ≤ LT (N = 110)

Variable	**ET (*n* = 55)**	**LT (*n* = 55)**	***t* (108)**	***p***	***g***
Maternal education (years)	17.94 (2.52)	17.40 (2.48)	1.03	0.30	0.20
Music lessons (years)	5.17 (1.45)	5.09 (1.23)	0.31	0.76	0.06
Weekly practice (hours)	3.28 (1.94)	2.95 (2.46)	0.78	0.44	0.15
Working Memory Index (scaled score)	23.76 (4.51)	22.51 (3.92)	1.55	0.12	0.30
Matrix Reasoning (scaled score)	12.47 (2.74)	12.31 (2.69)	0.31	0.76	0.06

Table 3.2. Matched Demographic, Practice-Related and Cognitive Variables in Early-Trained (ET) and Late-Trained (LT) Musicians; ET < 6 ≤ LT (*N* = 96)

Variable	**ET (*n* = 48)**	**LT (*n* = 48)**	***t* (94)**	***p***	***g***
Maternal education (years)	17.97 (2.56)	17.08 (2.29)	1.79	.08	0.37
Music lessons (years)	4.65 (1.31)	4.59 (1.31)	0.22	.83	0.05
Weekly practice (hours)	2.80 (1.63)	2.14 (1.91)	1.81	.07	0.37
Working Memory Index (scaled score)	22.04 (3.04)	21.92 (4.69)	0.15	.88	0.03
Matrix Reasoning (scaled score)	11.98 (2.31)	12.13 (2.54)	0.30	.76	0.06

Table 3.3. Matched Demographic, Practice-Related and Cognitive Variables in Early-Trained (ET) and Late-Trained (LT) Musicians; ET < 7 ≤ LT (N = 52)

Variable	**ET(*n* = 26)**	**LT(*n* = 26)**	***t* (50)**	***p***	***g***
Maternal education (years)	17.20 (2.27)	16.96 (2.60)	0.31	.76	0.09
Music lessons (years)	4.20 (1.08)	4.29 (1.08)	0.37	.71	0.10
Weekly practice (hours)	1.95 (1.75)	1.79 (1.50)	0.35	.72	0.10
Working Memory Index (scaled score)	21.69 (3.04)	21.92 (4.85)	0.20	.84	0.06
Matrix Reasoning (scaled score)	11.65 (2.41)	12.08 (2.37)	0.65	.52	0.18

Figure 3.1. Examples of stimuli from the c-MDT Simple Melodies (L) and Transposed Melodies (R). Children listen to two melodies and decide whether the second was the same or different. Arrows represent the 'different' note. Figure adapted from (Karpati et al., 2016).

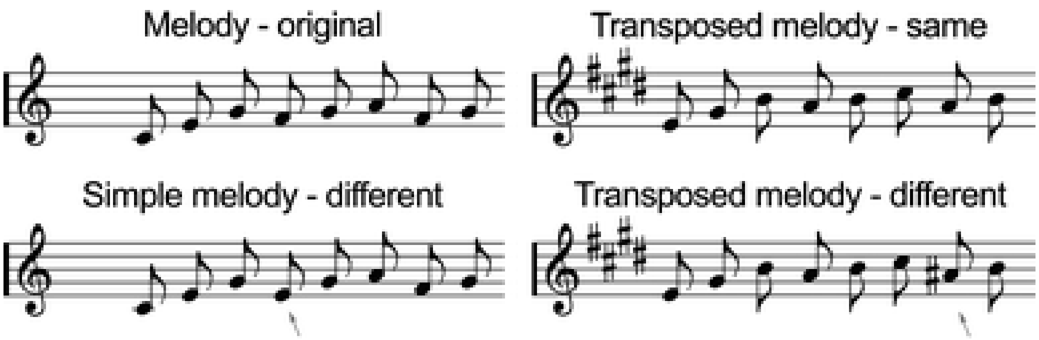


Figure 3.2. Graphical display of response probe for the c-MDT**.** Small elephant and monkey represent 'same' and 'different' response choices, respectively. Image is presented in full colour within the actual task.

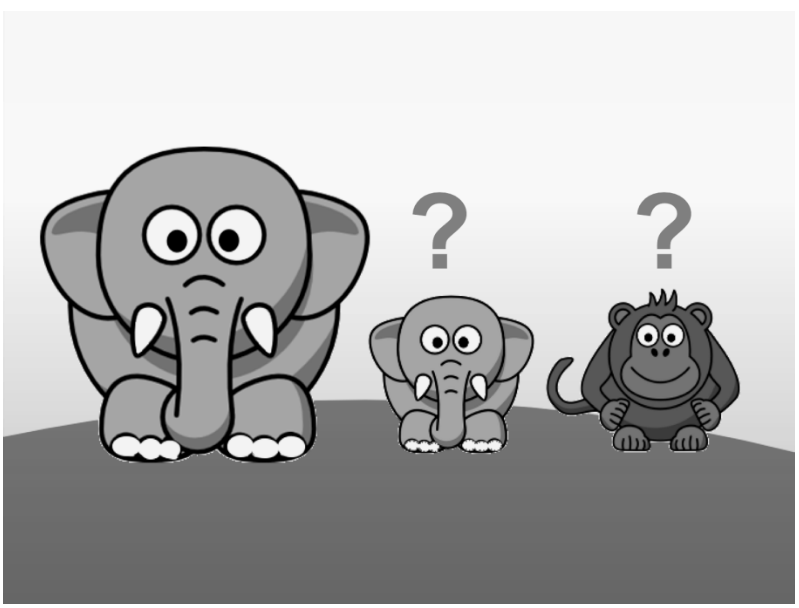


Figure 3.3. Procedure for the c-RST. The child listens and then taps along to a rhythm as it plays twice in a row. Figure adapted from (Tryfon et al., 2017).

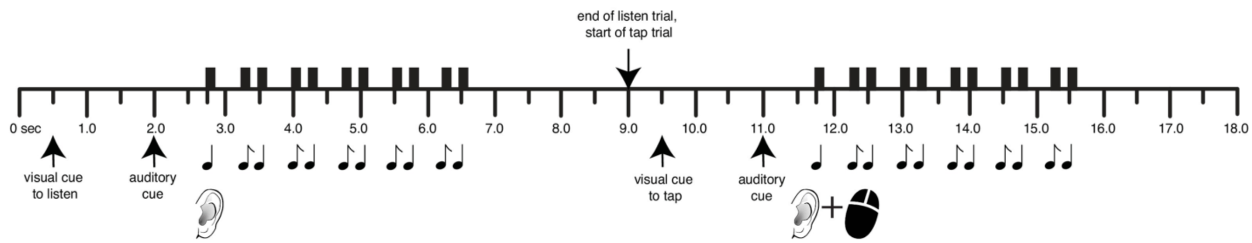


Figure 3.4. Graphical display for the c-RST. Giraffe's headphones are highlighted during 'listen' phase, and hoof is highlighted during 'listen + tap' phase. Image is presented in full colour within the actual task.

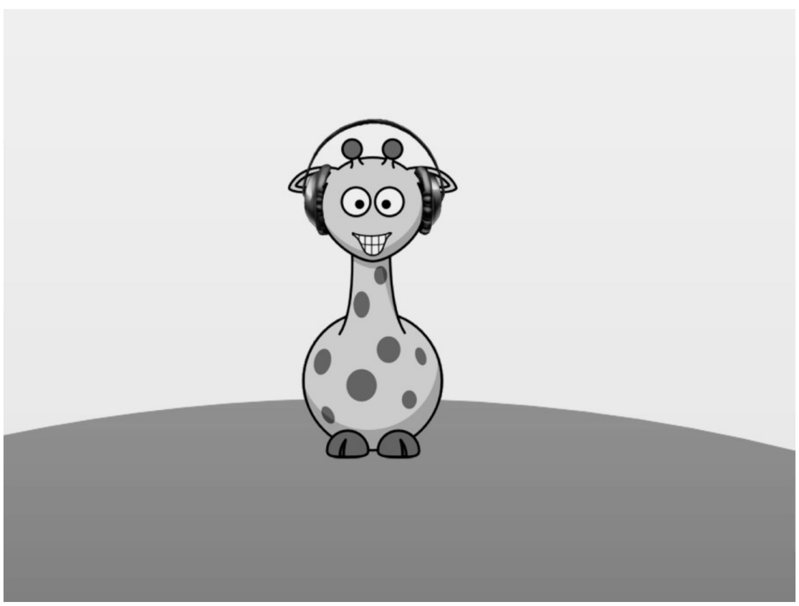


Figure 3.5. Results of one-way ANOVA for children's Melody Discrimination Task (c-MDT). Bars represent early-trained (ET) and late-trained (LT) musicians at three age of start cut-offs. Performance is measured as age-based z-scores for Simple Melodies (L) and Transposed Melodies (R).

