MUSICAL TRAINING AND EXECUTIVE FUNCTIONS IN ADOLESCENCE

FRANK ROBERTSON
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Department of Neuroscience
University of Lethbridge
LETHBRIDGE, ALBERTA, CANADA

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FRANK ROBERTSON

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Dr. Claudia Gonzalez	Professor	PhD
Dr. Robbin Gibb	Professor	PhD
Thesis Co-Supervisors		
Dr. Matthew Tata	Professor	PhD
Thesis Examination Committee Member		
Dr. Bryan Kolb	Professor	PhD
Thesis Examination Committee Member		
Dr. Artur Luczak	Professor	PhD
Chair, Thesis Examination Committee		

ABSTRACT

Music is an incredibly complex and beautiful activity, which involves nearly every cognitive function. There is evidence to suggest that musical training in children and adult musicians is associated with an improvement in several Executive Functions (EF). This thesis examined whether those associations persisted during adolescence, and whether there is a relationship between time spent in musical training and adolescents EF. Adolescents ages 14-18 completed a subjective survey of EF as well as a battery of objective EF tasks. They also completed questionnaire detailing their musical experience. Adolescent musicians were found to have improved inhibition relative to non-musicians and inhibition was found to be correlated with musical practice time. No other elements of EF were found to be associated with musical training. These findings suggest that the impact of musical training on executive functions is related to how similar the neuropsychological assessment is to the musical training in question.

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LIST OF ABRIEVIATIONS

BRIEF-SR	Behavioural Regulation Inventory of Executive Function Self Report Version
BRI	Behavioural Regulation Index
EF	Executive Function
IGT	Iowa Gambling Task
MI	Metacognition Index
ToH	Tower of Hanoi
WCS	Wisconsin Card Sorting Task

CHAPTER 1: INTRODUCTION

From lullabies to symphonies, campfires to clubs, birthday's to funerals, music is woven all the way through the human experience. Children respond to music starting in their very earliest moments and music is thought to predate speech evolutionarily (Levman, 1992). Music is a powerful driver of cognitive and neurological development involving the use of nearly every cognitive faculty. The impact of music throughout development is an area of interest across multiple disciplines. Music and language are both thought to have developed from a proto-musical faculty in our ancient ancestors. Both music and language allow us to communicate through sound, and both require the ability to process and produce precise sounds. The same abilities that allow us to sing and discern emotion from a melody, allows us to discern meaning from words (Levman, 1992). The communicative power that comes from our advanced facilities for music and language is what makes us distinctly human.

Music is a highly complex cognitive activity. A musician must coordinate fine motor movements in order to reproduce a memorized series of sounds while receiving auditory, somatosensory, and visual feedback. Becoming an expert musician requires years of dedicated practice. Music has been proposed as a model for cognitive and neurological plasticity because of the breadth and depth of the faculties exercised in this activity (Zatorre, 2005; Moreno & Bidelman, 2014).

It is not just those functions directly recruited to produce music that are impacted by it. Executive functions (EFs) are cognitive abilities that organize and direct the deployment of other cognitive processes. EF includes abilities such as goal setting, working memory, task monitoring, planning, and attention. These EFs are involved throughout musical training and have been found to be improved by engagement with music. Higher EF is associated with improved outcomes in school and life, and so has been a focus of research in the last decade (Diamond 2011).

Musical training has been shown to improve EF in children. Short-term musical interventions of a few months to a year have been found to be effective in raising children's EF and verbal intelligence (Schellenberg, 2004; Moreno et al., 2011; Janus et al., 2016). Children engaged with music have been shown to have better Efs and higher intelligence than age-matched children without musical training (Schellenberg, 2006; Zuk, 2014).

A great deal of research has focused on adult musicians and demonstrates a variety of behavioural and neurological benefits associated with this long-term musical training. Adult musicians have been shown to have improved Efs compared with non-musicians especially when considering measures of inhibition or working memory (Degé et al., 2011; Moussard et al., 2016). Beyond behavioural research, the brains of long-time musicians have been found to be structurally and functionally distinct from the brains of non-musicians (Gasser & Schlaug, 2003; Schneider et al., 2002). These changes are thought to underlie the cognitive benefits found to be associated with musical training.

Unfortunately, the literature has so far neglected to examine the impact of music on adolescents thoroughly. Adolescence is the period between childhood and adulthood, beginning at the onset of puberty around 11 years of age, and continuing until adulthood (Blakemore & Choudhurry, 2006). Adolescence is an important period of development; physically, socially, and cognitively. During this period, adolescent brains restructure and become more efficient through a process called synaptic pruning. By the time a person reaches puberty their grey matter and synaptic density in the frontal lobes is at its highest point. From here, adolescents experience a loss of grey matter in the frontal lobes and an increase in the volume of the white matter tracts connecting those regions (Blakemore & Choudhury, 2006). These underlying brain changes are important for the development of skills and abilities that these teens will carry into adult life.

This thesis will examine the association between musical training and EF in adolescence. Music has the ability to induce neuroplasticity and produce cognitive benefits in a wide variety of domains. The next section will explore the theoretical and neurological basis for these benefits. The impact of music on EF, specifically, will follow. Finally, the importance of adolescence as a developmental period will be discussed. It is in this context that the opportunity provided by music during the teenage years becomes clear.

1.1 SKILL TRANSFER AND NEUROPLASTICITY

Music stimulates a wide range of cognitive processes, thus training in music may incidentally involve training in a variety of cognitive tasks. This enables skill transfer from musical training into the general abilities assessed by neuropsychological tests. Perhaps relatedly, music has been shown to induce neuroplasticity and is associated with broad functional and morphological changes across the brain. Musical experience is able to build skills and shape the brain generally because engaging with music requires all those faculties.

In his *Nature* review paper "Music, the food of neuroscience" Robert Zatorre argued that music was a fantastic window for exploring neuroscientific ideas because it involved nearly every cognitive process (2005). Consider a violinist performing in a symphony. She rests the violin on her shoulder, and places the bow on the strings in a single graceful movement. Every movement she makes has been drilled to the point where it comes naturally, effortlessly, when called on. She relies on cues she hears from other musicians, and what she sees coming from the conductor and the written sheet music in front of her, to tell her when to start and whether things are going well. This means she must constantly shift her attention, monitoring her own behaviour and the input from those around her. She must be precise not just in the movements that produce the music, but in executing them at exactly the right time. Having a sense of the feat that is accomplished by a performing musician gives context to the theory that musical training can result in skill transfer to EFs.

Skill transfer occurs when practicing some activity causes improvements in other semi-related domains. Thorndike's Common Elements Theory holds that the degree to which skills transfer between activities is determined by the common elements they share (Thorndike & Woodsworth, 1901; Schellenberg, 2011). Making music involves specialized motor movements, auditory processing and – in the case of written music – visual discrimination (Moreno & Bidelman 2014; Zatorre, 2005). All of these elements must be coordinated through EFs. This complexity means that producing music will involve getting practice in a wide variety of cognitive skills. The skill transfer from this practice could result in the diffuse cognitive benefits associated with musicianship.

It would be a mistake while discussing skill transfer from musical training to neglect the time invested in the training itself. Successful young musicians spend hours on top of their normal schedule practicing the craft. Many of these lessons take place outside of school, meaning students are using their free time to engage in cognitively complex exercises. There is some evidence that musical programs which supplement, rather than replace school instruction are associated with more cognitive improvements for children (Rickard et. al. 2012; Schellenberg, 2011). It is possible that the benefits of musical training come primarily from the extra time engaged in cognitively demanding work. If this were the case the cognitive benefits of music should be related to the amount of time spent in musical training.

Time spent in musical training has also been shown to induce neuroplasticity. Neuroplasticity is the ability of the brain to change based on external experience and training. The complexity of music has led several neuroscientists to propose musical expertise as a useful model of neuroplasticity. This is because it results in changes throughout the brain (Moreno & Bidelman 2014, Zatorre 2005). Strong evidence has been found for both functional and structural changes in the brains of musicians. While direct links between these changes and the musician's improved cognitive abilities have not been established, the fact that music has such wide-ranging impacts on the brain is consistent with the behavioural literature.

Some of the most significant changes in musicians' brains occur in regions responsible for auditory processing. Researchers have established that musicians have greater grey matter volume bilaterally in Heschl's gyrus, or the primary auditory cortex, within the Sylvian Fissure, (Schneider et al., 2002). This increase in grey matter has been found to relate to the degree of musical expertise, such that amateurs have more grey matter than non-musicians, and both of those groups had less than professional musicians (Gaser & Schlaug 2003). Functional changes in the auditory cortex have also been detected using Magnetoencephalography (MEG).

MEG works by detecting changes in the magnetic fields around the scalp induced by brain activity of the cortex. When a change in this magnetic field is associated with a particular behaviour or event that change is known as an event related field (ERF). Event related fields evoked by tonal cues in the primary auditory cortex are stronger in musicians than non-musicians (Schneider et al., 2002). This seems to indicate that the neuroplasticity produced by musical training results in functional improvements, as well as structural growth in the auditory cortex.

