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A comparative analysis of musical ability and performance on mathematical exams determined by brain activity and scoring

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COMPARATIVE ANALYSIS OF MUSICAL ABILITY AND PERFORMANCE ON MATHEMATICAL EXAMS DETERMINED BY BRAIN ACTIVITY AND SCORING

by

MADELEINE SCHUTTE

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Approved by

First Reader
Jonathan Wisco, Ph.D.
Professor of Anatomy and Neuroscience

Second Reader
Zachary Davis, Ph.D.
Professor of Chemistry
Wofford College

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ABSTRACT

Introduction: The correlation between musical training and academic performance has been explored through several different venues of research in the fields of music, mathematics, and neuroanatomy. Previous research has shown evidence that a correlation between musical abilities and improved performance in academic subjects such as reading, math, and IQ. However, the precise mechanisms by which music influences academic performance as well as how the processing of them may vary, remain unclear. The ability to play music is related to the development and enhancement of executive functioning skills, which are crucial in completing mathematical tasks (Janurik 2019). Executive functions are a set of cognitive processes that are largely associated with the prefrontal cortex and include working memory, attention shifting, decision making, and cognitive flexibility. The aim of this study is to determine the cognitions w/ music which music enhances executive functions, how this translates to performance in various mathematical subjects, and if this connection can be seen by differential activation of areas within the prefrontal cortex.

Methods: Eight male and female adults between the ages of eighteen and twenty-nine in the Boston area were recruited in this IRB- approved study. Their experience in musical training and mathematical knowledge was assessed, as well as their highest education level. Four subjects were determined to be musicians and four were determined to be non-musicians from their score on a music competence assessment, as well as their reported experience with musical training. Testing was the same for all subjects and the music assessment tested ear training, reading music, and rhythm. Participants also completed a math assessment that tested abilities in geometry, algebra, and sudoku. While completing the assessments, a functional near-infrared spectroscopy (fNIRS) headband was worn that measured activity in the prefrontal cortex bilaterally. Activity will be determined by looking at the area under the curve of the difference between concentration of oxygenated and deoxygenated hemoglobin in the right and left dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC), orbitofrontal cortex (OFC), and inferior fronto-lateral cortex (IFLC) for each task.

Results: Of the eight enrolled in the study, four participants were determined to be musicians and four determined to be non-musicians based on a self reported questionnaire as well as performance on a standardized musical and mathematical assessment. Musicians showed a significant difference in consumption of oxygen in the left VLPFC during the algebra task (p=0.043). Scores on both the musical and mathematical assessment predicted activation of the left hemisphere for the geometry task ($p < 0.038$), right DLPFC for the sudoku task ($p < 0.020$), and activation of the right DLPFC for the sudoku task ($p < .038$). Score on the music assessment predicted activation of the right DLPFC for the geometry task ($p < 0.020$). Correlations between all of the variables tested were also determined.

Conclusion: Participants with a higher score on the music assessment predicted activation of the left hemisphere with specialized use of the right DLPFC for geometry and sudoku problems when compared to non-musicians. Musicians showed significantly differential activation of the left VLPFC during the algebra task. A correlation was found between left hemispheric activation during the geometry task and activation of the right DLPFC for the rhythm task. These results indicate that musicians use different cognitive processes in solving various problems when compared to non-musicians.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADHD .... **Attention Deficit Hyperactivity Disorder**

ANS .... **Approximate Number System**

AUC .... **Area Under the Curve**

BOLD .... **Blood Oxygenation Level Dependency**

DLPFC .... **Dorsolateral Prefrontal Cortex**

fNIRS .... **Functional Near Infrared Spectroscopy**

FPPFC .... **Frontopolar Prefrontal Cortex**

HbO2 .... **Oxygenated Hemoglobin**

HbT .... **Total Hemoglobin**

HbR .... **Deoxygenated Hemoglobin**

IFC .... **Inferior Frontal Cortex**

IFLC .... **Inferior Fronto-Lateral Cortex**

IQ .... **Intellegence Quotient**

LIPFC .... **Lateral Inferior Prefrontal Cortex**

OFPFC .... **Orbitofrontal Prefrontal Cortex**

PFC .... **Prefrontal Cortex**

VLPFC .... **Ventrolateral Prefrontal Cortex**

CHAPTER ONE

Introduction

The Mozart Effect is a widely known phenomenon based on the ideas that listening to the classical music of Mozart would temporarily boost IQ scores in areas that correlate with spatial intelligence (Rauscher et al. 1997). While the results of this 1993 study were significant, further research has found them to be irreproducible. The factors that could account for inconsistenty in the results as well as the potential of enhanced academic achievement, has inspired further research on the association between music and intelligence. The first distinction that is crucial in exploring this connection is the difference in listening to music and having musical training. One explanation for the results of The Mozart Effect study is that listening to music enhances arousal, leading to more positive moods and better performance on tasks that require spatial-temporal reasoning (Thompson et al. 2001). However, with evidence that taking music lessons as a child is a predictor for intelligence as a young adult as well as for academic performance throughout high school, enhanced cognitions associated with music must be analyzed in relation to experience in musical training (Schellenberg 2006). The relevance of mathematics in academics combined with the striking similarities of music and mathematical systems, provide one avenue of examining this relationship. Previous research has included various aspects of these questions such as examining the structural similarities of music and math (Beer 1998), the various reasoning skills required for different mathematical categories (Dehaene et al. 1999), and the changes in the brain associated with playing music (Costa-Giomi 2015). While these studies provide insight into the connection between music and math, there is little data that directly compares the brain activity of a musician and mathematician with their corresponding performance in different mathematical categories (algebra, geometry, etc). Not only is the connection between musical abilities and mathematical performance in various tasks of interest, but also which component of playing music changes cognition. The variables within music that may have an impact on mathematical cognition include fractions, ratios, the understanding of complex systems, and manipulating numbers in an abstract space (Kells 2008). The next important factor in evaluating these relationships is to distinguish the different reasoning skills required to answer mathematical questions, specifically in various categories. One's mathematical intuition can change how problems are solved individually, whether it be from viewing numbers as a linear progression of magnitude, or as symbols dictated by previous experiences or language (Dehaene et al. 1999). The ability to complete more complex mathematical systems and problems begin with a foundational understanding of the number as a magnitude. Executive functioning (EF) skills allow us to recall and manipulate our knowledge of facts for flexible thinking and problem solving, crucial in our ability to solve complex math problems (Gilmore 2018). Moreover, certain aspects of music that are required of a musician, such as rhythm perception and reproduction, are associated with more advanced EF skills (Degé 2011, Moreno et. al 2011). With evidence that a high level of executive functioning is required and cultivated through both music and math, looking at brain activity in areas known to be associated with EF's in an individual performing both musical and mathematical tasks, would provide direct evidence for a correlation in processing and brain activity between the two. Our study aimed to find this link by using functional near infrared spectroscopy (fNIRS) to examine brain activity, and comparing this to scores on musical and mathematical assessments. The degree of competence in musical abilities was measured using tasks from a standardized exam adapted from the Carnegie Hall- Music Educators Toolbox, and mathematical ability will be measured using SAT problems of geometry and algebra. Performance in sudoku was also tested as a visual form of mathematics. Using fNIRS to measure brain activity within the prefrontal cortex; while performing these tasks, provide insight into the degree of brain activity during both the music and mathematical examination. The fNIRS device measures hemodynamic changes in the brain associated with increased activity or stimulation in an individual. This measurement provides further evidence of similarities and differences in mathematical processing between musicians and non-musicians within the prefrontal cortex. Brain activity along with the comparison of scores between the two assessments will provide data on the connection between being a musician and its effect on mathematical capabilities.