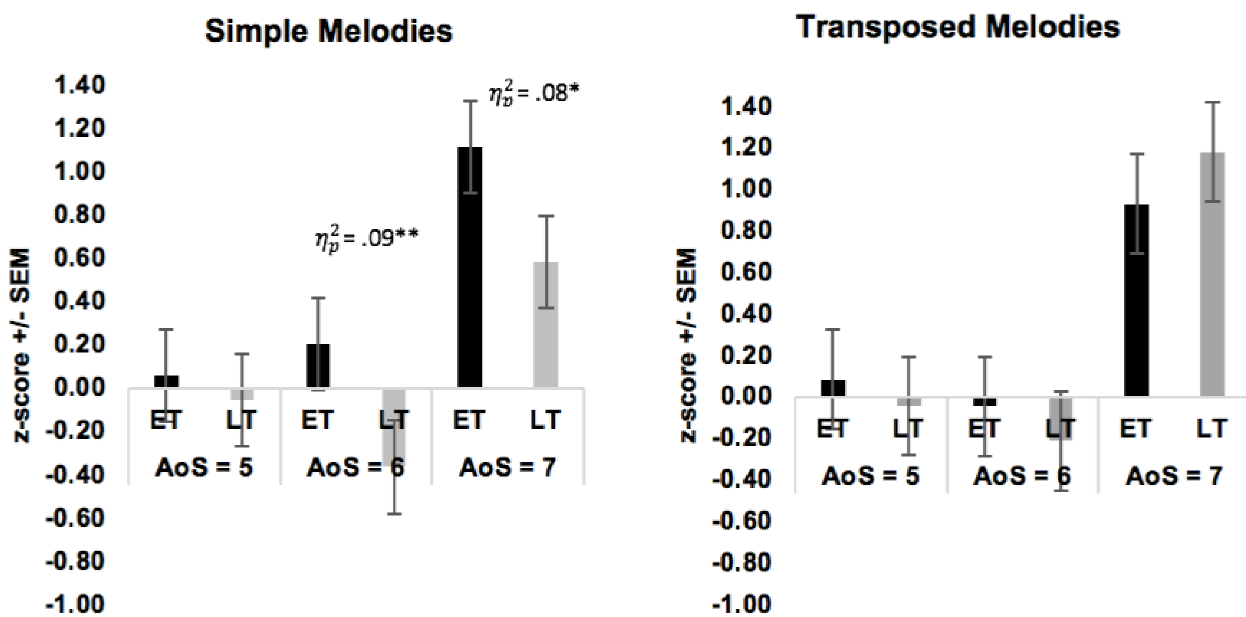
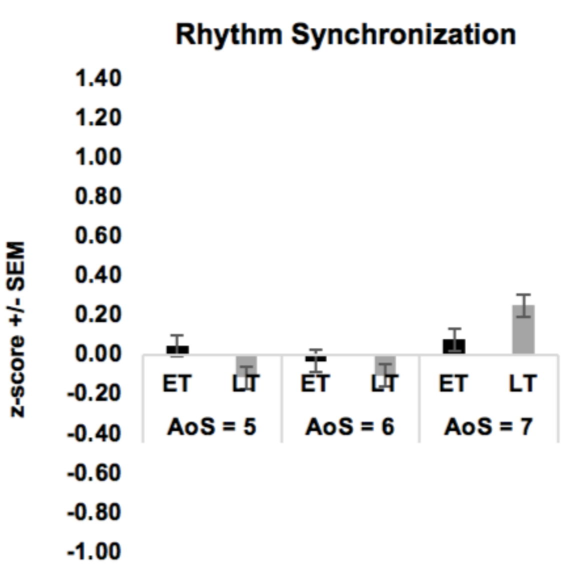


Figure 3.6. Results of one-way ANOVA for children's Rhythm Synchronization Task (c-RST). Bars represent early-trained (ET) and late-trained (LT) musicians at three age of start cut-offs. Performance is measured as age-based z-scores.



CHAPTER FOUR:
GENERAL DISCUSSION

Summary of Findings

The goal of this thesis was to test whether children who began their musical training earlier in childhood showed advantages over those who began later after an equivalent amount of training. To do this, we created child-friendly versions of rhythm and melody tasks that had been previously used to investigate the effects of training before age seven in adult musicians. We administered the children's Rhythm Synchronization Task (c-RST) and children's Melody Discrimination Task (c-MDT) to 213 children with and without musical training, and we calculated age-based scores to control for the effect of maturation. We estimated internal-consistency reliability and external validity for the tasks, and we used age-based scores to assess the contribution of early age of start (AoS) to task performance.

Our primary objective in Study 1 was to develop musical tasks with adequate reliability and validity for administration in primary school-aged children, and to calculate age-based scores for those with and without musical training. The c-RST and the c-MDT were found to have adequate convergent validity with adult analogues such that scores decreased as complexity increased. Thus, for the c-RST, scores were lowest for rhythms with the highest metric complexity (i.e., with the weakest sense of beat), and for the c-MDT, scores were lowest for melodies with the highest cognitive processing demands (i.e., in which transposition must be ignored). We also found that children with musical training outperformed those without training. These results replicate findings from studies of the same tasks with adults, and situate our results within a robust literature documenting a 'musician advantage' for tasks of auditory perception and auditory-motor integration (for a review, see Dalla Bella, 2015). We also found a large effect of age for both musical tasks. Consistent with models of child sensory and motor development (e.g., Gerber et al., 2010), this maturational effect is largest for the c-RST, which poses the highest demands in terms of integration of auditory and motor abilities. Finally, we found that auditory-verbal working memory was correlated with c-RST scores, but only in children with musical training; moreover, child musicians and non-musicians did not differ in their working memory ability. This correlational result supports the notion that musical training moderates a bidirectional relation between synchronization and working memory, such that each ability could both facilitate and be strengthened by the other.

For Study 2, we investigated the influence of AoS on task performance at three AoS cutoffs (age 5, 6, and 7) for early- and late-trained (ET and LT) child musicians. We used both categorical and continuous approaches to data analysis. We hypothesized that ET children, who had started lessons within a developmental sensitive period in the auditory system before age seven, would have higher scores compared to those who had started later. We controlled for other training-related factors, including duration of consecutive lessons and hours of weekly practice. We also controlled for demographic and cognitive variables which have been found to correlate positively with musical task performance, including SES, working memory, and global cognitive ability (Swaminathan & Schellenberg, 2018). Similar to previous studies with adult musicians, we found an AoS effect in children who had begun training before age seven. However, contrary to studies with adult ET and LT musicians, this effect was only observable for the easiest task, simple melody discrimination. Moreover, both AoS and global cognitive ability, as measured by a non-verbal reasoning task, independently predicted simple melody discrimination scores. There were no AoS effects for the more difficult transposed melody discrimination or rhythm synchronization tasks, and in fact both tasks were predicted by auditory working memory. Finally, weekly practice was an independent predictor of transposed melody discrimination. Together, these results support a multidimensional model of musical task performance in childhood that includes the interaction of developmental, training-related and cognitive factors (Penhune, 2019).

Situating our Findings: Development of Pitch and Rhythm

Musical ability, broadly defined as the ability to perceive, learn and remember music, can be considered a fundamental cognitive process that, similar to other abilities, develops naturally with age and is normally distributed in the population (Schellenberg & Weiss, 2013; Stalinski & Schellenberg, 2012). Supporting this perspective, we found that even children without musical training could engage with both of our musical tasks, and produced a range of scores within each age group presumably representing variation in ability. Moreover, we found that scores were highest in the oldest children, and this effect of age was smaller for the simple pitch discrimination task, and larger for the more complex transposition and sensorimotor synchronization tasks. This is consistent with what is known of the differential development of pitch and rhythmic processing and their neural correlates. The brain's response to auditory stimuli begins in utero and has a long developmental timeframe (Draganova et al., 2007; Ponton et al., 2002). Although the sensory processes required for simple pitch discrimination are fully developed by neonatal age (Perani et al., 2010), more complex processes such as transposition discrimination and rhythm synchronization develop later (Ismail, Fatemi, & Johnston, 2017).

Pitch discrimination and transposition. Melody discrimination, the ability to detect differences between pitches or sequences of notes, is in place very early in life, even before birth, such that near-term fetuses can detect a large change in pitch, roughly an octave (Lecanuet et al., 2000). Two-month-old infants can detect a difference of one semitone, the smallest interval in the Western scales, and they can respond to transposed songs, a more cognitively demanding task, by early childhood (Plantinga & Trainor, 2005, 2009). Children's auditory perceptual abilities become more attuned to culture-specific musical features as they move through the school years (Corrigall & Schellenberg, 2015). For instance, knowledge of key membership is acquired first, followed by implicit knowledge of harmony (Lynch, Eilers, Oller, & Urbano, 1990b; Schellenberg et al., 2005; Trainor & Trehub, 1994). This understanding begins around 6 years old and continues to develop until 11 years old (Costa-Giomi, 1999b). Transposition discrimination, the detection of a deviant note in another key, requires higher-order association and cognitive-control processes in order to retain a melody in a transposed form while ignoring contour, a highly salient feature of sound (Dowling & Fujitani, 1971). Adolescents (Sutherland et al., 2013) and adults with no musical training (Fig. 1.1) score similarly on the MDT. Moreover, task performance was correlated with lifetime practice in musically-trained adults (Foster & Zatorre, 2010b), and with weekly practice in our sample of child musicians (Ireland et al., 2018). Thus, transposition discrimination may not develop fully without musical training.

Rhythm synchronization. The ability to perceive simple rhythmic patterns and meters is present in the first year of life (Hannon & Johnson, 2005). The ability to synchronize, or align one's movements with a rhythmic cue, requires the integration of perceptual, motor and cognitive processes and develops over a longer time frame (Maróti, Honbolygó, & Weiss, 2019; Monier & Droit-Volet, 2019; Thompson et al., 2015). Synchronization ability appears to follow a roughly quadratic developmental curve across the lifespan, increasing sharply between ages 4-11 (Drake et al., 2000) and throughout adolescence (Thompson et al., 2015). It reaches a developmental peak in the early 20s, stabilizes in early and middle adulthood, then sharply decreases as one moves into old age (Drewing, Aschersleben, & Li, 2006; Thompson et al., 2015). Synchronization relies on the entrainment of the brain's natural oscillations with those of a periodic auditory stimulus (e.g., a pulse, or beat) and requires both an 'internal timekeeper' and a ‘motor responder’ (Dalla Bella et al., 2017; Wing & Kristofferson, 1973). Both of these theorized components were recently tested in a study of 6- and 7-year-olds with no musical training (Maróti et al., 2019). Children listened or tapped along to isochronous tone sequences of varying speed while brain activity in auditory and motor cortices was measured with EEG. There was no interaction between networks when listening alone (i.e., a test of the internal timekeeper) compared to tapping (i.e., a test of the motor responder). This provides further evidence that the neural substrates of rhythm synchronization mature later than those that underlie pitch processing.

Taken together, the abilities measured by our tasks (i.e., melody discrimination, transposition discrimination and rhythm synchronization) develop along different trajectories that are dependent on maturation of the underlying neural processes. Discrimination of simple pitches requires only basic perceptual processes and appears early in life. Transposition discrimination requires higher-order association and cognitive processes, and rhythm synchronization requires the integration of auditory and motor processes; both processes develop later in life. In our sample, ET child musicians (AoS < 7) showed better discrimination of simple pitches when controlling for age, musical training and practice, and pre-existing demographic and cognitive variables. This effect of early training for simple discrimination is consistent with having begun music lessons during or very soon after a sensitive period, or a window of heightened plasticity, in primary auditory cortex. In contrast, we found no ET effects for transposition discrimination or rhythm synchronization. This is consistent with an interactive model of complex musical abilities. In other words, children in our sample may have begun music lessons during a sensitive period in the underlying auditory, motor, or cognitive control regions, but it may not be possible to observe ET effects without both the complete maturation of these neural substrates and additional training.