Premotor and primary motor regions in the frontal lobe have also been found to be shaped by musical practice. Of note is an "omega sign" – a structural change in the precentral gyrus where extra folding causes the gyrus to look like the Greek symbol omega. This sign occurs unilaterally for violinists, and bilaterally in pianists, corresponding to control of the fingers necessary for playing their instrument (Bangert and Schlaug, 2006). As with the auditory regions, grey matter volume in the premotor and primary motor areas have been found to increase as a function of musical expertise (Gaser & Schlaug, 2003). This makes it clear that musical practice drives these neuroplastic changes.

Musicians have also been shown to have greater grey matter volume in several cerebellar regions. Gaser and Schlaug found increases in the right cerebellum of expert pianists which they attributed to improved coordination of finger movements (2003). More recent work has shown large bilateral regions of the posterior lobe of the cerebellum to have greater grey matter volume in musicians (James et al., 2014). Beyond their typical association with musical functions these regions of the cerebellum have been found to be associated with the prefrontal cortex and are activated during an auditory cognitive load task (Salmi et al., 2010). These findings raise the possibility that changes to the cerebellum in musicians contribute to both motor and cognitive functions.

Auditory and motor systems are not the only areas found to change due to musical training. A wide variety of brain regions have been investigated and found to be different between musicians and non-musicians. Broca's area – a frontal lobe region involved in the production of speech – has been implicated. Further studies have found evidence for music driven changes in the hippocampus, as well as in the arcuate fasciculus and the corpus callosum. These sorts of wide-ranging changes are understandable given music's complexity, and the variety of cognitive skills associated with it.

Broca's area is a brain region in the left posterior frontal lobe that is involved in the production of speech. Broca's area is also important for music production. Specifically, it is involved in processing musical syntax, becoming active during key changes, and abnormal chord progressions (Koelsch, 2006). Electrically stimulating Broca's area stops the production of speech, and it has also been shown to arrest music production in expert musicians (Leonard et al., 2018). This supports the hypothesis that Broca's area is necessary for processing and producing musical syntax. Given that Broca's area is so intimately connected to musical production it comes as no surprise that professional musicians have increased grey matter volume in this region compared with age-matched controls. This change is not observed in the right hemisphere, consistent with the hypothesis that musical production is dependent on the same neural substrates as language (Gaser & Schlaug 2003; Schlaug, 2015; Sluming et al., 2002).

According to a 2014 (Groussard et al., 2014) study the left hippocampus shows increased volume in musicians. The researchers compared non-musicians, against novices with less than eight years of experience, intermediates with less than twelve years, and experts with more than twelve years of experience. All three groups of musicians showed larger hippocampal volumes than non-musicians, and there was a linear relationship between the amount of musical training and the hippocampal volume observed. The left hippocampus is particularly associated with episodic memory and has been found to change in response to training in a variety of contexts (Burgess, Maguire, & O'Keefe 2002).

The arcuate fasciculus is a white matter tract connecting Broca's area with Wernicke's area in the temporal lobe in the left hemisphere and their homologues in the right hemisphere. A 2011 study found that the musicians had a larger tract volume, and higher fractional anisotropy than non-musicians (Halawai et al., 2011). Fractional anisotropy measures how constrained the liquid moving through a region is. A higher value indicates a denser tract. Short-term music-cued motor training has been found to increase fractional anisotropy of the arcuate fasciculus in children (Moore et al., 2017). This provides evidence that, at least in the case of this white matter tract, music induced neuroplasticity occurs in the same time frame as cognitive benefits in children. Increased fractional anisotropy in the arcuate fasciculus has been associated with increased IQ in children and is generally is associated with improved cognitive functions (Schmithorst et al., 2005). The association between music and density in the arcuate fasciculus therefore supports the hypothesis that musical training may benefit cognition.

The corpus callosum is another white matter tract associated with a preponderance of motor and cognitive functions. The corpus callosum is the largest collection of white matter within the brain and connects the right and left hemispheres. Gottfried Schlaug first demonstrated that musicians had larger corpus callosa than non-musicians in 1995. Since then, several teams have confirmed that musicians who begin practicing music before the age of seven have greater tract volume and density in this area than non-musicians or later trained musicians (Schlaug et al., 1995; Schmithorst, & Wilke, 2002; Steele, Bailey, Zatorre, & Penhune, 2013). This finding has been used to argue that musical training improves coordination between the hemispheres.

Musical training has been demonstrated to result in broad neurological changes throughout the brain. The complexity of music means that musical production requires the use of nearly all cognitive faculties. These facts have led some scientists to hypothesize that musical training would improve EFs. This hypothesis is consistent with the common elements theory, which holds that the degree of similarity between two tasks predicts how much training will transfer between them. The following sections will explore the evidence for music's generalized cognitive benefits.

The opportunity to learn music is an important advantage for neurological and cognitive development. Musical training has been shown to improve IQ, and EF, especially in contexts involving auditory processing. The benefits to intelligence are thought to be mediated by EF benefits. Working memory, inhibition, and cognitive flexibility have all been shown to be improved by musical training, though the results in this area are often inconsistent. What is clear is that musical training provides general cognitive benefits to anyone who has the enjoys the opportunity to participate.

Researchers in music and education have long been interested in the ability of musical skill to transfer into other cognitive domains. A 2017 meta-analysis (Sala & Gobet, 2017) examined studies including students younger than 14 that addressed how musical training impacted their cognitive abilities and school performance. They looked at 38 studies involving intelligence, memory, phonological awareness, mathematical ability, and literacy and found that music had a robust effect on intelligence and memory (with a Cohen's d effect size of 0.34, and 0.35). The effect was much smaller for more removed skills like literacy and mathematics, and the overall analysis showed a mean effect size of d = 0.16. This result is consistent with the common elements theory in showing that musical training has stronger associations with memory and intelligence, than with mathematics.

Musical training and intelligence have been known to be associated for many years. Glenn Schellenberg at the University of Toronto demonstrated that music lessons enhanced IQ in children with a randomized controlled trial in 2004. In this experiment, 6-year-old children were assigned to 36 weeks of piano, voice, or drama classes, and their IQs were measured before and after. Children in the two music classes showed significant improvement in intelligence throughout the year compared with children receiving either drama instruction or nothing (Schellenberg, 2004). A follow up to Schellenberg's 2004 study showed that children who were more regularly involved in extracurricular musical training had higher IQ's than those who were not. This effect remained significant even when accounting for parental income (Schellenberg, 2006; 2011; Moreno & Bidelman 2014). These findings established a potentially causal link between increased musical training and increased intelligence in children.

Benefits to intelligence from childhood music lessons have been shown to persist into adulthood. In a correlational follow-up to his 2004 study, Schellenberg reproduced the finding that music lessons improved intelligence in school children and further showed that undergraduates who had spent a significant amount of time in music lessons as children had higher IQs (2006). These effects were small but significant across all subdomains of intelligence as measured by the Weschler Adult Intelligence Scale-III. The potential for long-term improvements to cognitive function from musical training during development is what makes this field so exciting for educators and scientists alike.

The fact that musical training provides generalized benefits to intelligence has led researchers to hypothesize that those improvements result from underlying improvements in children's EF. Degé, Kubicek, and Schwarzer found that EFs were associated with musical training. They further found that the relationship between IQ and musical training was fully explained by the relationship between musical training and EF skills, (2011).

1.2 EXECUTIVE FUNCTIONS AND COGNITIVE DEVELOPMENT

EFs are those complex cognitive abilities not captured by intelligence. They are made up of a cluster of related abilities. Adele Diamond called inhibition, cognitive flexibility, and working memory the three core EFs (Diamond 2011). Each of these functions has several sub-categories which are sometimes included in tests of EF. These divisions help to make sense of the varied abilities included under the umbrella of EF.

EFs become more complex as people mature. In children, EF is best modeled as a unitary construct that tracks fluid intelligence in young children (van Aken et. al., 2016; Brydges et. al., 2012). As these children age, more complex models are needed to account for the variety of functions and these functions stop being so neatly associated with intelligence. Recent work by Lernier and Lonigan found that children between the ages of seven and nine had EF best described by a two-factor model including both working memory and inhibition (2014). Once people reach late adolescence their EFs disassociate somewhat from their intelligence. Friedman and colleagues examined twins between the ages of sixteen and eighteen. They found that these adolescents had EF best modeled using three factors – inhibition, working memory, and cognitive flexibility – and of those, only working memory remained associated with intelligence (2006).

These findings were supported by a recent meta-analysis from the University of Victoria that looked at studies using confirmatory factor analysis on objective tests of EF. They found that in studies of children younger than nine the most common accepted model of EF was a unitary model. In adults, a three-factor model was the most commonly accepted model (Karr et al., 2018). This finding is consistent with the idea that EFs continue developing past childhood and throughout our teenage years.

The first experiments probing EF attempted to understand a single function in the context of a laboratory test. Early researchers developed tools to look at attention, inhibition, working memory, and task switching. These tests have the advantage of interrogating a participant's ability directly, but do not always translate into real life. Self reported surveys are another popular method for determining a participant's level of EF. Surveys can tell researchers how participants experience EFs in real life, but they are subject to all the normal concerns with self-reported data. It is important therefore to understand each factor of EF in terms of objective and subjective measures.