Prefrontal Cortex

The prefrontal cortex (PFC) is widely responsible for several cognitive functions such as attention, decision making, and working memory that allow for a response based on sensory information coming from the environment. This integration of neurological networks is known as executive functioning (EF), and is critical for regulating behaviors in accordance with a desired or predicted result (Cragg & Gilmore 2014). The dorsolateral PFC (DLPFC), ventrolateral PFC (VLPFC), orbitofrontal cortex (OFC), and inferior frontal cortex (IFC) are areas within the PFC, each contributing to different levels of executive functioning. These areas are divided into the right and left hemispheres which work together in processing different aspects of information and cognition (Banich, 1998). The right hemisphere is responsible for aspects of working memory, cognitive flexibility, and perception of spatial relationships, while the left hemisphere is responsible for logical reasoning, verbal working memory, and sustained attention.

Within the right hemisphere, the DLPFC is responsible for the execution of complex behaviors such as decision making, that require goal setting and inhibition of undesirable actions (Gilbert 2006). Its role in manipulating information through working memory can be seen in tasks that require spatial reasoning and mental arithmetic. The right DLPFC is able to temporarily store newly presented information and combinie it with rules and facts previously encoded. The right IFC and VLPFC work together in switching attention to various mental sets, allowing for cognitive flexibility, which is crucial in complex tasks that require multiple different kinds of information or rules to be used. They also play a role in aspects of social cognition, such as interpreting facial expressions and tone of voice in order to make judgements about a situation (Hampshire 2010). The right OFC works in conjuction with other areas of the right hemisphere of the PFC, but its most important role is in encoding and retrieving emotional memories. This helps in determining a response to new stimuli, given its ability to consider potential outcomes based on previous experiences (Kringelbach 2004).

Within the left hemisphere the DLPFC plays a significant role in verbal fluency and processing language (Fuster 2013). The posterior left IFC is critical in language production, specifically in Broca's area. It's role in working memory is to store and update information that can then be manipulated by new information that is presented (Derrfuss 2005). The left VLPFC allows for the shifting of attention between tasks, inhibition of distracting information, identification of words used in lexical processing, as well as semantic processing of words. Dysfunction of the VLPFC is associated with attention and language disorders such as attention deficit hyperactivity disorder (ADHD) and aphasia (Badre 2007). The left OFC is critical in by evaluating potential outcomes that aid in decision making, as well as in the assessment of reward-related stimuli and potential reward of a behavior (Bolla 2003).

Mathematical Cognition

Various categories within the scope of mathematics such as algebra, calculus, and geometry, are evidence for different methods of solving problems. The cognitive processes that individuals use when solving these problems is dependent on their own concept of the "number" The root of these conceptual differences stem from perceptions of a number as a magnitude versus a symbol that represent a value within a larger system. Perceiving a number as a specific magnitude describes a non-symbolic processing of mathematics, while having a more symbolic concept of a number as a representation of magnitude within a system allows for a visuo-spatial approach (Dehaene et al. 1999). The approximate number system (ANS) is a template, (that falls within the non-symbolic processing of numbers), for the cognitive ability to understand quantities and is required in order to apply a meaning or mental representation of the number as a symbol in more advanced mathematical proceses (Dehaene 1999, Geary 2013).

The ability to compare different magnitudes that are represented visually begins at an early age and is seen across different cultures and in non-human species. An example of a task that requires this distinction can be seen in Figure 1. Performance on this non-symbolic number comparison or arithmetic task is known as number acuity (Chen and Li 2014). Once the distinguishment is made between separate quantities, applying a symbol to them becomes the basis of mathematics. The link between higher number acuity and better performance on symbolic mathematical tasks is evident in fractions and decimals, which allow for a symbolic representation of more exact quantities (Wong 2019). Neurological processes such as working memory and attention which are components of executive functions, and are predictors of children and adolescents ability to understand fractions (Bailey et al. 2014).

Symbolic mathematical skills are applied when using a visuo-spatial approach to completing problems that require decoding of the problem into an equation or a shape that is not seen directly. Examples of these include word problems that require the generation of an equation, mental rotation of a shape, applying mathematical concepts to a complex problem, and conceptualizing a shape that is represented numerically **(**Figure 2). More developed visuo-spatial reasoning skills are correlated with higher SAT scores and are a predictor of mathematical abilities (Tosto et al. 2014). Visuo-spatial reasoning of mathematics (symbolic system of mathematics) relies on a combination of the ability to manipulate and make judgements on new information while recalling previously encoded information.

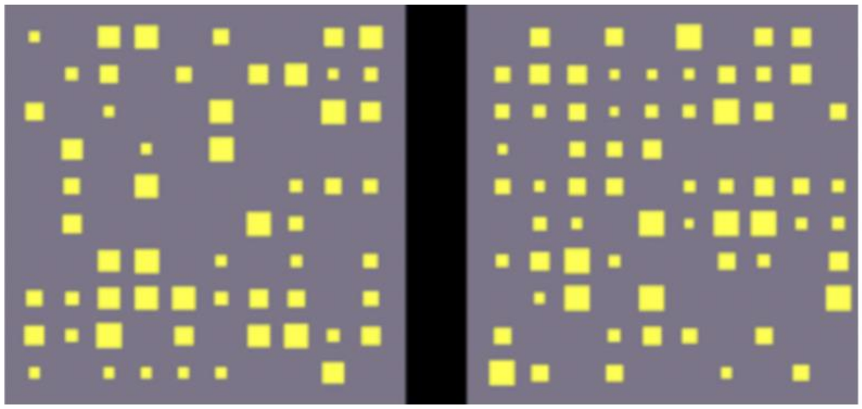

Figure 1. A magnitude comparison task. Completing this task asseses non-symbolic understanding of numbers and is related to later arithmetic performance (Finke et al. 2020).