Interactions of Development and Training

Researchers in our lab and others have found that, as adults, ET musicians outperformed LT musicians on complex sensorimotor synchronization tasks, when matched for training-related variables including duration of formal training, years of lessons, and hours of weekly practice (Bailey & Penhune, 2010; Bailey & Penhune, 2013; Vaquero et al., 2015). For instance, ET musicians had better synchronization to complex rhythms on the adult version of our Rhythm

Synchronization Task (Bailey & Penhune, 2010) and this result was replicated in a second sample (Bailey & Penhune, 2012). These researchers subsequently investigated the validity of AoS cut-off ages, and found that the correlation between AoS and rhythm synchronization performance differed the most when age 7 was used to divide the groups (Bailey & Penhune, 2013). Using this validated ET cut-off, others have found that musicians who had started before age 7 showed better timing with the left hand in a task in which piano sequences were learned by sight-reading (Vaquero et al., 2015).

Metaplasticity. Training during sensitive periods in brain development may also have long-term effects on how those regions adapt to future experience (Altenmueller & Furuya, 2016; Herholz & Zatorre, 2012). The concept of *metaplasticity* was proposed by researchers studying the physiology of hippocampal learning (Abraham, 2008), and describes how early experience can enhance the potential for later learning. Researchers in our lab have explored this phenomenon using learning tasks in ET and LT adult musicians (Steele et al., 2013; Watanabe et al., 2007). In both samples, ET musicians showed faster initial learning of visual-motor sequences, and better overall synchronization, than LT musicians, while controlling for formal training and music practice. This ET advantage was sustained over 2 days (Steele et al., 2013) and 5 days of learning (Watanabe et al., 2007).

In the context of our current results it appears that although there may be some degree of plasticity induced by early training, the effects observable in childhood are limited to simple abilities that were fully developed when training began (i.e., simple pitch discrimination). When combined with the results from studies in adults, this suggests that metaplastic changes likely occur as children mature and accrue more practice. Thus, although starting before age seven does not produce immediate effects on more complex skills, such as transposed melody discrimination or rhythm synchronization, that early exposure contributes to metaplastic effects, i.e., better learning later in development. To test this hypothesis, future studies could test new cohorts of children into late adolescence to assess when the effects of early training appear for these tasks. Moreover, a learning task should be added to the battery to test the hypothesis that early experience can allow for more rapid learning.

The most rigorous approach to validating the existence of sensitive periods for musical training in childhood would be to conduct a longitudinal, experimental study (Wiens & Gordon, 2018). Children in two age groups (ET and LT; AoS 5-6 and 8-9, respectively) would be randomly assigned to receive musical training, no training, or an 'active training' in a non-auditory modality, such as visual arts (e.g., Schellenberg, 2004) or sports (e.g., Habibi, Damasio, Ilari, Sachs, & Damasio, 2018). Group members would be matched for pre-existing differences in factors that facilitate engagement with or maintenance of training, including intellectual ability, working memory, SES, and motor development (Corrigall & Schellenberg, 2016; Gordon et al., 2015; Habibi et al., 2014; Monier & Droit-Volet, 2019). Following recommendations for treatment fidelity in music training interventions as advanced by Wiens & Gordon (2018), the theoretical rationale, mechanism(s) of change and dosage would be stated clearly, and interventions would be delivered by credentialed personnel using a standardized protocol. Outcomes would be assessed at baseline and follow-up, typically 1 and 2 years after training starts. In addition to our tasks, a separate musical measure would be used as a manipulation check (e.g., Barbaroux, Dittinger, & Besson, 2019), and a learning task would be added to verify metaplastic effects after training. Maturational effects would be controlled by using our tasks or others for which age-equivalent scores exist (e.g., Gordon, 1986). Carrying out this kind of study would be challenging. Researchers need to consider practical limitations (e.g., minimizing drop-out between baseline and follow-up) and ethical constraints (e.g., assigning children to early- and late-start groups).

Going Beyond: Music and Language

Knowing the developmental timelines for musical abilities tells us about the periods during which their underlying substrates are most sensitive to training. The study of experience-dependent plasticity is not limited to the musical domain. Indeed, sensitive periods are proposed in the domain of language acquisition, such that earlier AoS for a new language results in enhancements in language processing later in life (Berken, Gracco, Chen, & Klein, 2016). Although infants are born with the capacity to perceive the phonemes of all spoken languages, this declines rapidly without exposure to other languages. By 9 months, babies can no longer perceive non-native speech sounds and by 12 months, they are completely 'tuned in' to the phonological properties of their own language or languages (Werker & Tees, 1984). Although additional languages can be acquired throughout the lifespan and long after this period of 'perceptual narrowing,' earlier AoS relates to better language proficiency as assessed by accent in one's non-native language (Flege et al., 1995). Thus, sensitive periods may operate similarly in music and language, in that they reflect developmental windows during which intensive training differentially affects proficiency later in life.

The primary objective of this thesis was to explore near-transfer effects of musical training; that is, enhancements in musical abilities that are present in musically-trained children (Ullén et al., 2016). There is also considerable research interest in far-transfer effects, in which musical training promotes neuroplasticity and/or improves performance in other cognitive domains, such as language abilities (Gordon et al., 2015; Patel, 2011; Ullén et al., 2016; Wiens & Gordon, 2018). Language and music are thought to be processed according to common principles of auditory perceptual organization including grouping, segmentation and temporal regularity, and thus might be expected to influence each other (Hannon, Nave-Blodgett, & Nave, 2018; Stevens, 2012). For example, Japanese and English speakers preferred non-linguistic rhythmic sequences that more closely resembled accent patterns in their native language (Iversen, Patel, & Ohgushi, 2004). Moreover, native Mandarin speakers, who use changes in pitch to derive linguistic meaning, are better at detecting key violations when compared to English speakers (Wong et al., 2012). Exposure to language thus affects musical development.

A conceptual framework, known as the OPERA hypothesis, has been proposed to explain why transfer from music to language may occur (Patel, 2011). According to this hypothesis, five conditions must be met. First, music and language must share a common, *overlapping* neural substrate (O). Next, musical training must require more *precision*, in terms of neural processing, than the language function to which it transfers (P). Third, music must stimulate strong, positive *emotion* (E). Fourth, the musical activities that stimulate language must be *repeated* frequently (R). Finally, the musical training must engage the *attentional* network (A). The OPERA hypothesis was originally applied to the spectral domain of music (i.e., pitch). More recently, OPERA has been extended to the temporal domain (i.e., rhythm): the Precise Auditory Timing Hypothesis (PATH) uses OPERA criteria to explain why rhythmic entrainment may facilitate some language skills (Tierney & Kraus, 2014). These conceptual frameworks are supported by evidence that musical abilities independently predict language abilities in typically developing children (Gordon et al., 2015; Woodruff Carr, White-Schwoch, Tierney, Strait, & Kraus, 2014; Zuk, Andrade, Andrade, Gardiner, & Gaab, 2013).

Empirical investigations of transfer from music to language. Researchers are interested in studying the efficacy of musical interventions on aspects of language processing (Wiens &

Gordon, 2018). For example, a 'rhythmic priming effect' has been proposed, such that hearing a strongly rhythmic auditory sequence prior to hearing a sentence may improve grammar processing abilities. This priming effect been observed in well-controlled experimental studies of typically developing children (Chern, Tillmann, Vaughan, & Gordon, 2018) and a variety of clinical populations including congenitally deaf children with cochlear implants (Bedoin et al., 2018), children with specific language impairments (Bedoin et al., 2016), and children with dyslexia (Przybylski et al., 2013). Others have assessed the use of musical training as an intervention to increase aspects of reading ability including phonological processing. For example, 8-year-old children were given 6 months of weekly group music or painting classes. Those in the music group showed better performance on an age-corrected reading task (Moreno et al., 2009). Dégé and Schwarzer (2011) found that kindergarten-aged children showed improvements in phonological awareness (rhyme detection, syllable segmentation) after 5 months of daily, 10-minute music lessons compared to sports. Similarly, phonological processing improved in 3- to 6-year-olds after 8 months of group lessons in a music conservatory's Early Childhood Education program (Hutchins, 2018).

Others have investigated transfer effects within community-based music programs (Barbaroux et al., 2019; Slater et al., 2015). Such programs are offered free of cost, and were developed to improve civic engagement and social-cognitive skills in children of low SES, who may be at risk of lower educational or occupational attainment (Lee & Burkam, 2002). One group followed 8-year-old children for a year of either musical training in the school-based Harmony Project in Los Angeles, or a waitlist. Children in the music group showed enhanced perception of speech in noise, an important factor in everyday communication (Slater et al., 2015). Another group assessed children aged 7-12 years, before and after 18 months of weekly group music lessons offered by the Paris Philharmonic Orchestra. Children's scores on age-normed tests of reading abilities improved, as did their scores on a musical task, showing evidence for both near- and far-transfer effects (Barbaroux et al., 2019). These studies have less experimental control, likely due in part to the practical and ethical limitations mentioned above. Nevertheless, they demonstrate the importance of addressing issues of accessibility and generalizability of scholarly research on the potential benefits of musical training.

Transfer from music to language is likely based on common brain networks, including the dorsal and ventral auditory processing streams (Rauschecker & Scott, 2009). Multiple features of both music and speech are processed along these pathways, with music being more right lateralized and speech left lateralized (Zatorre & Zarate, 2012). The dorsal and ventral auditory processing pathways originate in the posterior and anterior primary auditory cortex, respectively, and arrive at different targets in the frontal lobes. Along the dorsal pathway, features of sound are converted to motor representations, linking sound to action (Rauschecker & Scott, 2009). This pathway would be recruited during speech production or while strumming a guitar, although it also contributes to perception. Along the ventral pathway, features of sound are extracted and parsed hierarchically, allowing for auditory object identification and higher-level organization (Rauschecker & Scott, 2009). This pathway links sound to meaning, as in understanding both the words and grammar of a sentence or musical phrase.