1.3 INHIBITION

Inhibition is the ability to resist doing something natural or instinctual and instead engage in some effortful activity. Having high inhibition means having the ability to sort out irrelevant information and remain focused on a given task. Inhibition deficits are a major part of attention deficit disorder and describes those patients' inability to avoid distraction (Willcutt et al., 2005). It is no surprise then that inhibition is a critical ability for academic success. Bull and Sceriff found that inhibition predicted seven to nine-year old's mathematical ability independent of their intelligence and reading ability (2001). Inhibition allows people to pause and consider other skills that can be used to solve the problems that are important to them.

Objective tests of inhibition focus on asking participants to respond to one type of stimulus while introducing some other competing stimulus that the participant must ignore. For example, in a go-no-go task participants will be asked to respond to one object like a right pointing arrow, but not to some other stimulus, like a left pointing arrow. Because the stimuli are nearly identical participants have to inhibit their automatic response and take the extra fraction of a second to consider before responding. Another popular test of inhibition is known as the Stroop task.

Here stimuli are presented in pairs and participants are asked to respond to the less salient stimulus. In the classic color-word Stroop participants are presented with color words of different colors (ie. green printed in green ink) and asked to respond to the color of the ink rather than reading the word. When these stimuli are congruent the task is simple, but when they do not match inhibition is required, leading to increased response time and a higher error rate (MacLeod, 1991).

Inhibition may be improved by the dedication required for musical training and thereby lead children to be more effective in developing their cognitive abilities. There is evidence that musical training in children improves inhibition more than equivalent forms of artistic training. Moreno and colleagues showed that twenty days of musical training was sufficient to improve kindergartener's performance on a visual Go-No Go task. The children were trained on pitch, tempo, melody, voice, and other basic concepts, using a computer program that focused on listening tasks. These children outperformed an active control group receiving an equivalent fine arts training (Moreno et al., 2011; 2014). This result suggests that there is something especially important about music in the development of inhibition.

The benefits to inhibition have been shown to persist in adults with a history of musical training. Bialystok and Depage showed that musicians performed better on an auditory Stroop test of inhibition than those with no musical training (2009). This result was confirmed last year (D'Souza, et al., 2018) with a full battery of inhibition tests, including the visual Stroop, a flanker task, and an auditory stop signal test. Musicians showed a significant advantage on each of these measurements compared with adult non-musicians. These improvements continue even as people age. In a study of professional musicians older than age 50, musicians were found to outperform non-musicians in a full battery of inhibition tasks including an auditory Stroop task, a go-no-go task, a distracted reading task and a Simon task – in which a colour appeared on one side of the screen, and participants had to hit a matching button, which was on the same side as the colour in congruent trials and on the opposite side in incongruent trials. While no difference was found in the visual Stroop condition, it is safe to say that the benefits of music practice in this area can be of benefit throughout life (Amer et al., 2013).

It is possible that certain kinds of musical practice improve inhibition better than others. Bialystok and Depage did not find any difference between vocalists and instrumentalists in their study, however recent findings have suggested that there may be differences between extremely different kinds of musical training (2009). For example, percussionists who must keep careful track of time may have better inhibition than other musicians. A 2017 study (Slater et al.) compared inhibition abilities between vocalists, percussionists, and non-musicians between the ages of 18 and 35 (Slater et al.). They found that percussionists outperformed both vocalists and non musicians in inhibitory control. This finding further supports the theory of common elements in that musical training which involves more inhibitory control improves inhibition more.

1.4 COGNITIVE FLEXIBILITY

Cognitive flexibility or task switching is an element of EF that requires a person to move back and forth between several tasks successfully. These are the abilities that allow for multitasking. In a dual task paradigm, cognitive flexibility is measured by combining two simple tasks together and measuring the difference between performance in the individual tasks and the dual task (Alzahabi & Becker, 2013). Cognitive flexibility can also be measured using tools like the Wisconsin Card Sorting task where participants complete multiple similar tasks back to back. Researchers measure how seamlessly participants transition to the new task by tracking the errors they make which would have been correct in the previous task (Berg, 1948). This ability to rapidly switch between tasks is required for successful navigation of a world where many complicated jobs and separate priorities are competing for attention.

Like other EFs, cognitive flexibility has been found to be associated with musical training. Degé and colleagues (2009) found that cognitive flexibility was correlated with time spent in musical training for children between the ages of 9 and 12. Despite this correlation, cognitive flexibility was not found to be a significant contributor to the relationship between intelligence and musical training in these children. A 2014 study failed to reproduce this finding in children but found that cognitive flexibility was improved in adult musicians (Zuk et al., 2014). These somewhat lackluster results hint towards the possibility that music has less of an impact on cognitive flexibility than on other EFs.

1.5 WORKING MEMORY

Working memory is the short-term task-oriented memory that allows people to remember what they are doing and to recall relevant information that allows for task completion. Working memory is distinct from short-term memory because working memory requires processing of the information remembered. This means that working memory is involved in accomplishing most objective tests of EF, as participants must at a minimum remember the rules of the task. On the other side of that coin, most classic tests of working memory are dual tasks, therefore requiring cognitive flexibility (Engle et al., 1999). One measure of planning and practical working memory ability is the Tower of Hanoi. The Tower requires participants to move a tower across a set of three spaces. The rules of the game are such that this maneuver takes a minimum of fifteen moves to complete. In order to avoid errors and complete the task in as few moves as possible participants must think through the rules and see multiple moves ahead (Humes et al., 1997). Working memory is a fundamental EF that allows for the planning and execution of goal-oriented behaviour.

Working memory has consistently been shown to have a strong relationship with musical training. A 2017 meta analysis including 18 studies testing the effect of musical training on children's working memory showed a significant overall effect size of d = 0.34 (Sala & Gobet). Bhide, Power and Goswami (2013) showed that short-term musical training improved working memory in a population of 6 and 7-year-olds who were struggling with reading. The children were engaged in 19 sessions over the two months, in which they were given rhythm training. At the end of the two months participants were shown to perform significantly better on a digit's backwards test of working memory. They also outperformed children who had received a rhyming and reading intervention in the memory task. This suggests that working memory can be moderately improved through musical interventions.

Other research has demonstrated this relationship between working memory and musical training in adults. Zuk and colleagues (2014) compared both children and adults with a history of musical training in a variety of EF tasks. They found that children had an advantage on verbal fluency and inhibition, but that in adult musicians the verbal fluency advantage was replaced with an advantage in working memory, and cognitive flexibility. Young adults who are consistently engaged in music have been found to have better working memory using a variety of techniques (Bialystok & Depage, 2009; D'Souza, Moradzadeh & Wiseheart 2018; Franklin et al., 2008).

1.6 EMOTIONAL CONTROL AND HOT EF

Hot EF is an area of EF including decision making under emotionally charged conditions and related to emotional control. Emotional control includes the ability to make decisions under pressure and to remain calm in stressful situations. Emotional control is difficult to assess in an objective neuropsychological task but has been found to be associated with tasks measuring "hot" EFs where participants experience losses (Poon, 2018; Zelazo, Qu & Kesek 2010). Emotional control and hot EF allow teenagers to engage socially and deal with setbacks in a way that allows for successful adult life.

Adolescence is a critical period for the development of hot EF. Prencipe et al. (2011) found that tasks involving more emotional control reached adult levels more slowly than other kinds of EFs and were still developing rapidly between the ages of fourteen and fifteen. They examined the development of hot and cold EFs between the ages of 8 and 15. Cool EFs showed rapid development early in this age range, whereas development of hot EFs were delayed until later in adolescence (2011). This finding was supported by work from Hooper et al. (2004) who found significant improvements on the Iowa Gambling Task in participants between the ages of nine and eighteen. These findings open the possibility that musical training during adolescence will improve hot EF in the same way that musical training in early childhood tends to improve cool EFs.

The potential of music to impact hot EF has only recently begun to generate interest from the research community. Last year, a study published in *Psychology of Music* examined the effect of childhood musical training on performance in the Iowa Gambling Task (Smayda, Worthy & Chandrasekaran, 2018). Researchers found that musicians who began their training in late childhood (8 years old or older) were significantly better at the task than either earlier trained musicians, or non-musicians. They hypothesized that the later start of musical training might provide an advantage by putting the initial skill development closer to a critical period for the development of these hot EF skills.This finding was undermined by a similar study published in 2017, which found that musicians trained early were the ones who had an advantage in hot EF (Hou et al., 2017). Still, since hot EF tends to develop during this adolescent period, musical training at this time may be particularly beneficial for hot EF.

The development and diversification of EF throughout childhood and adolescence is shaped by experience. Researchers examining the cognitive benefits of musical training have consistently found small but significant effects. Inhibition and working memory are the functions found to be most strongly associated with musical training. This has been shown both in children and in adults with significant musical training. Several researchers have suggested that these benefits are related to critical periods in cognitive development and neuroplasticity. It is therefore important to contextualize the issue of musical training in the broader world of cognitive and neurological development.

1.7 DEVELOPMENT

Adolescence and early childhood are both periods of high neuroplasticity and rapid cognitive development. These two windows of elevated neuroplasticity provide opportunities to help youth cultivate the faculties which they will carry with them into adulthood. Because musical training has been so thoroughly demonstrated to enhance cognitive development in early childhood it is worth asking whether musical training in adolescence is also effective in increasing EF skills.