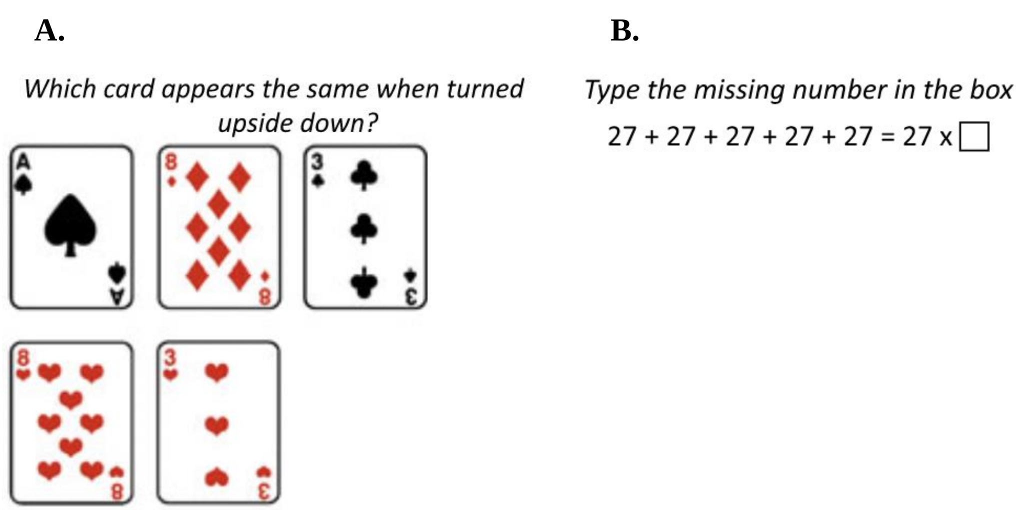

Figure 2. Examples of symbolic mathematical thinking. Problem A requires a non-numerical process that relies on mental rotation and reflection. Problem B requires an understanding of numeric and algebraic processes to be applied. (Tosto et al. 2014).

Mathematics and the Prefrontal Cortex

Working memory, shifting attention between tasks, and inhibition of unnecessary information and actions are crucial in completing tasks with complex schemas such as in mathematics (Cragg & Gilmore 2014). These EF cognitions are crucial to several different academic fields and is a predictor of performance in mathematics. Specifically, there is a relationship between the ability to temporarily hold and manipulate information in working memory and proficiency in mathematics. A model of working memory created by Baddeley is frequently used by researchers as a framework for mathematical cognition. The four main components of this are the phonological loop, visuospatial sketchpad, episodic buffer, and the central executive (Agostino 2010). The purpose of the phonological loop and visuospatial sketchpad are to process content and facts, such as verbal information, rules to a schema, or visual-spatial knowledge. While this content is being processed, the episodic buffer works to integrate the different types (i.e. phonological, visual, and spatial) information together. The central executive component is theorized to control this information, relate it to long term memory, and regulate the outcome of this information (Baddeley 1998). The fronto-parietal network of the brain is responsible for mathematical processes, linked to executive functioning (Wang 2019).

Both numerical processing and arithmetic functions involve the PFC, however previous research shows differential activation within the PFC when completing symbolic versus non-symbolic, numerical mathematical tasks (Cantlon et al. 2009). As described above, a non-symbolic understanding of magnitudes and quantities is necessary prior to completing abstract mathematical problems that require mental manipulation. Therefore, children rely on non-symbolic processing of mathematics more heavily than adults, due to less knowledge and experience in mathematics. The left inferior frontal gyrus shows increased activity both in children and in adult subjects who complete magnitude comparison tasks, showing the role of this area of the prefrontal cortex with fundamental mathematical knowledge (Cantlon et. al 2009, Venkatraman 2005). One explanation for this is that in juvenile sibjects with less knowledge of mathematical rules and schemas, there is an increased effort to encode patterns and representations. In more complex mathematical tasks, mental manipulation of numbers requires working memory, a core component of executive functioning (Zago 2008). Research has shown increased activation in the DLPFC for tasks require several aspects of working memory, such as manipulating information and associating it with previously encoded information (Janurik 2019). The working memory function within the DLPFC is used in completing mathematical tasks that are presented differently and that require distinct methods of processing such as algebra and geometry. However, its activation is also dependent on prior knowledge of mathematics and already exsiting ability to use executive functioning cognitions. A study by Koenigs et al. in 2009 showed that the left DLPFC was critical in spatial working memory tasks by having participants differentiate shapes separated by a delay, and applying transcranial magnetic stimulation to one hemisphere of the DLPFC during the delay. Disruption of the left DLPFC impaired the participants ability to recognise geometric shapes (Koenigs et al. 2009). Furthermore, the ability to recall visuo-spatial information from working memory is a predictor of mathematical performance in children, due to processing more complex mathematical problems with less experience (Menon 2016). Activation of the left DLPFC and right VLPFC are associated with visuo-spatial abilities in increased problem- complexity (Figure 3). This study had adults with an IQ above 80 complete working memory tasks that involved recalling quantities of dots that had been presented previously, as well as recall the length of a string that was previously shown (Metcalfe et al. 2013). With increased activation of the DLPFC and VLPFC in children compared to adults and in operations that require working memory, it is proposed that these areas are important in completing complex mathematical tasks. The proposed correlation between the prefrontal cortex and mathematical reasoning in this study is that the left DLPFC is associated with the retrieval of mathematical rules and general knowledge of numerical quantity, while the right VLPFC is responsible for making judgements on the information (Menon 2016). Similarly, left hemispheric activation of the PFC in solving basic arithmetic problems was found in a study by Venkatraman et al. (2005); however this study found evidence for increased activation of the left VLPFC, suggesting that mathematical problems can be solved with direct knowledge of arithmetic facts.