In sum, there is compelling evidence of far-transfer effects, whereby musical training can enhance specific aspects of language including phonological awareness and grammar processing. This likely reflects a combination of common neural processing pathways and similar developmental trajectories. There is also evidence for sensitive period effects in both language and music, and the degree of transfer may depend on the AoS of experience. Researchers interested in far transfer use a variety of cross-sectional, experimental and longitudinal study designs. Our tasks could be used in the context of such studies to examine changes in musical abilities and their associations with measures of language or cognitive ability, while accounting for maturation with age-equivalent scores.

Given the requisite conditions for carrying out rigorous longitudinal research, studying the long-term effects of musical training in childhood can be a challenge for any single laboratory. Therefore, a secondary goal of this thesis was to expand the reach of our tasks by sharing them freely with the scientific community. Indeed, as of this writing we have shared our tasks with seven different groups conducting research in both basic science and applied clinical settings. One group has used the c-RST as a covariate in a rhythmic reading intervention study for children with dyslexia (A. Cancer, 2018, personal communication). Another is using both the c-RST and c-MDT within a battery of pre- and post-training measures for a 6-month music intervention aimed at improving word learning (N. Ramos-Escobar, 2018, personal communication). Yet another used the c-RST in conjunction with MRI to investigate the behavioural and neurostructural outcomes of a 6-month intervention comparing music, sports, and no training in late childhood (P. Cantou, 2018, personal communication). The c-RST has also been shared with researchers who work with typically developing school-aged children (S. Hennessy, 2019, personal communication), young children with autism spectrum disorder (C. Bowsher-Murray, 2019, personal communication), young children with specific language impairments (R. Pfeiffer, 2016, personal communication) and school-aged children with dyslexia (J. Zuk, 2019, personal communication). Final results have not yet been published but it is our hope that in comparing task performance across a variety of samples, the community can use this information to decide upon the most suitable applications. A final extension of this project is to develop a user manual. This will include a description of the underlying conceptual framework, test design, psychometrics, and norms. Authorized users of these tasks will have access to the manual, which will be linked to a shared data repository for continuous updating of psychometric properties.

Considerations for Future Research

Musical Tasks. Our two musical tasks, though useful to address our research questions, do not assess the full spectrum of musical behaviours. They were selected because they had previously been found to be sensitive enough to detect differences between adult ET and LT musicians, and we wanted to be able to compare the outcomes of our work in children to those in adults. Unfortunately, at that time we did not consider creating an entire battery that would cover a wider range of musical abilities. As described in this thesis, the two tasks differ greatly in the degree of basic sensory, motor, and cognitive resources required. The c-RST is a rhythmic production task while the c-MDT is a pitch perception task. A comprehensive battery of musical abilities should, then, contain tasks assessing the complementary abilities of pitch production (e.g., singing or tone-matching; Hutchins, 2018) and rhythm perception (e.g., discrimination; Gordon et al., 2015b). Cultural factors should also be considered, as these can affect both pitch discrimination ability (Wong et al., 2012) and synchronization ability (Cameron, Bentley, & Grahn, 2015). As with language, children readily acquire the musical features (e.g., pitches, timbres, and rhythms) to which they are exposed most regularly (Hannon et al., 2018); those who grew up hearing more complexity in pitch or rhythms may thus show ceiling effects on our tasks. The stimuli are based on a Western major tonal system and use Western rhythms; thus, they would need to be tested in a cross-cultural context.

Musicianship. Another consideration for future research into sensitive periods is more accurately operationalizing the term 'musicianship' in terms of frequency, intensity, and nature of musical activities in childhood (Zhang, Susino, McPherson, & Schubert, 2018). Standard measures in adulthood are years of experience, or cumulative hours of lifetime experience, years of formal training and hours of weekly practice. Children by definition cannot accrue the amount of training often reported in studies of adult musicians, and their lessons and time of practice may be more erratic. This necessitates a more fine-grained tracking of the frequency and intensity of musical activities, and perhaps also an expansion of the activities that are included beyond formal training. For instance, many children do not attend private music lessons, but are given group lessons at school. Still others do not have music lessons in school, but participate in other rhythmic or musical activities such as dance lessons. It is proposed that multimodal training, which engages the motor system in addition to sensory processes, has greater potential to promote neuroplasticity than training in a single modality (Dalla Bella, 2015). However, even informal exposure to music at home, via parents and family members, is associated with enhanced auditory processing (Putkinen, Tervaniemi, & Huotilainen, 2013). Therefore, more precise measurement of the 'dosage' of musical exposure received in childhood could be helpful in understanding the effects of engagement with music, instrumental or otherwise. Beyond the dose, another important consideration in tracking of musicianship is the type, or pedagogical approach, of any training the child is receiving. Child musicians in our study were students of the Suzuki method, which has a standardized curriculum and is often used in music cognition studies (Fujioka et al., 2006; Shahin et al., 2004; Wiens & Gordon, 2018). Suzuki training emphasizes learning by ear and starting early in life, often in the preschool years. With simple pitch discrimination also developing prior to age 5, Suzuki training may differentially enhance this ability. Similarly, rhythm-based approaches to music pedagogy such as Dalcroze Eurhythmics, might enhance rhythmic skills during periods of higher plasticity in auditory-motor networks. Both the c-RST and c-MDT could be used to compare performance across methodologies, given the diversity of auditory, motor, and cognitive processes that are recruited by these tasks.

General Conclusion

Previous work has proposed possible sensitive periods for musical training, such that starting musical training in childhood predicts better learning and performance on complex musical tasks in adult musicians. The goal of this thesis was to assess whether sensitive period effects could be observed in a sample of early- and late-trained children matched for years of experience and other relevant cognitive factors. To do this we developed, validated, and normed two tests of musical ability for pitch discrimination and rhythm synchronization. Because these are among the very few tests of musical ability with up-to-date age norms for children, they are already being used by a number of different researchers studying both near- and far-transfer effects of musical training in childhood. The development of these tasks allowed us to compare ET and LT children and to identify evidence that early start of training produces effects on basic pitch discrimination, but not rhythm processing after 3 years of practice. Because the effect of AoS was only observed for simple pitch discrimination, and not rhythm synchronization as had been observed in adult musicians, we hypothesize that, while there may be metaplastic changes induced by early training, these are not observable for more complex tasks until children are older and have accrued more musical training. These findings enrich our understanding of how AoS can impact the interaction between maturation and experience, giving us a more sophisticated model of sensitive periods in human development.

References

Abdul-Kareem, I. A., Stancak, A., Parkes, L. M., Al-Ameen, M., AlGhamdi, J., Aldhafeeri, F. M., … Sluming, V. (2011). Plasticity of the Superior and Middle Cerebellar Peduncles in Musicians Revealed by Quantitative Analysis of Volume and Number of Streamlines Based on Diffusion Tensor Tractography. *The Cerebellum*, *10*(3), 611. https://doi.org/10.1007/s12311-011-0274-1

Abraham, W. C. (2008). Metaplasticity: tuning synapses and networks for plasticity. *Nature Reviews. Neuroscience*, *9*(5), 387. https://doi.org/10.1038/nrn2356

Altenmueller, E., & Furuya, S. (2016). Brain Plasticity and the Concept of Metaplasticity in Skilled Musicians. In J. Laczko & M. L. Latash (Eds.), *Progress in Motor Control: Theories and Translations* (pp. 197–208). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-47313-0_11

Altenmueller, E., & McPherson, G. (2008). Motor learning and instrumental training. *Neurosciences in Music Pedagogy*, *5*, 121–143.

Amunts, K., Schlaug, G., Jäncke, L., Steinmetz, H., Schleicher, A., Dabringhaus, A., & Zilles, K. (1997). Motor cortex and hand motor skills: Structural compliance in the human brain. *Human Brain Mapping*, *5*(3), 206–215. https://doi.org/10.1002/(SICI)1097-0193(1997)5:3<206::AID-HBM5>3.0.CO;2-7

Aschersleben, G. (2002). Temporal Control of Movements in Sensorimotor Synchronization. *Brain and Cognition*, *48*(1), 66–79. https://doi.org/10.1006/brcg.2001.1304

Baer, L. H., Park, M. T., Bailey, J. A., Chakravarty, M. M., Li, K. Z., & Penhune, V. B. (2015). Regional cerebellar volumes are related to early musical training and finger tapping performance. *NeuroImage*, *109*, 130–139. https://doi.org/10.1016/j.neuroimage.2014.12.076 [doi]

Bailey, J. A., & Penhune, V. B. (2010). Rhythm synchronization performance and auditory working memory in early- and late-trained musicians. *Experimental Brain Research*, *204*(1), 91–101. https://doi.org/10.1007/s00221-010-2299-y

Bailey, J. A., Zatorre, R. J., & Penhune, V. B. (2014). Early musical training is linked to gray matter structure in the ventral premotor cortex and auditory-motor rhythm synchronization performance. *Journal of Cognitive Neuroscience*, *26*(4), 755–767. https://doi.org/10.1162/jocn_a_00527

Bailey, J., & Penhune, V. (2013). The relationship between the age of onset of musical training and rhythm synchronization performance: validation of sensitive period effects. *Frontiers in Neuroscience*, *7*, 227. Retrieved from http://journal.frontiersin.org/article/10.3389/fnins.2013.00227

Bailey, J., & Penhune, V. B. (2012). A sensitive period for musical training: Contributions of age of onset and cognitive abilities. *Annals of the New York Academy of Sciences*, *1252*(1), 163–170. https://doi.org/10.1111/j.1749-6632.2011.06434.x

Balasubramaniam, R., Wing, A. M., & Daffertshofer, A. (2004). Keeping with the beat: Movement trajectories contribute to movement timing. *Experimental Brain Research*, *159*(1), 129–134. https://doi.org/10.1007/s00221-004-2066-z

Barbaroux, M., Dittinger, E., & Besson, M. (2019). Music training with Démos program positively influences cognitive functions in children from low socio-economic backgrounds. *PLOS ONE*, *14*(5), e0216874. Retrieved from https://doi.org/10.1371/journal.pone.0216874

Barros, C. G., Swardfager, W., Moreno, S., Bortz, G., Ilari, B., Jackowski, A. P., … Cogo-Moreira, H. (2017). Assessing music perception in young children: Evidence for and psychometric features of the M-factor. *Frontiers in Neuroscience*, *11*(JAN), 1–14. https://doi.org/10.3389/fnins.2017.00018

Bedoin, N, Besombes, A.-M., Escande, E., Dumont, A., Lalitte, P., & Tillmann, B. (2018). Boosting syntax training with temporally regular musical primes in children with cochlear implants. *Annals of Physical and Rehabilitation Medicine*, *61*(6), 365–371. https://doi.org/https://doi.org/10.1016/j.rehab.2017.03.004

Bedoin, Nathalie, Brisseau, L., Molinier, P., Roch, D., & Tillmann, B. (2016). Temporally Regular Musical Primes Facilitate Subsequent Syntax Processing in Children with Specific Language Impairment . *Frontiers in Neuroscience* . Retrieved from https://www.frontiersin.org/article/10.3389/fnins.2016.00245

Bella, S. D. (2015). Oxford Handbooks Online Music and Brain Plasticity, (February), 1–16. https://doi.org/10.1093/oxfordhb/9780198722946.013.23

Bengtsson, S. L., Nagy, Z., Skare, S., Forsman, L., Forssberg, H., & Ullén, F. (2005). Extensive piano practicing has regionally specific effects on white matter development. *Nature Neuroscience*, *8*(9), 1148.