Weintraub and colleagues found evidence for two developmental windows in childhood and adolescence while assessing the cognitive battery included in the NIH Toolbox for the assessment of Neurological and Cognitive Function (2013). They found that in measures of memory, and general EF there was a sharp increase in proficiency between the ages of 3 and 6. A second smaller spike in executive function development occurs starting at 12 years old and continuing until early adulthood at age 25 (see figure 1).

The windows of development in childhood and adolescence are not identical. Instead certain skills are primed to develop at particular times. A 2015 paper in *Trends in Cognitive Sciences* detailed the evidence that adolescence was a second window of increased neuroplasticity. In particular they found evidence for increased sensitivity to environmental factors in emotional processing and memory functions (Fuhrmann, Knoll & Blakemore, 2015). Brain pathways, and habits of thinking are malleable during this period and present an opportunity for interventions and experiences that will improve cognition in these youth for years to come. The fact that memory, and emotional control in particular, undergo change during this period opens the question of whether musical training at this time might improve these functions.

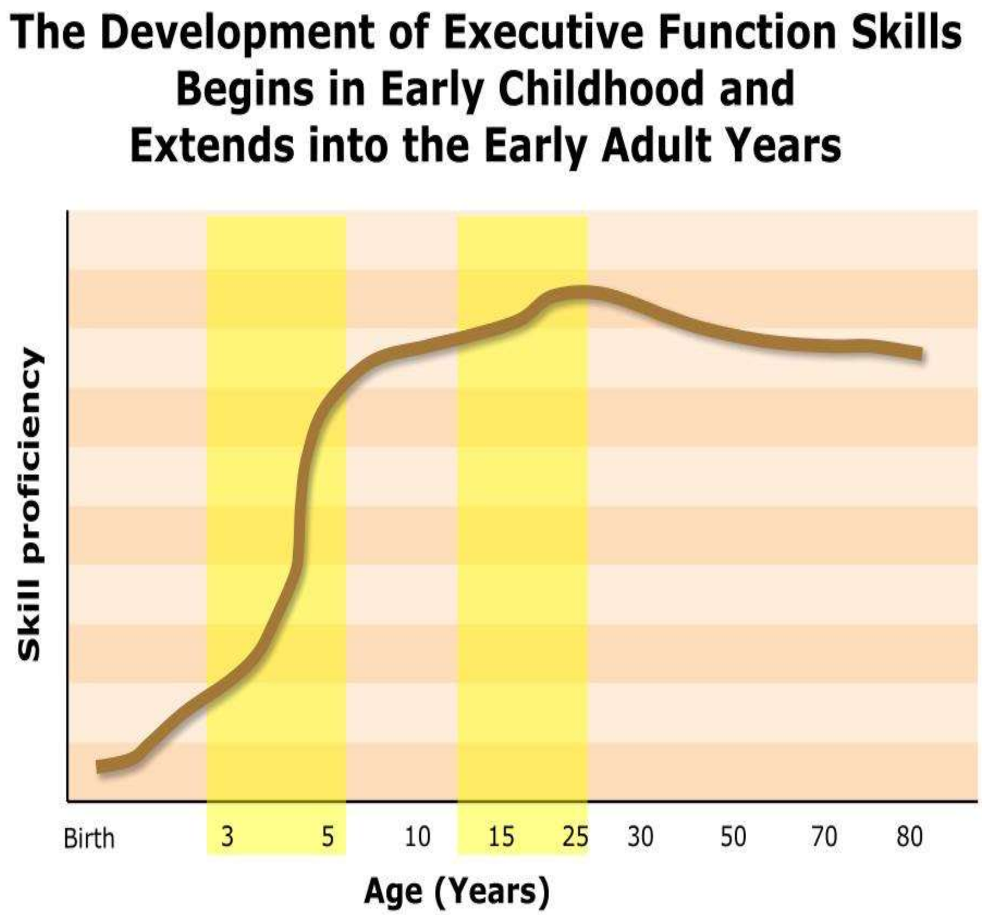

Figure 1: Developmental windows in childhood and adolescence. Young childhood and adolescence both see spikes in cognitive skill proficiency. Data from Weintraub, et al. (2013). Figure from the Harvard Center for the Developing Child.

While music's impact on EF during the window of childhood has been extensively examined, the question of how music changes EF in adolescence has been largely neglected. One longitudinal study from 2014, did examine the impact of musical training on working memory. This study followed 352 individuals between the ages of 6 and 35, and tested them three times; in 2007, 2009, and 2011. Musicians were found to outperform non-musicians on all working memory tasks. More than that, the researchers found a dose dependant association between time spent on musical practice and the improvement for working memory (Bergman, Darki & Klingberg. 2014). This study supports the hypothesis that working memory is associated with musical training through adolescent development, but leaves open whether other EFs are involved. Unfortunately, this thesis was unable to verify the relationship between working memory and musical training in adolescence because no dedicated measure of working memory was included in the battery, (see further discussion of this limitation on pages 35 and 36). There is a need for research which addresses the impact of musical training on adolescents when it comes to the diverse array of EFs.

1.8 CONCLUSION

Musical training has been shown to improve many elements of cognitive functioning in children and long-time musicians. Musical skills are thought to transfer into cognitive domains because of the complexity of musical tasks. These skill transfers are accompanied by changes in musicians' brains, some of which – like the increased volume in the corpus callosum – are dependant on musical training occurring in early childhood. It is possible that musical training will improve these cognitive abilities if it occurs during a critical period of cognitive development.

Despite receiving most of the attention in this area, childhood is not the only important period of development. Adolescents are also going through an intense period of cognitive and neurological change – especially in the area of EF. In order to examine the relationship between musical training and EF mid to late adolescents were tested on a battery of EF tasks, and completed a survey detailing their musical experience. This sample was used to address several questions raised by the existing literature.

First, does musical training have the same positive associations with EF development in adolescents as it does in young children? We know that even short musical interventions can have significant impacts on children's EF, and that child musicians engaged in extra curricular musical training show improved EF across a variety of domains (Moreno et al., 2011; Janus et al., 2016). It is possible that these benefits wash out by the adolescent years, as other children catch up through other activities. However, if music does have a uniquely strong ability to train EFs as indicated by the existing literature, adolescent musicians will continue to exhibit improved cognitive abilities.

Second, is there a relationship between the time spent in musical training and adolescent executive function. In their longitudinal study of working memory in musicians, Bergman, Darki, and Klingberg found that the time spent in musical training was significantly correlated with a variety of memory tasks (2014). Common elements theory of skill transfer treats the impact of music on EF as a simple matter of practice. The more time adolescents spend engaged with musical training, the more practice in these cognitive skills they should obtain. This should result in a correlation between time spent in training and cognitive ability.

Music is an incredibly powerful educational and developmental tool. Musical training engages all of our most important and uniquely human cognitive abilities. The association between musical engagement and executive function development in adolescence is unfortunately understudied. The window of neuroplasticity afforded in adolescence means that there is a real opportunity for musical training to have a lifelong impact. This thesis will clarify the strength of the association of music with a variety of EFs in adolescence, and help to direct researchers and educators working in this population.

CHAPTER 2: METHODS AND RESULTS

2.1 PARTICIPANTS

Forty adolescents (21 Females, 19 Males) between the ages of 14-18 were recruited from the Chinook High, Winston Churchill High, and Gilbert Patterson Middle School in Lethbridge Alberta. Participants self-identified as right-handed, and were healthy, with no history of neurological impairment. Participants were not told the purpose of the study, but were told about each of the tasks they would complete before giving consent. Parental consent was obtained for participants younger than 18 before they arrived for testing. Eighteen-year-old participants had the option of giving consent before hand, or waiting until they had arrived for testing.

2.2 PROCEDURE

Each participant completed an executive function questionnaire (BRIEF-SR), and a battery of objective executive function tasks (Tower of Hanoi, Wisconsin Card Sort, Iowa Gambling Task, and Stroop Color-Word). The entire experiment took between 35-45 minutes to complete.

2.2.1 BRIEF-SR

Participants completed the Behavioural Regulation Inventory of Executive Function (BRIEF) self report version (Guy et al., 2004). The BRIEF-SR is an 80-item questionnaire, for adolescents between the ages of 13 and 18. The BRIEF-SR asks how often a participant has had difficulty with every day executive function tasks (i.e. completing homework) in the last six months. We recorded a raw score for each of the BRIEF subscales, and two indexes used in the BRIEF – Behavioural

Regulation Index (BRI), and the Metacognition Index (MI). The total BRIEF score is called the General Executive Composite (GEC).