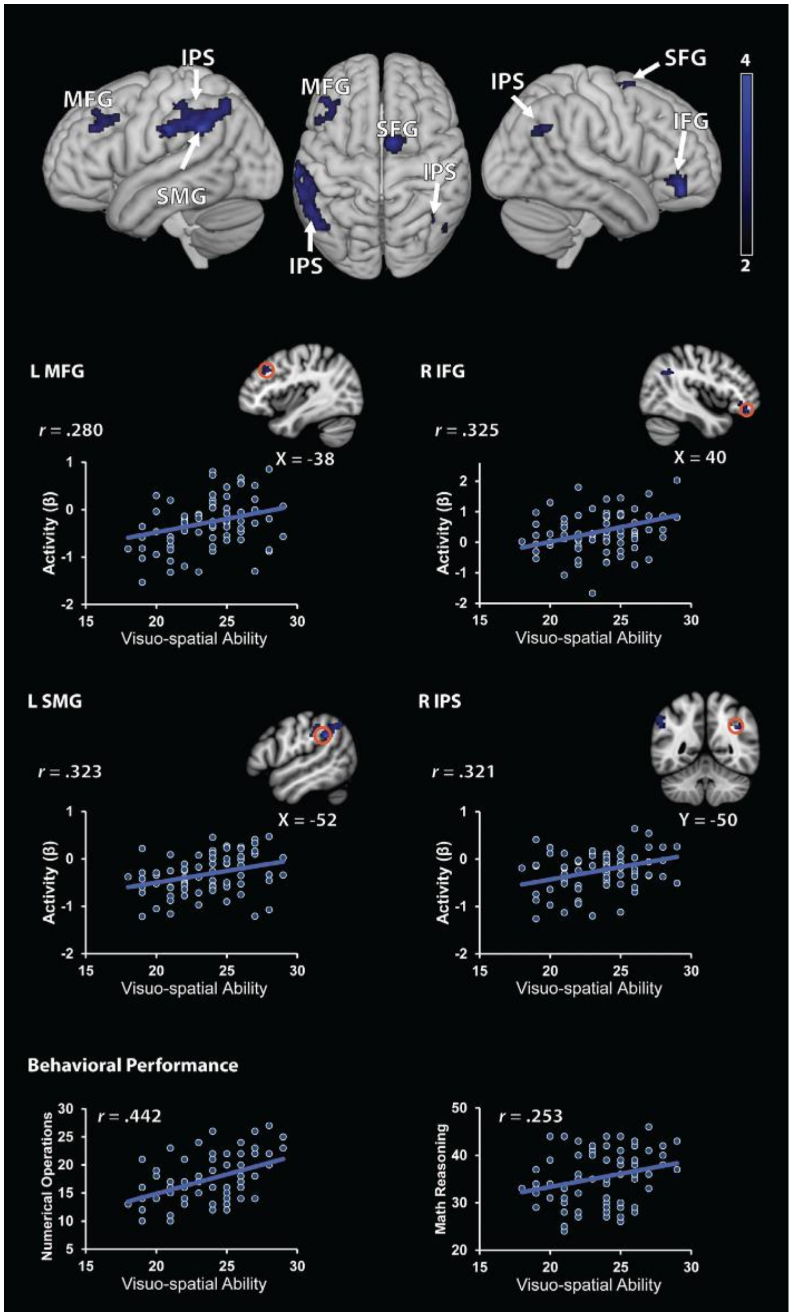

Figure 3. Activation of the brain associatied with the processing of visuo-spatial information. Increased response from the left DLPFC, right VLPFC, and the bilateral posterior parietal cortex including the intra-parietal sulcus in adults completing working memory tasks. (Metcalfe et al. 2013).

To better understand the role of the prefrontal cortex in solving simple arithmetic problems and problems that require more complex mathematical reasoning, a study done in 2012 aimed to determine the role of the prefrontal cortex in visuospatial reasoning (Ayaz et al. 2012). The goal was to examine the PFC's role in complex arithmetic problems and spatial reasoning without interference from areas of the PFC responsible for simple number tasks and recall. They did this by having participants complete a tangram task (a geometric puzzle) that required mental manipulation of an object in space

Figure 4. Tangram task for determining prefrontal cortex activity with visuospatial logic. Participants of this study were asked to fit the blue pieces into the white shapes (Ayez et al. 2012).

Brain activity from the PFC was measured with an fNIRS device that showed concentration changes of oxygenated hemoglobin (HbO2) and total hemoglobin concentration (HbT) within the prefrontal cortex. These concentration changes represent changes in activation while completing this task. The results from this study showed significant difference in activity of the right PFC when completing problems that required working memory and problem solving (Figure 5).

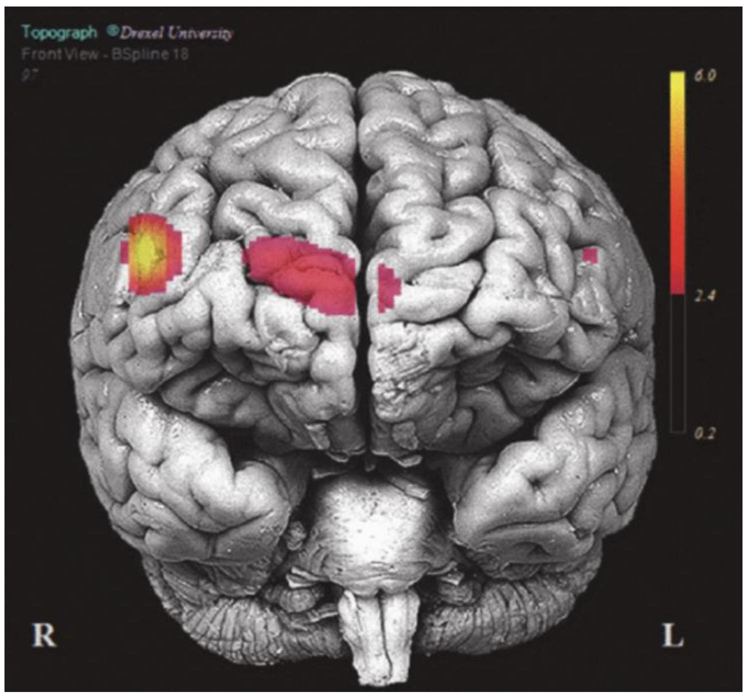

Figure 5. Right hemisphere activation during problem solving Task. Significantly different activation of the right hemisphere in participants completing the problem solving task compared to the control task ($p< 0.05$). (Ayez et al. 2012).

With the results of this study finding significantly more activation in the right hemisphere with tasks that don't require simple arithmetic calculations, it is expected that bilateral action will be present where both mental processes are required. For example, a task such as sudoku where both direct and abstract knowledge of numbers is required, the medial regions of the PFC are activated showing the connection between the right and left hemispheres of both the DLPFC, and VLPFC (Ashlesh et al. 2020).

Musical Cognition

Playing, reading, and listening to music inherently involves the translation of numbers into an abstract form of art. Fractions are embedded within the structure of music in dividing time, as well as in scales and arpeggios. In order to play music, there must be a general understanding of the structure and rules of music itself, pitch discrimination, and rhythm; each of which require a high level of executive function (Okada and Slevc 2018). The working memory component of executive functioning is critical to the ability to play music, such as when an individual recalls their knowledge of musical structure and sounds to comply with a given rhythm, and subsequently combines this with new information in order to make decisions and predict patterns (Degé 201). In major-minor tonal music, chords exist in a schema that is regular and recognizable in people with musical abilities. The ability to recognize a chord that does not fit within this musical schema, as well as inhibition of playing a chord out of sequence are common uses of working memory in musicians (Koelsch et al. 2005). Because of the complexity of the various aspects of music, the act of playing music requires shifting attention, describing cognitive flexibility. Not only does the act of playing require these cognitions, but posessing musical skills such as rhythm perception and reporoduction have been shown to improve it (Degé 2011). Other studies have found a relationship between higher executive functioning and the ability to discriminate components of melody and pitch (Janurik et al. 2022).

Music and the Prefrontal Cortex

Previous research with musicians and non-musicians has aimed to identify differences not only in brain activation, but also differences in the structure of the brain itself. As described above, several aspects within executive functioning skills are required of musicians, thus, the prefrontal cortex is of particular interest in understanding the mechanism in which music enhances these skills. One proposed mechanism is that musical syntax has shown to be localized in the interior-fronto lateral cortex (IFLC) (Maess et al. 2001). Musical syntax describes the rules and structures embedded within music and include the recognition and reproduction of rhythm and pitch, as well as reading and interpreting musical symbols and notes. Recognizing and predicting patterns as well as distinguishing when something does not fall into a pattern, are key components of executive functioning. An example of this function in pattern recognition can be seen in examining tonic chords vs. Neopolitan chords. Tonic chords are regular occurances in musical structure and are played within the same key, while Neopolitan chords contain a diminished note and are irregular. Tonic chords are easily predictable and recognizable by musicians due to the frequency in which they occur as well as knowledge of musical structure. A previous study found that in adults that were played Neopolitan (irregular) as opposed to tonic (regular) chords, both hemispheres of the IFLC and orbital frontolateral cortex (OFLC) were more activated in musicians when compared to non-musicians (Koelsch et al.2005) (Figure 6). This study also found that when the same experiment was done in children, those with musical training showed increased activation in the right IFLC compared to non-musicians. The results of this study align with other research that found pitch and melody to be associated with right hemispheric activation, while rhythm is associated with left hemispheric activation (Limb 2006).