Bergman Nutley, S., Darki, F., & Klingberg, T. (2014). Music practice is associated with development of working memory during childhood and adolescence. *Frontiers in Human Neuroscience*, *7*, 926.

Berken, J. A., Gracco, V. L., Chen, J.-K., & Klein, D. (2016). The timing of language learning shapes brain structure associated with articulation. *Brain Structure and Function*, *221*(7), 3591–3600.

Besson, M., Schön, D., Moreno, S., Santos, A., & Magne, C. (2007). Influence of musical expertise and musical training on pitch processing in music and language. *Restorative Neurology and Neuroscience*, *25*(3–4), 399–410.

Brody, N. (1992). *Intelligence* (2nd ed.). San Diego: Academic Press.

Cameron, D. J., Bentley, J., & Grahn, J. A. (2015). Cross-cultural influences on rhythm processing: Reproduction, discrimination, and beat tapping. *Frontiers in Psychology*, *6*(MAR), 1–11. https://doi.org/10.3389/fpsyg.2015.00366

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008). Moving on time: Brain network for auditory-motor synchronization is modulated by rhythm complexity and musical training. *Journal of Cognitive Neuroscience*, *20*(2), 226–239. https://doi.org/10.1162/jocn.2008.20018

Chern, A., Tillmann, B., Vaughan, C., & Gordon, R. L. (2018). New evidence of a rhythmic priming effect that enhances grammaticality judgments in children. *Journal of Experimental Child Psychology*, *173*, 371–379. https://doi.org/10.1016/j.jecp.2018.04.007

Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (1983). Applied multiple regression for the behavioral sciences. *Laurence Erlbaum, Hillsdale, NJ*.

Cohen, R. A. (2014). *The Neuropsychology of Attention*. *The Neuropsychology of Attention*. https://doi.org/10.1007/978-0-387-72639-7

Corrigall, K. a., & Schellenberg, E. G. (2015). Predicting who takes music lessons: parent and child characteristics. *Frontiers in Psychology*, *6*, 1–8. https://doi.org/10.3389/fpsyg.2015.00282

Corrigall, K. A., & Schellenberg, E. G. (2015). Music cognition in childhood. In *The child as musician: A handbook of musical development* (pp. 1–27).

Corrigall, K. A., & Schellenberg, G. E. (2016). Music cognition in childhood. *The Child as Musician: A Handbook of Musical Development*, 81–101.

Corriveau, K. H., & Goswami, U. (2009). Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat. *Cortex*, *45*(1), 119–130. https://doi.org/10.1016/j.cortex.2007.09.008

Costa-Giomi, E. (1999a). Young children's harmonic perception. *Annals of the New York Academy of Sciences*, *999*(1), 477–484.

Costa-Giomi, E. (1999b). Young children's harmonic perception. In G. Avanzini, C. Faienza, D. Minciacchi, L. Lopez, & M. Majno (Eds.), *The neurosciences and music: Annals of the New York Academy of Sciences* (p. Vol. 999, 477-484). New York: New York Academy of Sciences.

Dalla Bella, S., Farrugia, N., Benoit, C.-E., Begel, V., Verga, L., Harding, E., & Kotz, S. A. (2017). BAASTA: Battery for the Assessment of Auditory Sensorimotor and Timing Abilities. *Behavior Research Methods*, *49*(3), 1128–1145. https://doi.org/10.3758/s13428-016-0773-6

Degé, F., & Schwarzer, G. (2011). The effect of a music program on phonological awareness in preschoolers. *Frontiers in Psychology*, *2*(JUN). https://doi.org/10.3389/fpsyg.2011.00124

Desrochers, A., Comeau, G., Jardaneh, N., & Green-Demers, I. (2006). L'élaboration d'une échelle pour mesurer la motivation chez les jeunes élèves en piano. *Revue de Recherche En Éducation Musicale*, *24*, 13–33.

Dowling, W. J., & Fujitani, D. S. (1971). Contour, Interval, and Pitch Recognition in Memory for Melodies. *The Journal of the Acoustical Society of America*, *49*(2B), 524–531. https://doi.org/10.1121/1.1912382

Draganova, R., Eswaran, H., Murphy, P., Lowery, C., & Preissl, H. (2007). Serial magnetoencephalographic study of fetal and newborn auditory discriminative evoked responses. *Early Human Development*, *83*(3), 199–207. https://doi.org/https://doi.org/10.1016/j.earlhumdev.2006.05.018

Drake, C. (1993). Reproduction of musical rhythms by children, adult musicians, and adult nonmusicians. *Perception & Psychophysics*, *53*(1), 25–33. https://doi.org/10.3758/BF03211712

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. https://doi.org/10.1016/S0010-0277(00)00106-2

Drewing, K., Aschersleben, G., & Li, S.-C. (2006). Sensorimotor synchronization across the life span. *International Journal of Behavioral Development*, *30*(3), 280–287. https://doi.org/10.1177/0165025406066764

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., & Taub, E. (1995). Increased Cortical Representation of the Fingers of the Left Hand in String Players. *Science*, *270*(5234), 305–307. Retrieved from http://www.jstor.org/stable/2888544

Flege, J. E. (1991). Age of learning affects the authenticity of voice-onset time (VOT) in stop consonants produced in a second language. *The Journal of the Acoustical Society of America*, *89*(1), 395–411. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/2002177

Flege, J. E., Munro, M. J., & MacKay, I. R. (1995). Factors affecting strength of perceived foreign accent in a second language. *The Journal of the Acoustical Society of America*, *97*(5 Pt 1), 3125–3134. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/7759652

Foster, N. E. V, Halpern, A. R., & Zatorre, R. J. (2013). Common parietal activation in musical mental transformations across pitch and time. *NeuroImage*, *75*, 27–35. https://doi.org/10.1016/j.neuroimage.2013.02.044

Foster, N. E. V, & Zatorre, R. J. (2010a). A role for the intraparietal sulcus in transforming musical pitch information. *Cerebral Cortex*, *20*(6), 1350–1359. https://doi.org/10.1093/cercor/bhp199

Foster, N. E. V, & Zatorre, R. J. (2010b). Cortical structure predicts success in performing musical transformation judgments. *NeuroImage*, *53*(1), 26–36. https://doi.org/10.1016/j.neuroimage.2010.06.042

Fujioka, T., Ross, B., Kakigi, R., Pantev, C., & Trainor, L. J. (2006). One year of musical training affects development of auditory cortical-evoked fields in young children. *Brain*, *129*(10), 2593–2608. https://doi.org/10.1093/brain/awl247

Galván, A. (2010). Neural plasticity of development and learning. *Human Brain Mapping*, *31*(6), 879–890. https://doi.org/10.1002/hbm.21029

Gerber, R. J., Wilks, T., Erdie-lalena, C., Gerber, R. J., & Wilks, T. (2010). Developmental Milestones : Motor Development. https://doi.org/10.1542/pir.31-7-267

Glenn Schellenberg, E., & Winner, E. (2011). Music Training and Nonmusical Abilities: Introduction. *Music Perception: An Interdisciplinary Journal*, *29*(2), 129–132. https://doi.org/10.1525/mp.2011.29.2.129

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., …

Thompson, P. M. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences*, *101*(21), 8174–8179. https://doi.org/10.1073/pnas.0402680101

Gordon, E. E. (1979). Developmental music aptitude as measured by the Primary Measures of Music Audiation. *Psychology of Music*, *7*(1), 42–49. https://doi.org/10.1177/030573567971005

Gordon, E. E. (1986). A factor analysis of the Musical Aptitude Profile, the Primary Measures of Music Audiation, and the Intermediate Measures of Music Audiation. *Bulletin of the Council for Research in Music Education*, *87*, 17–25.

Gordon, R. L., Fehd, H. M., & McCandliss, B. D. (2015). Does music training enhance literacy skills? A meta-analysis. *Frontiers in Psychology*, *6*(DEC), 1–16. https://doi.org/10.3389/fpsyg.2015.01777

Gordon, R. L., Jacobs, M. S., Schuele, C. M., & Mcauley, J. D. (2016). Perspectives on the rhythm–grammar link and its implications for typical and atypical language development. *Annals of the New York Academy of Sciences*, *1337*, 16–25. https://doi.org/10.1111/nyas.12683.Perspectives

Gordon, R. L., Shivers, C. M., Wieland, E. A., Kotz, S. A., Yoder, P. J., & Devin McAuley, J. (2015a). Musical rhythm discrimination explains individual differences in grammar skills in children. *Developmental Science*, *18*(4), 635–644. https://doi.org/10.1111/desc.12230

Gordon, R. L., Shivers, C. M., Wieland, E. A., Kotz, S. A., Yoder, P. J., & Devin McAuley, J. (2015b). Musical rhythm discrimination explains individual differences in grammar skills in children. *Developmental Science*, *18*(4), 635–644. https://doi.org/10.1111/desc.12230

Group, B. D. C. (2011). Total and regional brain volumes in a population-based normative sample from 4 to 18 years: the NIH MRI Study of Normal Brain Development. *Cerebral Cortex*, *22*(1), 1–12.