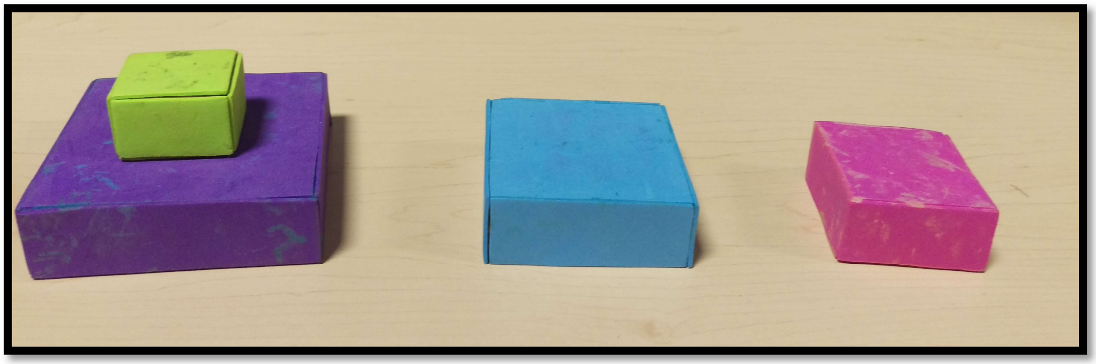

Figure 2: Tower of Hanoi. This task measures planning and working memory. Participants moved blocks from the left space to the right, according to a set of specific rules. Completing the ToH requires a minimum of 15 moves. Moves to complete is the measure of EF in this task.

2.2.2 TOWER OF HANOI

The Tower of Hanoi is a classic executive function task, used to measure planning and working memory components of EF (Humes et al. 1997). Four square blocks were stacked on each other, on the first of three marked spaces. Participants began the task centered on the second space, with both hands on the table. They were asked to move the tower of blocks to the third space, stacked in the same order that they began. Participants were only allowed to move one block at a time, and could only stack blocks on top of larger blocks. Participant's hands were filmed while completing this task. Time to complete, total moves performed, and right-hand use throughout the task was recorded. Completing the task requires a minimum of fifteen moves, and anything lower than twenty is good.

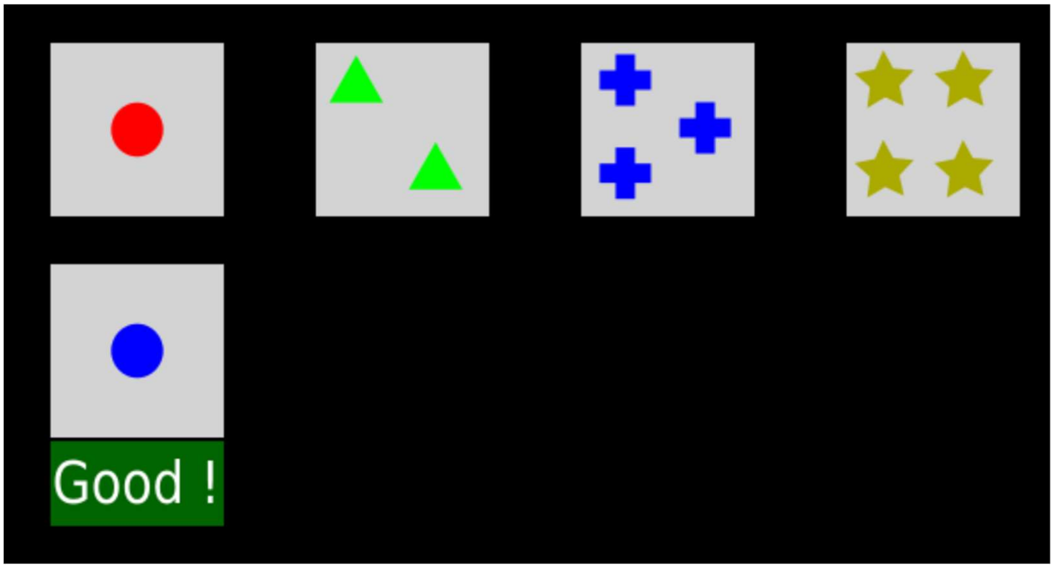

Figure 3: Wisconsin Card Sort. Participants clicked on the cards at the top in order to match with the card at the bottom. Cards could match based on the number, color, or type of shapes on the card, and this rule changed throughout the session.

2.2.3 WISCONSIN CARD SORTING TASK

The Wisconsin Card Sort measures cognitive flexibility (and inhibition). This study used a computerized version available on PsyToolkit, (Stoet, 2010; Stoet, 2017). Four square cards appeared at the top of the screen. Left to right they contained one red circle, two green triangles, three blue crosses, and four yellow stars. A fifth card appeared at the bottom of the screen, containing a random combination of colored shapes. Participants were asked to click the card at the top of the game window which matched the card at the bottom of the game window according to either shape, color, or number. Which rule to use was not disclosed to the participant, and changed several times throughout the session. When a participant clicked the correct card, a bell rang and a white "Good" flashed on the screen. In the case of an incorrect trial a white "No" flashed on the screen and was spoken by a robotic voice. Total errors were recorded as well as preservation errors, where participants continued using a previous rule in the next round of trials.

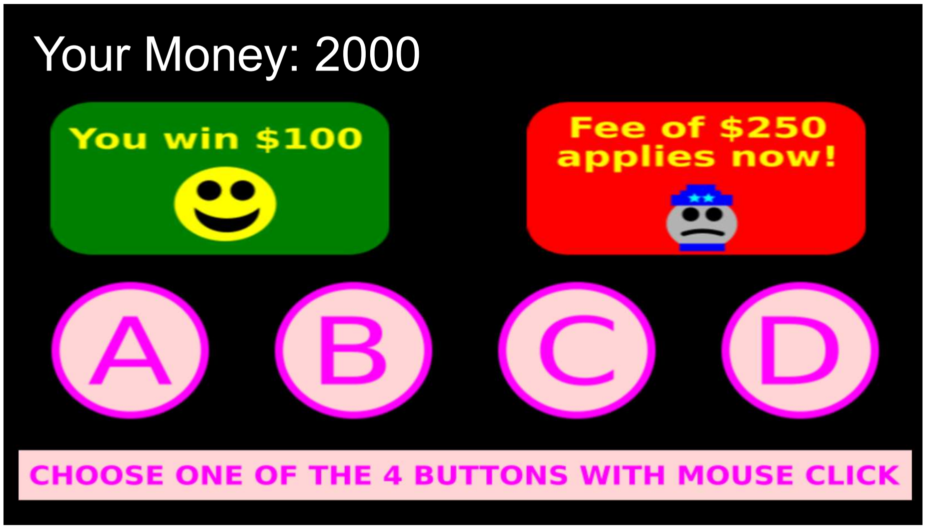

Figure 4: Iowa Gambling Task. Participants chose buttons over the course of 100 trials. Upon clicking one of the buttons a green winnings card always appeared, about half the time a red fee card also appeared. Participants had to learn that the buttons delivering the smaller amounts were net positive, and then stick with those as much as possible.

2.2.4 IOWA GAMBLING TASK

Participants completed a computerized version of the Iowa Gambling Task also available on PsyToolkit. Participants begin with 2000 points, and are instructed to make as many more points as they can over 100 trials. Each trial consists of pushing one of four buttons, A, B, C, and D. Each button followed a random reinforcement schedule, with gains and losses. Gains were scheduled to occur twice as often as losses. Buttons A and B were net negative, making 100 points on a gain, and losing 250 points on a loss. Buttons C and D were net positive, making 50 points on a gain, and losing 50 points on a loss.

Participants must recognize that the larger gains do not make up for the larger losses, and be willing to accept the slower progress. Success at this task is meant to indicate improved hot EF or emotional control, as participants must overcome the emotional allure of higher gains. In each trial the button pressed was recorded, and a total score was calculated by subtracting net negative button presses from net positive button presses. Therefore, a higher score indicated a participant who had better hot EF, and a lower or negative score indicated poor hot EF.

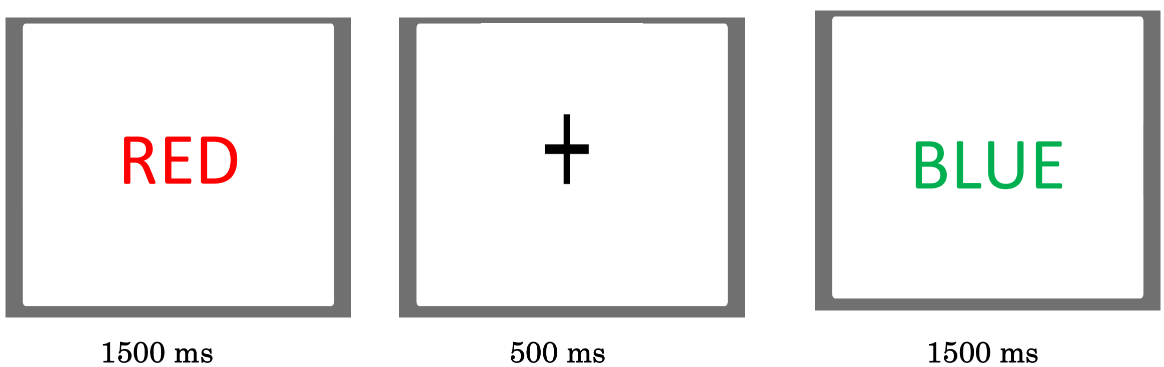

Figure 5 Stroop Color Word Task.: Participants responded to a series of words by pressing a key corresponding to the color that the word was printed in. Each word appeared on the screen for 1500ms. A fixation mark appeared on the screen for 500ms before each trial. Trials were categorized as congruent and incongruent, and errors were recorded for each condition.