In further examining the mechanism in which melody, pitch, and rhythm effect executive functions, it is important to note that these components of music all involve patterns; thus, activation of the PFC associated with the disruption of an expected pattern must be considered. Evidence for right hemispheric activation associated with pitch and melody is seen in comparing musicans with absolute pitch and musicians without absolute pitch. Absolute pitch is the ability to recognize a note purely from memory as opposed to recognizing it in the context of other notes, described as relative pitch. In musicians that did not have absolute pitch, increased activation of the right hemisphere was seen when determining notes from a musical sequence when compared to musicians with absolute pitch. The proposed reason for this is that musicians that have absolute pitch were able to simply recall the notes, instead of using working memory to determine them (Limb 2006). A similar study by Ohnishi found results that differ from the study described above, but that are concurrent with the mechanism. Results from this study revealed that musicians had significantly more activation of the left DLPFC while completing a task meant to assess absolute pitch ability when compared to non-musicians. The left DLPFC is known to have a role in the lexical naming and

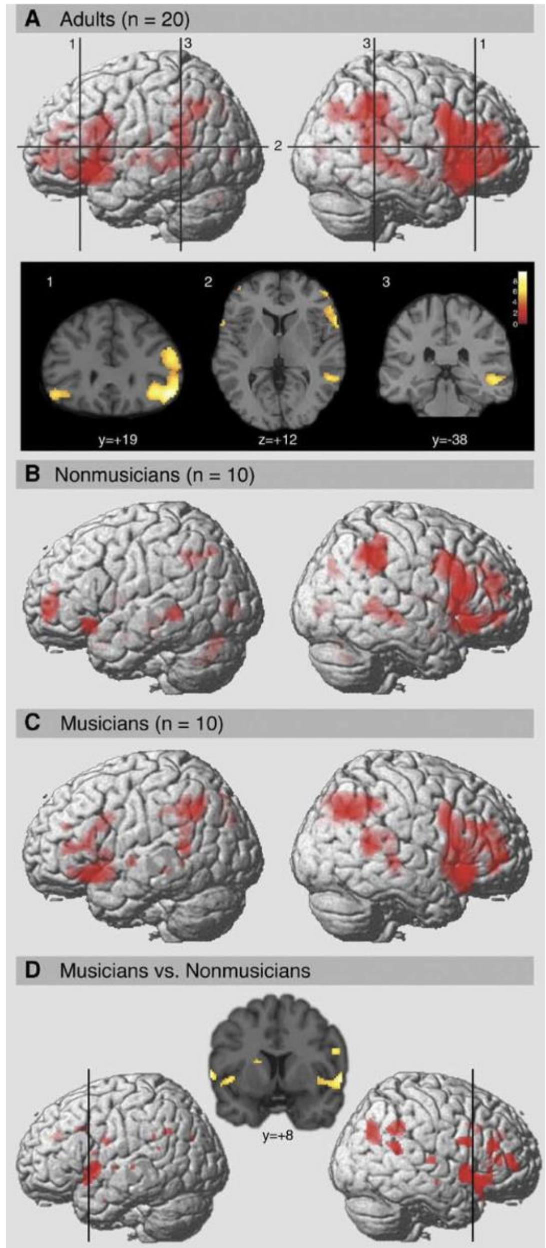

Figure 6. Brain activity in musicians vs. non-musicians. When listening to an irregular vs. regular chord within a sequence, adults (n=20) showed bilateral activation of the IFLC and OFLC for the irregular chord as seen in section A. Sections B and C are representations of this when musicians and non-musicians are separated. Musicians showed increased activation of the right and left IFLC compared to non-musicians. (Koelsch et al. 2005).

retrieval processes of language, similar to how notes must be labeled for processing absolute pitch (Ohnishi et al. 2001). As musicians have more knowledge of these notes compared to non-musicians, determining pitch is using recall rather than working memory. Further evidence for right hemispheric specialization of pitch and melody is that in examining tone discrimination in subjects with damage to the right hemisphere, ability of the subjects to process musical tones was impaired. Similar results are displayed when examining rhythm, which requires temporal processing as well as the understanding of intervallic information. Integer-based or quantized rhythm is associated with left hemispheric activation in musicians, eluding to their knowledge and experience using this cognition within music. There is significant data that musicians display dominance in the left hemisphere when completing musical tasks when compared to non-musicians, however this is an over-simplification of the neuroscience of music given the variation of skills that are required to play it. For example, a study that examined differences in executive functioning between musicians and non-musicians found that in a musical task that requires the shifting of attention, musicians showed significantly more activation in the right VLPFC when compared to non-musicians. Conversely, musicians showed more activation in the left VLPFC in completing all executive functioning tasks (Zuk et al. 2015). The combination of these results elude to less use of right hemisphere dominanted working memory for advanced musicians, as well as enhanced use of the right hemisphere when required to use working memory (Ohnishi et al. 2001).

Similarities in Music and Math

The connection between ability to play music and subsequent IQ or academic performance begins with how different aspects of music are processed, and which cognitions are different in those with musical abilities. Complex musical tasks require combining auditory information with cognitive operations, leading to a distinct method of processing information (Peretz 2005). Previous research has shown that this template of processing is similar to the process of reading and language systems, as both require a unique combination of phonological awareness, retention, and manipulation of factual information (Ziegler and Goswami 2005). The result of this is a higher level of executive functioning skills, that transfer to abilities in other fields such as mathematics (Moreno et al 2011). To begin examining the correlation between performance on different subjects of math and musical abilities that are mediated by executive functions, music will be examined in three different contexts: rhythm, reading music, and pitch perception.

Rhythm is a vital component of music as it sets the tempo in which the melody and notes are subdivided and counted. The most obvious requirement in understanding rhythm is the ability to count (Roberts 2016). In order to count beats in a musical piece to occur, the timing of each note must be determined from the notation of what is written, as well as the ability to hold counts while thinking ahead to the next note. The length of time that a note is held is determined by how it is written. For example, a whole note is open in the middle and has no stem (Figure 7). Furthermore, each successive note is half the length of the previous note, forming a geometric sequence.

Symbol:	𝅝	𝅗𝅥	𝅘𝅥	𝅘𝅥𝅮	𝅘𝅥𝅯	𝅘𝅥𝅰
Name of note:	whole	half	quarter	eighth	sixteenth	thirty-second
Number of beats:	4	2	1	1/2	1/4	1/8

Figure 7. Notation of Musical Notes that determine the Length of Time a Note is Held. The way that a note is written determines how long it is held and subdivided based on the tempo of a musical piece. (Gareth E Roberts 2016).

The sequence shown above can become a geometric series by finding the sum of the notes, similar to how the timing of different notes are accounted for within a measure. For example, the most common time signature is 4/4, where each measure is four beats and a whole note is equal to four. Within a measure of four beats, the combination of notes played must be subdivided to equal four, or tied to the next measure to account for one if that measures four beats. For advanced musicians, this mental addition and subtraction of notes becomes a pattern and is easily repeated and recognized (Figure 8). Research has shown that rhythm training or having rhythm perception through music training is correlated with higher performance on arithmetic tasks (Janurik et al. 2019). The understanding of rhythm is translated to mathematical processes involving working memory in holding information of patterns and counts as seen in arithmetic. It also translates to having a better “number sense” in understanding quantities and magnitudes, that translate to a symbolic understanding of numbers in more complex tasks.