Habibi, A., Cahn, B. R., Damasio, A., & Damasio, H. (2016). Neural correlates of accelerated auditory processing in children engaged in music training. *Developmental Cognitive Neuroscience*, *21*, 1–14. https://doi.org/10.1016/j.dcn.2016.04.003

Habibi, A., Damasio, A., Ilari, B., Sachs, M. E., & Damasio, H. (2018). Music training and child development: A review of recent findings from a longitudinal study. *Annals of the New York Academy of Sciences*, *1423*(1), 73–81. https://doi.org/10.1111/nyas.13606

Habibi, A., Damasio, A., Ilari, B., Veiga, R., Joshi, A. A., Leahy, R. M., … Damasio, H. (2017). Childhood Music Training Induces Change in Micro and Macroscopic Brain Structure: Results from a Longitudinal Study. *Cerebral Cortex*, 1–12. Retrieved from http://dx.doi.org/10.1093/cercor/bhx286

Habibi, A., Damasio, A., Ilari, B., Veiga, R., Joshi, A. A., Leahy, R. M., … Damasio, H. (2018). Childhood Music Training Induces Change in Micro and Macroscopic Brain Structure : Results from a Longitudinal Study, (March), 1–12. https://doi.org/10.1093/cercor/bhx286

Habibi, A., Ilari, B., Crimi, K., Metke, M., Kaplan, J. T., Joshi, A. A., … Damasio, H. (2014). An equal start : absence of group differences in cognitive , social , and neural measures prior to music or sports training in children, *8*(September), 1–11. https://doi.org/10.3389/fnhum.2014.00690

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. https://doi.org/10.1016/j.cogpsych.2004.09.003

Hannon, E. E., Nave-Blodgett, J. E., & Nave, K. M. (2018). The Developmental Origins of the Perception and Production of Musical Rhythm. *Child Development Perspectives*.

Hannon, E. E., & Trehub, S. E. (2005). Metrical Categories in Infancy and Adulthood. *Psychological Science*, *16*(1), 48–55. https://doi.org/10.1111/j.0956-7976.2005.00779.x

Harrison, P. M. C., Collins, T., & Müllensiefen, D. (2017). Applying modern psychometric techniques to melodic discrimination testing: Item response theory, computerised adaptive testing, and automatic item generation. *Scientific Reports*, *7*(1), 3618. https://doi.org/10.1038/s41598-017-03586-z

Hebb, D. O. (1949). *The organization of behavior; a neuropsychological theory. The organization of behavior; a neuropsychological theory.* Oxford, England: Wiley.

Herholz, S. C., & Zatorre, R. J. (2012). Musical Training as a Framework for Brain Plasticity: Behavior, Function, and Structure. *Neuron*, *76*(3), 486–502. https://doi.org/10.1016/j.neuron.2012.10.011

Honing, H., ten Cate, C., Peretz, I., & Trehub, S. E. (2015). Without it no music: cognition, biology and evolution of musicality. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *370*(1664), 20140088. https://doi.org/10.1098/rstb.2014.0088

Hudziak, J. J., Albaugh, M. D., Ducharme, S., Karama, S., Spottswood, M., Crehan, E., … Botteron, K. N. (2014). Cortical Thickness Maturation and Duration of Music Training: Health-Promoting Activities Shape Brain Development. *Journal of the American Academy of Child & Adolescent Psychiatry*, *53*(11), 1153-1161.e2. https://doi.org/https://doi.org/10.1016/j.jaac.2014.06.015

Hutchins, S. (2018). Early Childhood Music Training and Associated Improvements in Music and Language Abilities. *Music Perception: An Interdisciplinary Journal*, *35*(5), 579–593. https://doi.org/10.1525/mp.2018.35.5.579

Hyde, K. L., Lerch, J., Norton, A., Forgeard, M., Winner, E., Evans, A. C., & Schlaug, G. (2009a). Musical Training Shapes Structural Brain Development. *Journal of Neuroscience*, *29*(10), 3019–3025. https://doi.org/10.1523/JNEUROSCI.5118-08.2009

Hyde, K. L., Lerch, J., Norton, A., Forgeard, M., Winner, E., Evans, A. C., & Schlaug, G. (2009b). The effects of musical training on structural brain development: a longitudinal study. *Annals of the New York Academy of Sciences*, *1169*, 182–186. https://doi.org/10.1111/j.1749-6632.2009.04852.x [doi]

Ilari, B. S., Keller, P., Damasio, H., & Habibi, A. (2016). The Development of Musical Skills of Underprivileged Children Over the Course of 1 Year: A Study in the Context of an El Sistema-Inspired Program. *Frontiers in Psychology*, *7*, 62. https://doi.org/10.3389/fpsyg.2016.00062

Ireland, K., Iyer, T. A., & Penhune, V. B. (2019). Contributions of age of start, cognitive abilities and practice to musical task performance in childhood. *PLOS ONE*, *14*(4), e0216119. Retrieved from https://doi.org/10.1371/journal.pone.0216119

Ireland, K., Parker, A., Foster, N., & Penhune, V. (2018). Rhythm and Melody Tasks for School-Aged Children With and Without Musical Training: Age-Equivalent Scores and Reliability . *Frontiers in Psychology* . Retrieved from https://www.frontiersin.org/article/10.3389/fpsyg.2018.00426

Ismail, F. Y., Fatemi, A., & Johnston, M. V. (2017). Cerebral plasticity: Windows of opportunity in the developing brain. *European Journal of Paediatric Neurology*, *21*(1), 23–48. https://doi.org/10.1016/j.ejpn.2016.07.007

Iversen, J. R., Patel, A. D., & Ohgushi, K. (2004). Perception of nonlinguistic rhythmic stimuli by American and Japanese listeners. In *Proceedings of the International Congress of*

Acoustics, Kyoto.

James, C. E., Oechslin, M. S., Van De Ville, D., Hauert, C.-A., Descloux, C., & Lazeyras, F. (2014). Musical training intensity yields opposite effects on grey matter density in cognitive versus sensorimotor networks. *Brain Structure & Function*, *219*(1), 353–366. https://doi.org/10.1007/s00429-013-0504-z

Karpati, F. J., Giacosa, C., Foster, N. E. V, Penhune, V. B., & Hyde, K. L. (2016). Sensorimotor integration is enhanced in dancers and musicians. *Experimental Brain Research*, *234*(3), 893–903. https://doi.org/10.1007/s00221-015-4524-1

Klein, D., Mok, K., Chen, J.-K., & Watkins, K. E. (2014). Age of language learning shapes brain structure: A cortical thickness study of bilingual and monolingual individuals. *Brain and Language*, *131*, 20–24. https://doi.org/https://doi.org/10.1016/j.bandl.2013.05.014

Kline, R. B. (2011). *Principles and Practice of Structural Equation Modeling* (3rd ed.). New York.

Kline, Rex B. (2004). *Beyond significance testing: Reforming data analysis methods in behavioral research. Beyond significance testing: Reforming data analysis methods in behavioral research.* Washington, DC, US: American Psychological Association. https://doi.org/10.1037/10693-000

Kline, Rex B. (2008). *Becoming a behavioral science researcher: A guide to producing research that matters*. Guilford Press.

Knudsen, E. I. (1998). Capacity for Plasticity in the Adult Owl Auditory System Expanded by Juvenile Experience. *Science*, *279*(5356), 1531 LP – 1533. https://doi.org/10.1126/science.279.5356.1531

Knudsen, E. I. (2004). Sensitive Periods in the Development of the Brain and Behavior, 1412–1425.

Kovacs, K., & Conway, A. R. A. (2016). Process Overlap Theory: A Unified Account of the General Factor of Intelligence. *Psychological Inquiry*, *27*(3), 151–177. https://doi.org/10.1080/1047840X.2016.1153946

Kral, A., & Eggermont, J. J. (2007). What's to lose and what's to learn: Development under auditory deprivation, cochlear implants and limits of cortical plasticity. *Brain Research Reviews*, *56*(1), 259–269. https://doi.org/https://doi.org/10.1016/j.brainresrev.2007.07.021

Law, L. N. C., & Zentner, M. (2012). Assessing Musical Abilities Objectively: Construction and

Validation of the Profile of Music Perception Skills. *PLoS ONE*, *7*(12). https://doi.org/10.1371/journal.pone.0052508

Lecanuet, J. P., Graniere-Deferre, C., Jacquet, A.-Y., & DeCasper, A. J. (2000). Fetal discrimination of low-pitched musical notes. *Developmental Psychobiology*, *36*(1), 29–39. https://doi.org/10.1002/(SICI)1098-2302(200001)36:1<29::AID-DEV4>3.0.CO;2-J

Lee, V. E., & Burkam, D. T. (2002). *Inequality at the starting gate: Social background differences in achievement as children begin school.* ERIC.

Lynch, M. P., Eilers, R. E., Oller, D. K., & Urbano, R. C. (1990a). Innateness, experience, and music perception. *Psychological Science*, *1*(4), 272–276. https://doi.org/10.1111/j.1467-9280.1990.tb00213.x

Lynch, M. P., Eilers, R. E., Oller, D. K., & Urbano, R. C. (1990b). Innateness, Experience, and Music Perception. *Psychological Science*, *1*(4), 272–276. https://doi.org/10.1111/j.1467-9280.1990.tb00213.x

Manturzewska, M. (1990). A Biographical Study of the Life-Span Development of Professional Musicians. *Psychology of Music*, *18*(2), 112–139. https://doi.org/10.1177/0305735690182002

Maróti, E., Honbolygó, F., & Weiss, B. (2019). Neural entrainment to the beat in multiple frequency bands in 6–7-year-old children. *International Journal of Psychophysiology*, *141*, 45–55. https://doi.org/https://doi.org/10.1016/j.ijpsycho.2019.05.005

Matthews, T. E., Thibodeau, J. N. L., Gunther, B. P., & Penhune, V. B. (2016). The Impact of Instrument-Specific Musical Training on Rhythm Perception and Production. *Frontiers in Psychology*, *7*(February), 69. https://doi.org/10.3389/fpsyg.2016.00069

McDermott, J. H., Keebler, M. V, Micheyl, C., & Oxenham, A. J. (2010). Musical intervals and relative pitch: Frequency resolution, not interval resolution, is special. *The Journal of the Acoustical Society of America*, *128*(4), 1943–1951.