2.2.5 STROOP COLOR WORD TASK

The Stroop Color Word Task is a classic test of executive function that examines inhibition. This experiment utilized a computerized version of the Stroop available at expfactory.github.io (Sochat, 2018). Participants were instructed to identify the color of words printed on the screen as either red, blue, or green, by pressing buttons on the keyboard. Each trial began after a 500 ms fixation and words were present on the screen for 1500 ms or until participants responded. Participants completed 23 practice trials, followed by 96 measured trials.

Forty-eight of these trials were congruent, meaning the color of the word matched the printed meaning of the word, (e.g. Red in red ink). Forty-eight were incongruent, meaning the color of the word did not match its printed meaning, (e.g. Green in red ink). Errors were recorded for both the congruent and incongruent conditions.

2.2.6 MUSIC SELF REPORT QUESTIONNAIRE

Participants completed a self-report questionnaire detailing their musical training. Each participant recorded whether they were currently playing any instruments or singing a vocal part. They recorded each of those instruments and gave the time spent practicing each week, and the years spent practicing that instrument. They then repeated the exercise for any musical experience they had had in the past and subsequently abandoned. Finally, participants were asked to rank their knowledge of music theory, ability to read music, and general musical aptitude on a five-point scale (1-5), where 1 was no ability and 5 was exceptional.

We considered participants to be musicians if they had at least three years of musical training, and a minimum of five hundred reported lifetime hours engaged in musical training. This eliminated participants who had only just begun engaging with music, and allowed this study to focus on the long-term impacts of musical training.

2.3 RESULTS

2.3.1 GENERAL EXECUTIVE BENEFITS FOR MUSICIANS

In order to test the hypothesis that teenagers with a history of musical training would have higher executive function than those without, a series of Welch non-parametric T-tests were conducted. This test was chosen because it does not assume normalcy, and is more robust to dependency between multiple comparisons. Musician status was used as the independent variable and the General Executive Composite, Stroop Errors, Wisconsin Card Sort Errors, Tower of Hanoi Moves, and Iowa Gambling Task Scores were dependant variables. In order to account for multiple comparisons Bonferroni correction was used. Only Stroop Errors were found to be significantly different between musicians and non-musicians. Musicians were found to commit significantly fewer errors than non-musicians.

Musicians did not score significantly better on a self reported measure of general executive function than non-musicians. Further they did not perform better on objective tests of cognitive flexibility, hot executive function, or planning. Musicians did outperform controls in an objective measure of inhibition.

Table 1: Musicians make significantly fewer errors in the Stroop Task than non-musicians. BRIEF-SR scores are a summed Likert Scale Score, lower scores indicate better EF. Tower of Hanoi scores are moves to complete, lower scores indicate better EF. WCS errors are preservation errors, lower scores indicate better EF. IGT score is the net number of positive choices minus negative choices, higher scores indicate better EF. Stroop score is measured by the total errors, lower scores indicate better EF. Significance testing was done using Welch pairwise two tailed T-tests. *$p < 0.05$, p-values met Bonferroni correction.

Variable	Musician Mean	Musician SE	Non-Musician Mean	Non-Musician SE	t Statistic	p-value
BRIEF-SR	122.22	5.02	132.16	5.05	1.4159	0.1656
Tower of Hanoi	32.889	3.53	26.684	3.47	-1.2717	0.5593
WCS Errors	7.750	0.770	9.500	1.09	1.2744	0.2124
IGT Score	13.529	7.78	20.188	7.49	0.59025	0.2119
Stroop Errors	4.389	0.759	9.737	1.40	3.3774	0.0022*

Correlation Between Musical Practice Time and Executive Function

In order to examine whether increased musical training time, or self reported musical ability was associated with executive function, a Pearson's Product-Moment Correlation analysis was performed. This analysis allowed us to treat musicianship as a continuous variable, and to evaluate whether increased musical training time was associated with better EF in the absence of any categories.

Self reported musical ability correlated with all BRIEF-SR indices. Self reported musical ability did not correlate with any objective measures of executive function. Musical training time correlated only with Stroop Errors. It failed to correlate with self reported executive function, or with self reported musical ability.

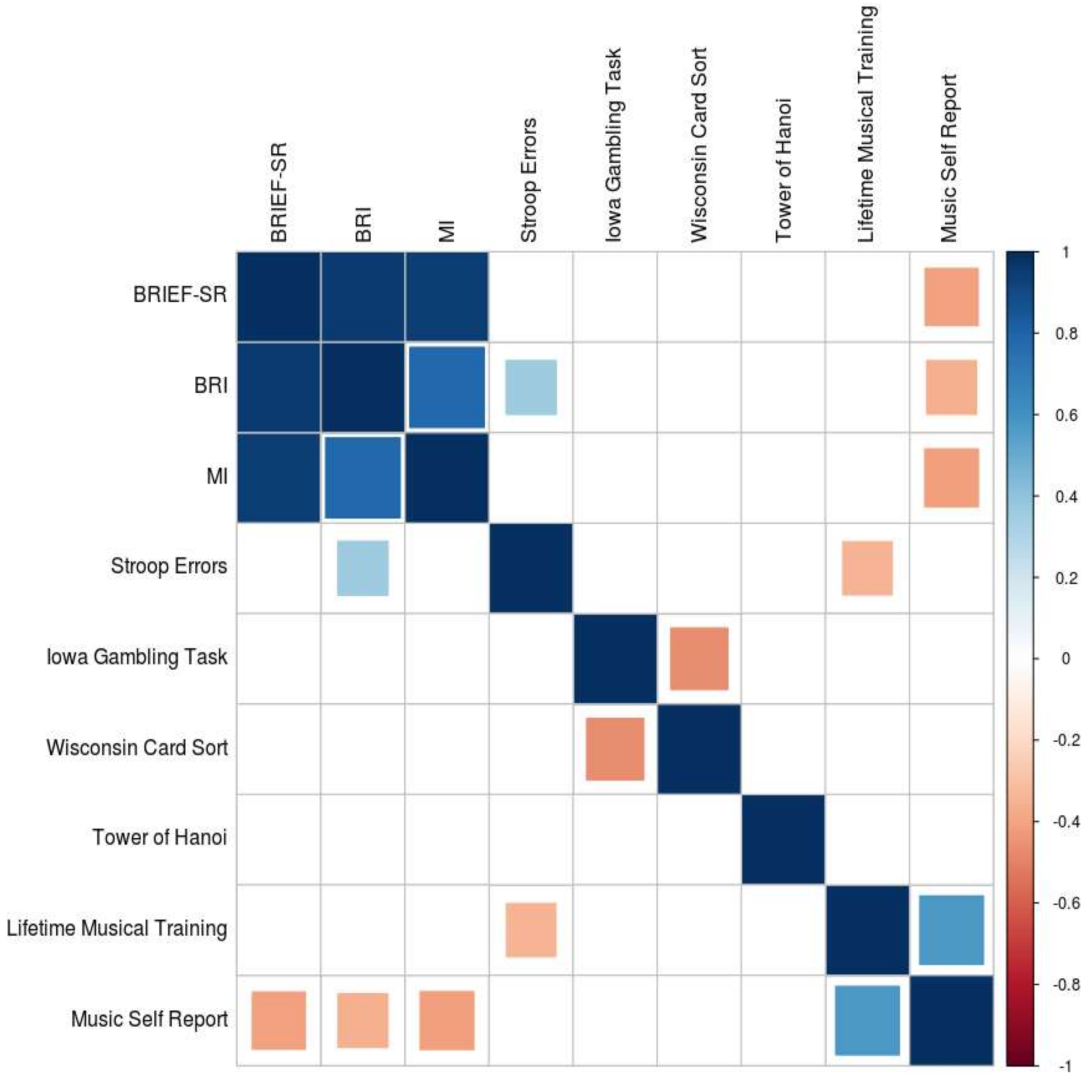

Figure 6: Correlation Matrix. Significant correlations at $\alpha = 0.05$ are shown, non-significant relationships are blank. Stroop Errors correlate with years played, and mean lifetime hours of practice. BREIF-SR scores correlate with self reported musical ability.

CHAPTER 3: DISCUSSION

This thesis attempted to fill a gap in our understanding of the impact of music on EF. While music has been demonstrated to have positive associations with EF in childhood and adulthood, the impact that music has on EF throughout adolescence is less well understood. The results of this thesis showed a modest positive association of musical training with EF. The only element of EF that was associated with musical training was inhibition. Two research questions were investigated: 1) Does musical training have the same positive associations with EF in adolescence as it does in young children? Inhibition – as measured by the Stroop Color Word Task – was the only domain of EF in which adolescents with musical training differed from non-musicians; adolescent musicians had better EF. The Stroop is closely correlated with the Behavioural Regulation Index (BRI) of the BRIEF-SR which includes inhibition, indicating that the Stroop is in fact measuring inhibition. This thesis failed to find a significant effect of musical training in the domains of cognitive flexibility, planning, or emotional control either subjectively (i.e. BRIEF-SR) or objectively (WCS, Tower of Hanoi, Iowa Gambling Task). Musical training therefore, only affects inhibition or it exerts the strongest effect on this EF. This last finding is consistent with other studies in children and adult musicians which have found that improvement in inhibition is the most reliable effect that musical training has on EF across a variety of tasks, and throughout the lifespan. Children's inhibition improves in response to musical interventions and long-term private music education (Moreno et al., 2011; 2014; Schellenberg 2006; Zuk et al., 2014). Adult musicians have improved inhibition that persists into old age (Amer et al., 2013; D'Souza et al., 2018, Moussard et al., 2016). The current study demonstrates that the relationship between musical training and inhibitory control is not disrupted throughout the tumultuous developmental years of adolescence.