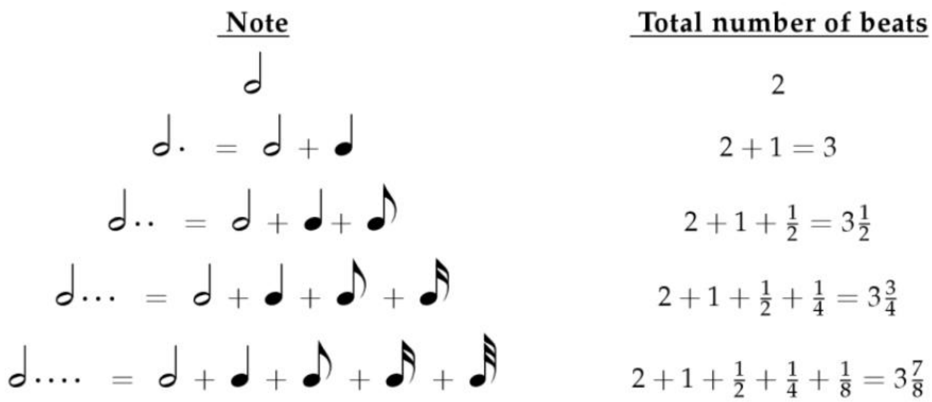

Figure 8. Summation of notes with various types of notes given a 4/4 time signature. Each note represents a distinct amount of time within each measure and must sum to the time given. (Roberts 2016).

Musical perception is the processing of auditory information that is heard from a musical piece. This is done in various levels such as in the melody, harmony, and pitches of individual notes. Perception and understanding can vary based on culture and language, and is more innate in certain individuals. Similar to rhythm, patterns that are heard within a song are also structured as fractions and ratios. These ratios begin with scales and arpeggios, which then are applied to a song by a designated key signature. The key signature determines what pattern each note will be a part of, with the exception of accidentals. With this developed recognition of musical structure within sounds, musicians are more likely to recognize incorrect notes (Levitin & Tirovolas 2009). In a study that aimed to find the correlation between aspects of music and various cognitions within executive functions, pitch and melody perception were correlated with working memory (Janurik et al. 2019). The proposed explanation for this is through the ability to maintain several sounds in memory storage, while adapting to new auditory stimuli and new pattern recognization. In discriminating pitches between those stored in memory and what is being heard, as well as relating them to each other within a single musical sequence, phonological awareness is heightened (Anvari et al. 2002). Musical training improves phonological awareness and visuo-spatial working memory, and has been linked to mathematical achievement in third graders through quantity-number competencies (Krajewski & Schneider 2009). Furthermore, evidence of a relationship between musical abilities and performance on geometry problems has also been found (Asbury & Rich 2008).

Various subjects within math require the use of working memory to apply knowledge of rules and structure to new information. Completing algebra problems requires direct knowledge of quantities as it relates to fractions, ratios, and finding the value of an unknown variable. Geometry problems require similar knowledge of numbers, however the application of new information can vary. For example, a word problem that describes an angle between two lines or in comparing angles between a picture of two shapes. Ability to process these problems that are portrayed differently depends on experience with these tasks themselves, or in other areas such as language and musical training. Similarly, prior musical training experience causes playing and perceiving music to be done in a different manner. This can be seen in evidence that musicians exhibit leftward asymmetry of the prefrontal cortex during processing of rhythms, melodies and pitches (Levitin & Tirovolas 2009). The proposed explanation for this is that musicians have more experience and knowledge of these musical schemas, and do not use working memory as much to process them. Further evidence of this is found in left sided activation of the DLPFC in processing tonal relationships, and IFLC in processing musical syntax (Levitin & Tirovolas 2009). Previous research has shown increased activation in the left prefrontal cortex in musicians while performing a math task, which is evidence for proficiency in working memory (Schmithorst & Holland 2004) (Figure 9). When musical norms are violated such as playing a note that does not fall into the pattern or an unexpected rhythm shift, activation of the right PFC is seen in musicians. This right hemispheric shift is evidence of working memory from processing irregularities and is seen for non-musicians in regular musical patterns.

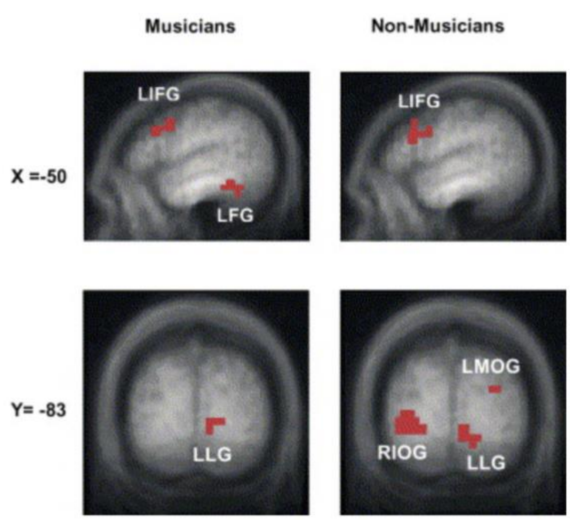

Figure 9. Activation patterns of musicians and non-musicians performing mental addition measured by MRI. There was greater activation in the left fusiform gyrus and left prefrontal cortex for musicians. (Schmithorst 2004).

In examining the combination of results from the studies described, we expected that participants with a high score on the music assessment will score higher on all sections of the mathematical assessment. When viewed with activity of the PFC in solving algebraic problems that require simple arithmetic, it is expected that monitoring PFC activity will reveal increased activation of the left DLPFC and VLPFC for all participants, with differences in the amount of activation in both the left and right hemisphere between musicians and non-musicians. Conversely, it is anticipated that increased activation of the right DLPFC and VLPFC will be seen while solving problems that require application of arithmetic concepts to abstract or visuo-spatial processing tasks; such as geometry and sudoku. For these tasks, it is expected that participants with a high score on the music assessment would show less right sided activation while completing these more complex problems compared to non-musicians, due to heightened EF skills gained from musical training. Sudoku requires both simple arithmetic required in algebra and visuo-spatial manipulation of numbers, therefore it is anticipated that more bilateral activation will be seen for participants during this task.

CHAPTER TWO

Methods

Participant Recruitment and Procedure

Adults that fall within the average age range of undergraduate students in Boston (ages 18 to 29) were recruited to participate in this study. Adults that have experience in mathematics, music, both, or experience in neither of these subjects consented to participate in the study. Once expressing interest in completing the study, a consent form and screening questionnaire was sent to determine eligibility. Exclusion criteria included being an age outside of the required range, having a hearing disability, or not having the ability to read. The questionnaire determined level of education, as well as the subject of focus in their career or academics (such as business, chemistry, humanities, etc.). After screening and consenting to participate, an in-person meeting was scheduled in which both the music and mathematical assessments were completing while recording brain activity uding an fNIRS device. Participants were aware that audio and video were to be recorded to ensure accuracy of results, as well as the accuracy of the fNIRS data. At the beginning of each session, each subject was fitted for the fNIRS headband and decided whether they were comfortable wearing the headband for the duration of the study in completing the assessments. If they were comfortable, the fNIRS device recorded baseline activity and they began the music assessment. This is a pilot study and the data represented is from two cohorts consisiting of musicians and non-musicians. This will allow for insight into the connection between music and math in the four cohorts described above. A total of eight subjects completed the experiment, and background in music and math was accounted for in all of them.