Meng, X., Rosenthal, R., & Rubin, D. B. (1992). Comparing correlated correlation coefficients. *Psychological Bulletin*, *111*(1), 172–175. https://doi.org/10.1037/0033-2909.111.1.172

Meyer, M., Elmer, S., Ringli, M., Oechslin, M. S., Baumann, S., & Jancke, L. (2011). Long-term exposure to music enhances the sensitivity of the auditory system in children. *European Journal of Neuroscience*, *34*(5), 755–765. https://doi.org/10.1111/j.1460-9568.2011.07795.x

Monier, F., & Droit-Volet, S. (2019). Development of sensorimotor synchronization abilities: Motor and cognitive components. *Child Neuropsychology*, 1–20. https://doi.org/10.1080/09297049.2019.1569607

Moore, J. K. (2002). Maturation of human auditory cortex: implications for speech perception. *Annals of Otology, Rhinology & Laryngology*, *111*(5_suppl), 7–10.

Moore, J. K., & Guan, Y.-L. (2001). Cytoarchitectural and axonal maturation in human auditory cortex. *Journal of the Association for Research in Otolaryngology*, *2*(4), 297–311.

Moore, J. K., & Linthicum Jr, F. H. (2007). The human auditory system: a timeline of development. *International Journal of Audiology*, *46*(9), 460–478.

Moreno, S., & Besson, M. (2006). Musical training and language-related brain electrical activity in children. *Psychophysiology*, *43*(3), 287–291. https://doi.org/10.1111/j.1469-8986.2006.00401.x

Moreno, S., & Bidelman, G. M. (2014). Examining neural plasticity and cognitive benefit through the unique lens of musical training. *Hearing Research*, *308*, 84–97. https://doi.org/10.1016/j.heares.2013.09.012

Moreno, S., Friesen, D., & Bialystok, E. (2011a). Effect of Music Training on Promoting Preliteracy Skills: Preliminary Causal Evidence. *Music Perception: An Interdisciplinary Journal*, *29*(2), 165–172. https://doi.org/10.1525/mp.2011.29.2.165

Moreno, S., Friesen, D., & Bialystok, E. (2011b). Effect of Music Training on Promoting Preliteracy Skills: Preliminary Causal Evidence. *Music Perception: An Interdisciplinary Journal*, *29*(2), 165–172. https://doi.org/10.1525/mp.2011.29.2.165

Moreno, S., Marques, C., Santos, A., Santos, M., Castro, S. L., & Besson, M. (2009). Musical Training Influences Linguistic Abilities in 8-Year-Old Children: More Evidence for Brain Plasticity. *Cerebral Cortex*, *19*(3), 712–723. Retrieved from http://dx.doi.org/10.1093/cercor/bhn120

Moritz, C., Yampolsky, S., Papadelis, G., Thomson, J., & Wolf, M. (2013). Links between early rhythm skills, musical training, and phonological awareness. *Reading and Writing*, *26*(5), 739–769. https://doi.org/10.1007/s11145-012-9389-0

Nettelbeck, T., & Wilson, C. (2004). The Flynn effect: Smarter not faster. *Intelligence*, *32*(1), 85–93. https://doi.org/10.1016/S0160-2896(03)00060-6

Nicholas, J. G., & Geers, A. E. (2007). Will they catch up? The role of age at cochlear implantation in the spoken language development of children with severe to profound hearing loss. *Journal of Speech, Language, and Hearing Research : JSLHR*, *50*(4), 1048–1062. https://doi.org/10.1044/1092-4388(2007/073)

Pantev, C., Oostenveld, R., Engelien, A., Ross, B., Roberts, L. E., & Hoke, M. (1998). Increased auditory cortical representation in musicians. *Nature*, *392*(6678), 811.

Patel, A. D. (2011). Why would Musical Training Benefit the Neural Encoding of Speech? The OPERA Hypothesis. *Frontiers in Psychology*, *2*, 142. https://doi.org/10.3389/fpsyg.2011.00142

Patel, A. D. (2012). The OPERA hypothesis: Assumptions and clarifications. *Annals of the New York Academy of Sciences*, *1252*(1), 124–128. https://doi.org/10.1111/j.1749-6632.2011.06426.x

Penhune, V. B. (2011). Sensitive periods in human development: Evidence from musical training. *Cortex*, *47*(9), 1126–1137. https://doi.org/10.1016/j.cortex.2011.05.010

Penhune, V. B. (2019). Musical Expertise and Brain Structure: The Causes and Consequences of Training. In *The Oxford Handbook of Music and the Brain*.

Perani, D., Saccuman, M. C., Scifo, P., Spada, D., Andreolli, G., Rovelli, R., … Koelsch, S. (2010). Functional specializations for music processing in the human newborn brain. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(10), 4758–4763. https://doi.org/10.1073/pnas.0909074107

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*.

Plantinga, J., & Trainor, L. J. (2005). Memory for melody: Infants use a relative pitch code. *Cognition*, *98*(1), 1–11. https://doi.org/10.1016/j.cognition.2004.09.008

Plantinga, J., & Trainor, L. J. (2009). Melody recognition by two-month-old infants. *The Journal of the Acoustical Society of America*, *125*(2), EL58–EL62. https://doi.org/10.1121/1.3049583

Ponton, C., Eggermont, J. J., Khosla, D., Kwong, B., & Don, M. (2002). Maturation of human central auditory system activity: separating auditory evoked potentials by dipole source modeling. *Clinical Neurophysiology : Official Journal of the International Federation of Clinical Neurophysiology*, *113*(3), 407–420. https://doi.org/10.1016/S1388-2457(01)00733-

7
Przybylski, L., Bedoin, N., Krifi-Papoz, S., Herbillon, V., Roch, D., Léculier, L., … Tillmann, B. (2013). Rhythmic auditory stimulation influences syntactic processing in children with developmental language disorders. *Neuropsychology*. Tillmann, Barbara: Lyon Neuroscience Research Center, CNRS-UMR 5292, INSERM U1028, Universite Lyon 1, Team Auditory Cognition and Psychoacoustics, 50 Av. Tony Garnier, Lyon, France, F-69366, Cedex 07, barbara.tillmann@olfac.univ-lyon1.fr: American Psychological Association. https://doi.org/10.1037/a0031277

Putkinen, V, Tervaniemi, M., & Huotilainen, M. (2013). Informal musical activities are linked to auditory discrimination and attention in 2-3-year-old children: an event-related potential study. *The European Journal of Neuroscience*, *37*(4), 654–661. https://doi.org/10.1111/ejn.12049

Putkinen, Vesa, Tervaniemi, M., Saarikivi, K., Ojala, P., & Huotilainen, M. (2013). Enhanced development of auditory change detection in musically trained school-aged children: A longitudinal event-related potential study. *Developmental Science*, *17*(2), 282–297. https://doi.org/10.1111/desc.12109

Rauschecker, J. P., & Scott, S. K. (2009). Maps and streams in the auditory cortex: nonhuman primates illuminate human speech processing. *Nature Neuroscience*, *12*, 718. Retrieved from https://doi.org/10.1038/nn.2331

Raven, J., Raven, J. C., and Court, J. H. (1998). *Manual for Raven's Progressive Matrices and Vocablary Scales*. Oxford, United Kingdom: Oxford Psychologists Press.

Raznahan, A., Shaw, P. W., Lerch, J. P., Clasen, L. S., Greenstein, D., & Berman, R. (2014). Longitudinal four-dimensional mapping of subcortical anatomy in human development, *111*(4). https://doi.org/10.1073/pnas.1316911111

Repp, B. H. (2010). Sensorimotor synchronization and perception of timing: Effects of music training and task experience. *Human Movement Science*, *29*(2), 200–213. https://doi.org/10.1016/J.HUMOV.2009.08.002

Repp, B. H., & Su, Y.-H. (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic Bulletin & Review*, *20*(3), 403–452. https://doi.org/10.3758/s13423-012-0371-2

Roden, I., Grube, D., Bongard, S., & Kreutz, G. (2014). Does music training enhance working memory performance? Findings from a quasi-experimental longitudinal study. *Psychology of Music*, *42*(2), 284–298. https://doi.org/10.1177/0305735612471239

Roden, I., Könen, T., Bongard, S., Frankenberg, E., Friedrich, E. K., & Kreutz, G. (2014). Effects of Music Training on Attention, Processing Speed and Cognitive Music Abilities — Findings from a Longitudinal Study. *Applied Cognitive Psychology*, *28*(July), 545–557. https://doi.org/10.1002/acp.3034

Salimpoor, V. N., Benovoy, M., Larcher, K., Dagher, A., & Zatorre, R. J. (2011). Anatomically distinct dopamine release during anticipation and experience of peak emotion to music. *Nature Neuroscience*, *14*(2), 257–262. https://doi.org/10.1038/nn.2726

Salimpoor, V. N., Benovoy, M., Longo, G., Cooperstock, J. R., & Zatorre, R. J. (2009). The rewarding aspects of music listening are related to degree of emotional arousal. *PLoS ONE*, *4*(10). https://doi.org/10.1371/journal.pone.0007487

Sallat, Stephan; Jentschke, S. (2015). Music Perception Influences Language Acquisition: Melodic and Rhythmic-Melodic Perception in Children with Specific Language Impairment. *Behavioural Neurology*, *2015*. https://doi.org/10.1155/2015/606470

Savion-Lemieux, T., Bailey, J. A., & Penhune, V. B. (2009). Developmental contributions to motor sequence learning. *Experimental Brain Research*, *195*(2), 293–306. https://doi.org/10.1007/s00221-009-1786-5 [doi]

Schellenberg, E. Glenn. (2004). Music lessons enhance IQ. *Psychological Science*, *15*(8), 511–514. https://doi.org/10.1111/j.0956-7976.2004.00711.x

Schellenberg, E G, Bigand, E., Poulin-Charronnat, B., Garnier, C., & Stevens, C. (2005). Children's implicit knowledge of harmony in western music. *Developmental Science*, *8*(6), 551–566. https://doi.org/10.1111/j.1467-7687.2005.00447.x

Schellenberg, E G, & Weiss, M. W. (2013). Music and cognitive abilities. In D. Deutsch & D. Deutsch (Ed) (Eds.), *The psychology of music.* (pp. 499–550). Schellenberg, E. Glenn, Department of Psychology, University of Toronto at Mississauga, Mississauga, ON, Canada, L5L 1C6: Elsevier Academic Press. https://doi.org/10.1016/B978-0-12-381460-9.00012-2

Schlaug, G., Jancke, L., Huang, Y., Staiger, J. F., & Steinmetz, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia*, *33*(8), 1047–1055.