The second question that this thesis investigated was: 2) Is there a relationship between time spent on musical training and adolescent EF? The results of the Stroop Color Word task showed a positive correlation with lifetime musical training (i.e. total number of lifetime practice hours); the more hours engaged in practice, the better the adolescent's EF. Once again, the Stroop was the only measure of EF associated with musical training. This suggests that spending more time engaged in musical training could result in greater improvements to inhibition. The opposite could also be true: that accumulating hours of practice playing an instrument requires inhibition. Other research has confirmed that increased musical practice time is correlated with improved EF, but this finding has not been previously explored with respect to inhibition. Bergman, Darki, and Klingberg (2014) conducted a longitudinal study of adolescent musicians wherein they tested working memory every two years. They found that the musicians' working memory improved proportionally to the number of weekly practice hours they reported. Moradzedeh, Blumenthal, and Wiseheart (2015) also found that there was a relationship between weekly practice hours and the degree of EF improvement. Musicians were shown to have increased cognitive flexibility relative to non-musicians, but this entire effect was driven by musicians with high levels of practice. In the context of the current study, these findings confirm that there is a relationship between the time spent in musical training and EF. These studies undermine the notion that inhibition is uniquely involved in musical practice, as indicated by this thesis.

Thorndike's Common Elements Theory states that skills transfer between activities to the degree that those activities share common elements (Thorndike &

Woodsworth, 1901). In this context, the finding that musicians outperform non-musicians in a Stroop Task indicates that the Stroop shares relevant elements with musical production. During the Stroop Task participants are asked to parse an incoming stream of information and control their responses in a non-intuitive fashion. This is a central skill set for a musician attempting to properly respond to input from the current sounds, the sheet music, their fellow bandmates, and the sensorimotor feedback that comes with performing a piece of music. Musicians must inhibit a large number of possible responses to these stimuli in order to select the actions which will create the music they wish to produce. This is an activity which has much more in common with the Stroop Color Word Task than with Wisconsin Card Sorting, or the Tower of Hanoi.

Why is the Stroop task so much more related to musical training? Imagine a saxophone player attempting to sight read a new melody. The musician reads each oncoming note moments before they have to play it – just like a Stroop participant reads the next word as it flashes on the screen. Their fingers move to carefully practiced positions, each one unique to the note – just like a Stroop participant taps the correct key, unique to the colour. The Wisconsin Card Sort involves having to switch between unstated rule sets, where as before a musical performance all the rules are known, and the task does not change. The Tower of Hanoi requires participants to visualize spatial relationships, and plan movements, between blocks of wood, which they can execute in any way they wish, with no time restraint. A participant in the Tower of Hanoi can use untimed, and semi random movements, and still receive a perfect score as long as the overall order of those movements is correct. This is in sharp contrast with the kinds of movements which are visualized and planned in music, where precise and timely execution are the most important elements of the task. The Stroop Task is unique in how many common elements it shares with the experience of learning a new piece of music. The practice obtained in these common elements is likely the source of the relationship between the Stroop task and musical training.

An interesting result emerging from this thesis was the correlation between the global executive composite (GEC) and self-reported musical ability. Adolescents were asked to rate themselves on their ability to read music, perform music, understand music theory, and their overall musical skill. The higher the adolescent's score in this questionnaire the lower the score in the GEC (indicating better EF). This suggests that subjective measures of EF are measuring something different than the objective measures employed. This is further discussed in the next section.

3.1 NULL RESULTS

A few of the null results generated by this study deserve some consideration, as they raise questions about the nature of EF and its development throughout adolescence. 1) The finding that general subjective EF (measured by the BRIEF-SR) correlated with subjective musical ability, but not with objective time spent in musical training. 2) The failure to find an effect on cognitive flexibility – especially as it relates to childhood EF. 3) A failure to find an effect on hot EF, indicating that this element may in fact be quite separate from other types of EF. This section will address each of these issues in turn.

The General Executive Composite Score from the BRIEF-SR failed to correlate with any of the objective measures of EF employed in this study, and further failed to correlate with time spent in musical training. It did however correlate with subjectively rated musical ability. This indicates that these subjective measures of both musical ability, and EF are measuring something different than the objective measures employed. It may be that a subjective sense of being well organized and in control of life translates to a sense of competence in the domain of music, independent of the time spent actually playing. This could be interpreted as participants general confidence levels causing them to over or under report their abilities in all domains, leading to different results relative to objective measures. It may also indicate that more innately talented musicians have higher EF as measured by the BRIEF-SR, while those needing more practice become better at the Stroop. Regardless the reason, some caution should be taken in interpreting combined objective and subjective surveys attempting to evaluate the same elements of EF.

The fact that adolescent musicians in this sample do not show any improvement in the area of cognitive flexibility places them in an interesting position relative to existing literature. Zuk and colleagues found cognitive flexibility was improved in preadolescent children, but not in adults (2014). This finding places our mid to late adolescents more in line with the adult musicians than with the preadolescent children. Before this finding is overanalyzed however, it should be noted that other studies including measures of cognitive flexibility have found that music's impact on it are either weaker than in the case of inhibition, or general intelligence – or else non-existent (Degé et al., 2011; 2009). This study adds to a growing sense that cognitive flexibility is not a primary beneficiary of musical training.

Hot EF – as measured by the Iowa Gambling Task – was also found to have no significant relationship with musical training. Hot EF is defined as top down processing done in a motivationally charged environment. As a construct it was developed to address the concern that many of our decisions are made in the context of rewarding and punishing stimuli, and not merely as part of an intellectual exercise. Hot EF has not been well explored in the context of EF and music. The only two papers examining the effect of musical training on the Iowa Gambling Task used undergraduate musicians, and were published in 2017 and 2018. These studies found that musicians exhibited better performance on the Iowa Gambling Task than non-musicians, though they disagreed on whether this advantage was because of musicians who had began training in early or late childhood (Hou et al., 2017; Smayda, Worthy, & Chandrasekaran, 2018). The current study obviously fails to find any evidence of this relationship.

Despite disagreeing with the previous research, this null finding is consistent with common elements theory. Hot EF is related to the proper assessment of motivating stimuli, and this is a skill set that is fairly removed from the specialized training received by musicians. The Iowa Gambling task which is the most widely used and accepted measure of hot EF, attempts to isolate the ability of participants to respond appropriately to motivators, in the same way that the Stroop attempts to isolate participants inhibitory control. The fact that hot EF was not impacted by musical training is evidence against the idea that music improves a unified EF factor manifesting in skills across multiple domains – including hot EF. Instead it is consistent with a framework which sees EFs as mostly separate skills, bound together by the similarities in the measures used to examine them. The implications of this null finding will be discussed in a later section.

3.2 LIMITATIONS AND FUTURE RESEARCH

The current study has a number of limitations which ought to be addressed by future research in this area. A relatively small sample size meant that subdivisions between different types of musicians was inappropriate. This study only accepted participants in mid and late adolescence, making developmental inferences more difficult. The correlational nature of this study makes it impossible to make determinations about cause and effect. Finally, the uncertainty about the relationship between various EF's, and overlap in how these functions are measured is a general problem in the field which this thesis did not address. Future research could be designed in such a way that tackles these issues and allows for a more thorough understanding of adolescent EF.

There are a variety of distinctions between musical experiences that might be relevant to their impact on musical training. Training in different musical instruments or techniques might result in different cognitive advantages. For example, a vocalist borrows many of the specialized motor movements needed to make their music directly from speech, and therefore spend more of their time focused on discriminating and matching pitches. Singing ability has been associated with language imitation in children, which supports the idea that vocal training may be closely related to verbal abilities (Christiner & Reiterer, 2018). Percussionists do not need nearly the same kind of auditory discrimination, but must execute the most precise and internally motivated motor movements of any musician in order to keep time successfully. A 2017 study directly examining the differences between vocalists and percussionists in EF found that percussionists out performed vocalists, and non-musicians in the area of inhibition (Slater et al.). Previous research has shown no difference between vocalists and instrumentalists in the area of inhibition, which only serves to make the enhanced abilities of percussionists even more interesting (Bialystok & DePage, 2009). While little research has been done explicitly examining distinctions between forms of musical training, the differences we have seen are consistent with common elements theory, and worth further examination. The timing of musical training is another difference between musicians which might lead to distinct outcomes. Early musical training has been shown to increase the volume of the corpus callosum which later training does not – implying that musical training will have a larger effect if it occurs within some early critical period (Steele, Bailey, Zatorre, & Penhune, 2013). These findings indicate that some subdivisions by age of musical training, and by musical specialty may be significant to the EF differences observed here. This study was unable to account for these potential distinctions due to the limited sample size.