For the music assessment, participants were instructed to listen to a series of three notes, and then repeat them back when indicated. A mark was made on the time associated with the fNIRS tablet both before and after listening, as well as before and after repeating the notes. This was repeated three times for each series of notes. Time was marked for the beginning of the next section naming musical symbols, and marked again when the section was completed. The same process of marking time was done for the next two sections in reading musical notes, and clapping the rhythms written on the page. Upon completion of the music assessment, participants stood up and sat down twice in order for the fNIRS device to baseline before continuing to the mathematical assessment. The first section of the mathematical assessment was geometry problems. The time was marked at the beginning of the section and again when the section was completed. This was done for the second mathematics section containing algebra problems. The last section on this assessment contained a sudoku puzzle, in which participants were told they had ten minutes to fill in as many numbers as possible. Time was marked and recorded at the start of attempting the puzzle, as well as at the ten minute mark when participants were instructed to stop. If particpants did not know the rules of sudoku or had never done this puzzle before, the rules were explained to them before beginning this section.

The purpose of the first section of the music assessment was to determine the participants ability to recognize and repeat pitches from three different sequences, and time was marked before and after listening to each of the three sequences, as well as before and after playing each of the sequences back. Each mark in the data allowed for the recording of twelve tasks as shown below (Table 1). In participants that reported that they did not have musical training and could not repeat the three sequences of notes back, time was not marked. Therefore, those participants had three less tasks analyzed for a total of nine tasks compared to participants that were able to play the sequences back who had a total of twelve tasks . The tasks that were not completed in these participants were 2, 4, and 6.

TASK NUMBER	ACTIVITY COMPLETED
TASK 1	Listening to first sequence of notes
TASK 2	Playing first sequence of notes back
TASK 3	Listening to second sequence of notes
TASK 4	Playing second sequence of notes back
TASK 5	Listening to third sequence of notes
TASK 6	Playing third sequence of notes back
TASK 7	Musical symbol naming
TASK 8	Musical note naming
TASK 9	Clapping rhythms
TASK 10	Geometry problems
TASK 11	Algebra problems
TASK 12	Sudoku puzzle

Table 1. Tasks Completed in the Musical and Mathematical Assessments. Tasks were denoted by a mark in recording of time for the fNIRS device before and after each section of the assessments.

Functional Near Infrared Spectroscopy (fNIRS) Device

The fNIRS device measures the Blood Oxygenation Level Dependency (BOLD) signal via the absorption spectra of oxygenated hemoglobin (HbO2) and deoxygenated hemoglobin (HbR). From this, the HbO2 concentration ([HbO2]) and HbR concentration ([HbR]) were calculated using the Modified Beer-Lambert Law (MBLL) transformation. This data is plotted on time series graphs for four different cortical areas bilaterally: the ventrolateral prefrontal cortex (VLPFC), dorsolateral prefrontal cortex (DLPFC), frontopolar prefrontal cortex (FPPFC), and orbitofrontal prefrontal cortex (OFPFC). The changes in hemoglobin concentrations can be seen in real time as the participant is completing the assessments wearing the headband (Figure 10).

The NIRSIT system provides millimeter-level spatial resolution while also providing high temporal resolution (125 ms / 8 Hz). It is the culmination of three technologies: 1) dense packing of laser and photo diodes, 2) code-division multiple access (CDMA) and time division multiple access (TDMA) modulation for high temporal resolution, and 3) monolithic IC implementation for high SNR.

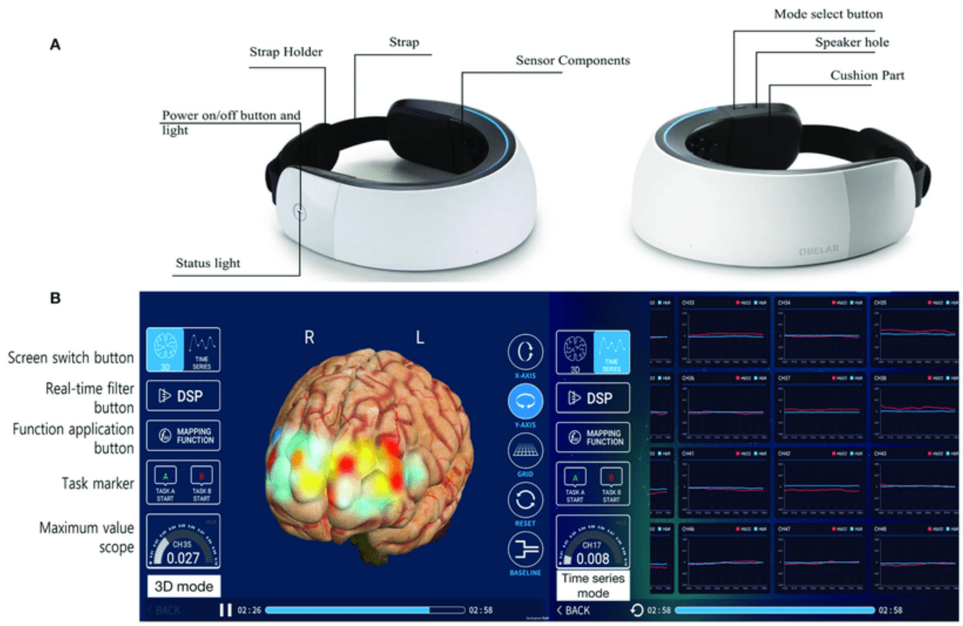

Figure 10. The fNIRS device worn during assessments. This is an example of the headband that will be worn as well as the screen showing changes in Hb concentration. (Kwon 2018).

Music and Math Assessments

The music assessment was adapted from the Carnegie Hall Music Educators Toolbox and is standardized to give a score relating to musical ability and contains four different sections: phonological accuracy and ear training, reading musical symbols, reading musical notes, and clapping the rhythm written on the page. For the first section testing phonological accuracy and ear training, the participant was asked to listen to three sets of musical sequences that each contain three varying notes. The first set was a simple progression of the notes A, B, and C, the second set of notes were the arpeggio of C, E, G, and the last set of notes were a random set of A, F, and D#. For this section the fNIRS recorded brain activity both while listening to and repeating the sequences played. The second and third section aimed to determine the participants knowledge of musical syntax and rules by naming the symbols represented to them in the line of music. For example, the correct answer to number four in Figure 11 is “Fermata”. In the third section, participants were asked to name the notes written on the line of music. Depending on the participant’s musical background, they could decide to determine the notes written in either the bass or treble cleff. If the participant was able to name notes in both cleffs, they were instructed to only name the notes in the cleff of their choice. The notes written for each cleff were the same. The last section aimed to assess participants knowledge of rhythm understanding and ability to repeat. The instructions for this section were asked to clap each rhythm represented in each of the four boxes (Figure 12). Each section was graded on a scale from 0 to 5, making a score of 20 the highest possible. A score of 3 or higher on each section for a total score of 12 represents musical competency.