Seashore, C. E. (1915). The Measurement of Musical Talent Author (s): Carl E . Seashore

Published by : Oxford University Press Stable URL : http://www.jstor.org/stable/738047 Accessed : 08-05-2016 14 : 27 UTC. *The Musical Quarterly*, *1*(1), 129–148.

Seashore, Carl E. (1915). The Measurement of Musical Talent. *The Musical Quarterly*, *1*(1), 129–148.

Shahin, A., Roberts, L. E., & Trainor, L. J. (2004). Enhancement of auditory cortical development by musical experience in children. *NeuroReport*, *15*(12), 1917–1921. https://doi.org/10.1097/00001756-200408260-00017

Skoe, E., & Kraus, N. (2014). Auditory Reserve and the Legacy of Auditory Experience. *Brain Sciences*, *4*(4), 575–593. https://doi.org/10.3390/brainsci4040575

Slater, J., Skoe, E., Strait, D. L., O'Connell, S., Thompson, E., & Kraus, N. (2015). Music training improves speech-in-noise perception: Longitudinal evidence from a community-based music program. *Behavioural Brain Research*, *291*, 244–252. https://doi.org/10.1016/j.bbr.2015.05.026

Slater, J., Strait, D. L., Skoe, E., O'Connell, S., Thompson, E., & Kraus, N. (2014). Longitudinal Effects of Group Music Instruction on Literacy Skills in Low-Income Children. *PLOS ONE*, *9*(11), e113383. Retrieved from https://doi.org/10.1371/journal.pone.0113383

Sluming, V., Barrick, T., Howard, M., Cezayirli, E., Mayes, A., & Roberts, N. (2002). Voxel-based morphometry reveals increased gray matter density in Broca's area in male symphony orchestra musicians. *NeuroImage*, *17*(3), 1613–1622.

Stalinski, S. M., & Schellenberg, E. G. (2010). Shifting perceptions: Developmental changes in judgments of melodic similarity. *Developmental Psychology*. Schellenberg, E. Glenn: Department of Psychology, University of Toronto Mississauga, Mississauga, ON, Canada, L5L 1C6, g.schellenberg@utoronto.ca: American Psychological Association. https://doi.org/10.1037/a0020658

Stalinski, S. M., & Schellenberg, E. G. (2012). Music Cognition: A Developmental Perspective. *Topics in Cognitive Science*, *4*(4), 485–497. https://doi.org/10.1111/j.1756-8765.2012.01217.x

Steele, C. J., Bailey, J. A., Zatorre, R. J., & Penhune, V. B. (2013). Early musical training and white-matter plasticity in the corpus callosum: evidence for a sensitive period. *Journal of Neuroscience*, *33*(3), 1282–1290.

Stevens, C. J. (2012). Music Perception and Cognition : A Review of Recent Cross-Cultural

Research, *4*, 653–667. https://doi.org/10.1111/j.1756-8765.2012.01215.x

Sutherland, M. E., Paus, T., & Zatorre, R. J. (2013). Neuroanatomical correlates of musical transposition in adolescents: A longitudinal approach. *Frontiers in Systems Neuroscience*, *7*. https://doi.org/10.3389/fnsys.2013.00113

Swaminathan, S., & Schellenberg, E. G. (2018). Musical Competence is Predicted by Music Training, Cognitive Abilities, and Personality. *Scientific Reports*, *8*(1), 9223. https://doi.org/10.1038/s41598-018-27571-2

Swaminathan, S., Schellenberg, E. G., & Khalil, S. (2016). Revisiting the association between music lessons and intelligence: Training effects or music aptitude? *Intelligence*, (March). https://doi.org/10.1016/j.intell.2017.03.005

Thompson, E. C., White-Schwoch, T., Tierney, A., & Kraus, N. (2015). Beat synchronization across the lifespan: Intersection of development and musical experience. *PLoS ONE*, *10*(6), 1–13. https://doi.org/10.1371/journal.pone.0128839

Tierney, A., & Kraus, N. (2013). The Ability to Move to a Beat Is Linked to the Consistency of Neural Responses to Sound. *The Journal of Neuroscience*, *33*(38), 14981 LP – 14988. Retrieved from http://www.jneurosci.org/content/33/38/14981.abstract

Tierney, A., & Kraus, N. (2014). Auditory-motor entrainment and phonological skills: precise auditory timing hypothesis (PATH). *Frontiers in Human Neuroscience*, *8*(November), 1–9. https://doi.org/10.3389/fnhum.2014.00949

Trainor, L J, & Trehub, S. E. (1994). Key membership and implied harmony in Western tonal music: developmental perspectives. *Perception & Psychophysics*, *56*(2), 125–132. https://doi.org/10.3758/BF03213891

Trainor, Laurel J. (2005). Are there critical periods for musical development? *Developmental Psychobiology*, *46*(3), 262–278. https://doi.org/10.1002/dev.20059

Trainor, Laurel J, & Corrigal, K. A. (2010). *Music Aquisition and Effects of Musical Experience*. (M. R. Jones, R. R. Fay, & A. N. Popper, Eds.), *Music Perception* (Vol. 36). New York, NY: Spinger New York. https://doi.org/10.1007/978-1-4419-6114-3_4

Trehub, S. E., & Degé, F. (2015). Reflections on infants as musical connoisseurs. *The Child as Musician: A Handbook of Musical Development*, *2*, 31–55.

Tryfon, A., Foster, N. E., Ouimet, T., Doyle-Thomas, K., Anagnostou, E., Sharda, M., & Hyde, K. L. (2017). Auditory-motor rhythm synchronization in children with autism spectrum disorder. *Research in Autism Spectrum Disorders*, *35*, 51–61. https://doi.org/10.1016/j.rasd.2016.12.004

Ullén, F., Hambrick, D. Z., & Mosing, M. A. (2016). Rethinking expertise: A multifactorial gene–environment interaction model of expert performance. *Psychological Bulletin*. Ullén, Fredrik: Department of Neuroscience, Retzius väg 8, Karolinska Institutet, Stockholm, Sweden, SE-171 77, Fredrik.Ullen@ki.se: American Psychological Association. https://doi.org/10.1037/bul0000033

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

Vaquero, L., Hartmann, K., Ripollos, P., Rojo, N., Sierpowska, J., François, C., … AltenmÃ¼ller, E. (2015). *Structural neuroplasticity in expert pianists depends on the age of musical training onset*. *NeuroImage* (Vol. 126). https://doi.org/10.1016/j.neuroimage.2015.11.008

Waber, D. P., Moor, C. De, Peter W. Forbes, C. R. A., Botteron, K. N., Leonard, G., Milovan, D., … Rumsey, J. (2007). The NIH MRI study of normal brain development: performance of a population based sample of healthy children aged 6 to 18 years on a neuropsychological battery. *Journal of the International Neuropsychological Society*, *13*(5), 729–746.

Watanabe, D., Savion-Lemieux, T., & Penhune, V. B. (2007). The effect of early musical training on adult motor performance: evidence for a sensitive period in motor learning. *Experimental Brain Research*, *176*(2), 332–340.

Wechsler, D. (2003). *WISC-IV technical and interpretive manual*. San Antonio, TX: 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 & Development*. Netherlands: Elsevier Science. https://doi.org/10.1016/S0163-6383(84)80022-3

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. https://doi.org/10.1016/j.humov.2007.11.007

White, E., Hutka, S., Williams, L., & Moreno, S. (2013). Learning, neural plasticity and sensitive periods: implications for language acquisition, music training and transfer across the lifespan. *Frontiers in Systems Neuroscience*, *7*, 90. https://doi.org/10.3389/fnsys.2013.00090

Wiens, N., & Gordon, R. L. (2018). The case for treatment fidelity in active music interventions: Why and how. *Annals of the New York Academy of Sciences*, 1–10. https://doi.org/10.1111/nyas.13639

Wiesel, T. N., & Hubel, D. H. (1965). Extent of recovery from the effects of visual deprivation in kittens. *Journal of Neurophysiology*, *28*(6), 1060–1072. https://doi.org/10.1152/jn.1965.28.6.1060

Wing, A. M., & Kristofferson, A. B. (1973). Response delays and the timing of discrete motor responses *, *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.

Wong, P. C. M., Ciocca, V., Chan, A. H. D., Ha, L. Y. Y., Tan, L.-H., & Peretz, I. (2012). Effects of Culture on Musical Pitch Perception. *PLOS ONE*, *7*(4), e33424. Retrieved from https://doi.org/10.1371/journal.pone.0033424

Woodruff Carr, K., White-Schwoch, T., Tierney, A. T., Strait, D. L., & Kraus, N. (2014). Beat synchronization predicts neural speech encoding and reading readiness in preschoolers. *Proceedings of the National Academy of Sciences*, *111*(40), 14559–14564. https://doi.org/10.1073/pnas.1406219111

Zatorre, R. J., & Zarate, J. M. (2012). *The Human Auditory Cortex* (Vol. 43). https://doi.org/10.1007/978-1-4614-2314-0

Zhang, J. D., Susino, M., McPherson, G. E., & Schubert, E. (2018). The definition of a musician in music psychology: A literature review and the six-year rule. *Psychology of Music*. https://doi.org/10.1177/0305735618804038

Zuk, J., Andrade, P., Andrade, O., Gardiner, M., & Gaab, N. (2013). Musical, language, and reading abilities in early Portuguese readers . *Frontiers in Psychology* . Retrieved from https://www.frontiersin.org/article/10.3389/fpsyg.2013.00288