While this study focused on mid to late adolescents, there is a strong argument for expanding this to include participants between 11 and 13. Adolescent brain development begins in prepubescence, and undergoes some critical stages right at the beginning of puberty. Synaptic density actually hits a peak right before puberty, and the developmental processes that continue into mid and late adolescence involve a significant amount of pruning from this starting point (Blakemore & Choudhury, 2006; Gogtay et al., 2004). An ideal investigation of the impact of musical training on EF throughout adolescence would involve a longitudinal study, beginning around 9 or 10 years of age, and continuing until early adulthood. Such a design would allow researchers to observe the change of each EF across time, without depending on the inferences required in cross sectional, and correlational work as is presented here.

This study was limited by its failure to include a dedicated measure of working memory. While the Tower of Hanoi includes elements of memory within its measurement of planning, this is a poor replacement for a dedicated memory task. This was a serious oversight because next to inhibition, working memory is the most reliably demonstrated beneficiary of musical training. A popular test of working memory which could have been used is the digit span backwards test, where participants are asked to memorize and repeat a string of numbers immediately after seeing them appear on the screen (Sala & Gobet 2017). It would be interesting to examine the differential impact of music on auditory and visual versions of this task, as was done for the Stroop by Bialystok and Depage (2009). Including a dedicated measure of memory would allow for a more complete assessment of the relationship between musical training and EF in adolescents.

Another issue not appropriately addressed by this study is the question of whether EF development in adolescence can be improved by direct musical intervention. While this study does establish a relationship between inhibition and musical training in adolescents, it is unclear whether musical involvement in the adolescent years is truly responsible for this improvement. It is possible that childhood musical training is responsible for the entire effect observed here. Similarly, it is possible that adolescents with stronger inhibitory skills are more likely to continue engaging in musical training even as they gain more independence in the mid adolescent years. In order to address this issue, it would be necessary to give adolescents musical interventions in the style that has been used to improve childhood EF. A study like this would involve taking adolescents without prior exposure to musical training and providing them with extracurricular arts training, and music training, and comparing these groups after a year. A study in this vein would allow researchers to determine whether musical training was causing these improvements in EF, and allow confounders from income and personality to be more controlled for.

While exploring musical interventions, it is worth considering what they are replacing in these adolescents' lives. There is some evidence to suggest that increasing musical training within school time is ineffective at improving cognition. Rickard and colleagues conducted a study of school children between the ages of 10 and 13, in which the researchers increased the amount of musical education available to some of the students. Students were assigned to one of three classes, where they received drama, art, or musical instruction. The participants then were given a battery of tests examining their IQ, mathematical and verbal ability as well as a few other indicators. Socioeconomic status was found to be balanced between the drama and music conditions, but not the art class. The musicians did not improve relative to the drama group on any measure (Rickard et al., 2012). This runs counter to findings from intervention studies which found that engaging children in extracurricular musical instruction did result in increased IQ (Schellenberg, 2004; 2006). One explanation is that the drama classes are equally effective at improving EF, leading to a wash out of the effect. Rickard and colleagues did report a slight improvement in these two groups relative to the arts group which is consistent with the findings from Schellenberg. However as previously mentioned this difference was confounded by a significant difference in the socio-economic status between the art group and the others. Regardless of the specific explanation, these findings demonstrate that the benefits which musical training provides to general cognition are available through other cognitively demanding tasks. Common elements theory implies that cognitively demanding activities will transfer discrete skills to other domains, if those skills are practiced during the activity.

Extra curricular musical training means practicing for hours every week, after school. While other children may take a break, or not have an opportunity to engage in a cognitive exercise after school, music students are struggling to translate dots on a page into music in the air. This extra period of instruction and practice may itself be the cause of the improved cognition observed across the board in musicians. It is also true that musical training costs money. This means that the average musician may be of higher socioeconomic status, which confounds these results by providing them with extra opportunities and safety. Again, intervention studies, where music lessons can be provided regardless of economic status, and musical training that can be compared against equally challenging programs are needed to address these issues.

3.3 DIVERSITY OF EXECUTIVE FUNCTIONS

Throughout this thesis so far EF has been treated as a meaningful united construct including multiple separate elements, however there are reasonable objections to this view of EF, some of which have an impact on these findings. EF has been modeled in a variety of ways throughout the years, with different assumptions making their way into subjective tests of EF. This is further complicated by the use of objective tests of EF, which cannot be reliably shown to correspond with the factors of EF they are meant to measure. Recent work has raised concerns that models of EF derived from objective tests may not be replicable, and are prone to portray EFs as more unified than they actually are (Karr et al., 2018). During a previous experiment earlier in my Masters, objective measures of EF did not correlate with each other, or with the subjective BRIEF-SR, and no factor model was accepted. These considerations throw into question the entire concept of EF as a unified collection of abilities which can be improved as a unit.

Subjective surveys of EF measure the different factors of EF by asking questions designed and confirmed to be measuring the same thing. Factor analysis is used in the development of measures like the BRIEF-SR, ensuring that the results of the survey will be reliable, and will correspond to a particular model of EF, as specified by the creators of the questionnaire (Guy, Isquith & Gioia, 2004). It is not at all guaranteed however that the factors generated in a subjective test of EF correspond to the same abilities that are measured by objective tests of EF. Furthermore, many tests of EF involve the use of multiple theorized factors of EF. The Wisconsin Card Sorting task for example has been used as a measure of inhibition as well as a measure of cognitive flexibility (Steinmetz & Houssemand. 2011). This overlap leads to a lack of clarity on the nature and definition of the various EFs.

A systematic review from the University of Victoria attempted to understand how the elements of EF changed throughout the lifespan. They included studies using objective measures of EF to construct models using confirmatory factor analysis. They identified the task or tasks being included in each model as a proxy for the factors of EF, and reanalyzed the data for all of the samples where sufficient information was supplied. Their reanalysis included a simulation of how often each model of EF would be accepted given that the findings of the original paper were accurate. They did find a general trend where EF became more complex, moving from single and bifactor models in childhood, to nested factor models as the most often accepted in adulthood. This headline view does however obscure the fact that most models failed to be accepted, with the simulation finding that for child and adolescent samples the accepted model of EF would only meet fit requirements 30-36% of the time, based on the most lenient analysis. This gives evidence for a publication bias in the literature for models of EF based on objective measures which are well fitting, but ultimately unlikely to replicate (Karr et al., 2018).

During pilot studies at the beginning of this project an attempt was made to establish the relationship between objective and subjective measures of EF. Undergraduates at the University of Lethbridge completed the BRIEF Adult

Version, as well as the battery of objective EF tasks that were used in this study. Pearson correlations, and exploratory factor analysis were performed in an attempt to demonstrate that both measurement techniques were examining the same EFs. No elements of objectively measured EF correlated significantly with BRIEF-A factors, and no model of EF met fit requirements. Although these results could be due to poor study design, they are illustrative of the ambiguity surrounding EF generally. There is no agreement between the various measures and tasks considered to be examining EF. Even tasks and questionnaires said to be querying the same element of EF do not always agree, and considerable caution should be taken when comparing subjective and objective measures together.

The concern here is that the relationship between the various EFs is fundamentally unclear. While all the examined elements of EF fit the definition of being high-level cognitive skills, recruiting and directing other capabilities, it is not clear whether or how they are otherwise related. A case in point from the current study relates to the examination of hot executive function. Hot executive function develops quite rapidly during late adolescence, and so was selected to be a part of this study in the hopes that it would be improved in musically trained adolescents (Principe et al., 2011). The Iowa gambling task is considered a good measure of hot EF because it isolates participants ability to respond appropriately to motivating stimuli, which is makes it a fairly distinct task within our battery. The null result observed here indicates that hot EF is not closely related enough to musical training to result in any kind of skill transfer. This result is in the same vein as Sala and Gobet's (2017) meta-analysis on the subject of skill transfer, which found that with the exception of memory and IQ, music did not appear to have any effect on children's academic or cognitive abilities (this study did not include a measure of inhibition). These findings suggest a framing in which EF is simply a label for a loosely related set of skills and abilities, each with their own independent associations.

These concerns also apply to the other elements of EF which have been discussed in this study. The simplest explanation for the results observed here is that the Stroop Task tests skills, which are also associated with long term musical training. Whether these skills correspond to the same thing as is referred to as inhibition in subjective surveys of EF, or other objective tests of inhibition is not addressed by this thesis. While a variety of EFs have been implicated in musical training by previous research, these results need to be assessed in terms of the specific tasks used to measure the EF.

3.4 CONTRIBUTION AND CONCLUSIONS

The current study examined the relationship between musical training and EF in mid to late adolescence. Musical training was found to be associated with better inhibition – as measured by the Stroop Task, - but otherwise to have no relationship with EF during these ages. The findings of this thesis provide evidence in support of Thorndike's Common Element Theory of skill transfer, because of how sharply limited the impact of music on EF was shown to be. Music was only shown to improve participants performance on the Stroop task, which bears important resemblance to the activity of practicing a new piece of music. This supports the hypothesis that the association between musical practice and EF is driven by common elements shared between music and the neuropsychological assessments used. Future research should focus on determining causality, and accessing whether it is feasible to use music to improve general inhibition in adolescents. These findings contribute to our understanding of the development of EF, and how skill transfer can contribute to this development.

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