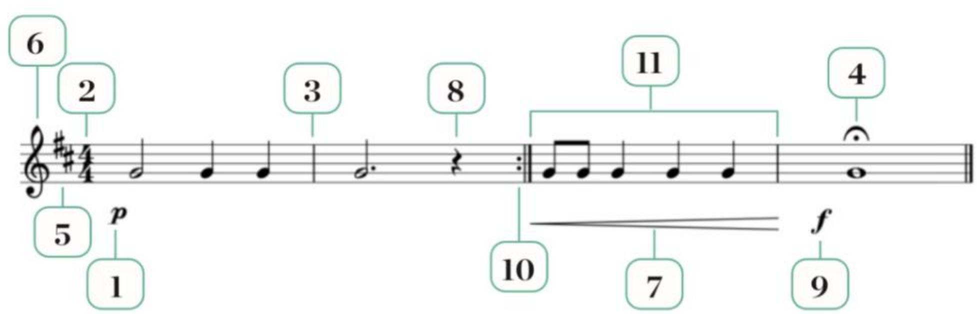

Figure 11. Musical symbol naming activity. The participants were asked to name each of the musical symbols written on the line. (Adapted from the Carnegie Hall Music Educators Toolbox).

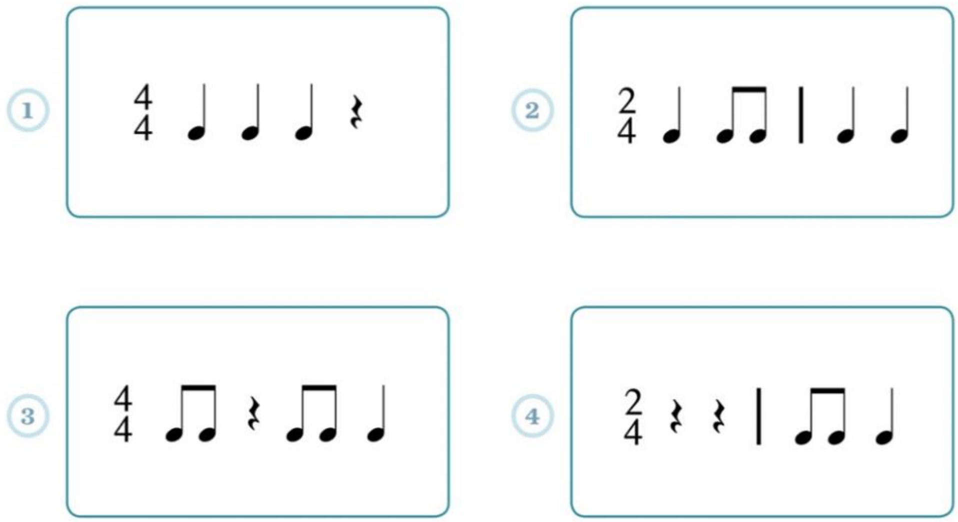

Figure 12. Rhythm activity on the music assessment. Participants were asked to clap the rhythm represented in each box according according to the time signature within the box. (Adapted from the Carnegie Hall Music Educators Toolbox).

The math assessment contains three sections in the order of geometry, algebra, and a sudoku puzzle. The geometry and algebra sections contain five problems each, all of which were taken from the College Boards official SAT set of practice problems. The sudoku puzzle was taken from the sudoku daily website that records users average times and was assessed as a medium difficulty puzzle. Participants were allowed to use a calculator and were given the formula sheet that is given during the actual SAT examination (Figure 13). Participants were given ten minutes to complete each section, and each was graded on a scale of 0 to 5. The highest possible score on this assessment is 15.

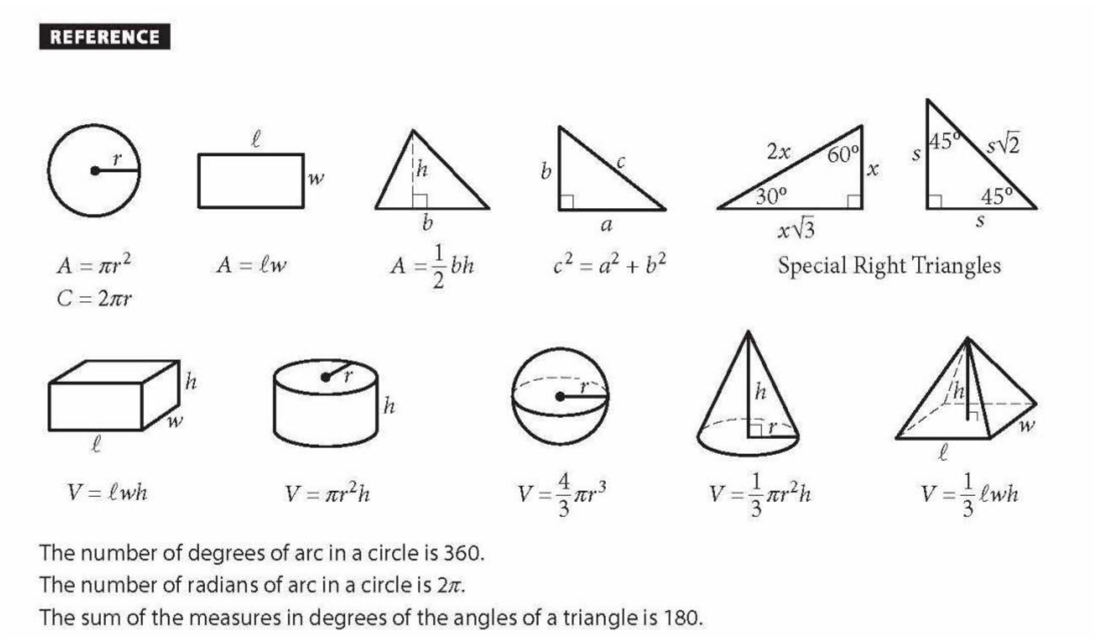

Figure 13. The formulas given to participants for the math examination. Formulas given to students taking the math portion of the SAT. (Taken from the College Boards SAT Math Reference Information).

Post-Assessment Questionnaire

After completing both assessments, the fNIRS recording was stopped and the participant removed the device. They were given a questionnaire in which they were asked to report how difficult they perceived each assessment to be. The purpose of the questionnaire is to better understand if the perceived difficulty correlates with either lower or higher exam scores, as well as which area of mathematics is preferred for musicians versus non-musicians.

Methods of Data Interpretation

The participants total scores on both the music and math assessment were tabulated and compared to the other in order to determine if there is a general correlation between high musical abilities and mathematical abilities. Each section of both examinations was also analyzed in order to determine if there was a connection between specific sections, i.e., a correlation between performance on the rhythm section and performance on the geometry section. After the scores from each assessment and sections were determined and compared, the trends found in the scores were compared to the fNIRS data that was recorded while completing those sections.

The fNIRS device measured the BOLD signal for the duration of both examinations. We used a continuous measures design in which activation was continually monitored for approximately one hour for each exam, compared with a baseline rest period of one minute in which subjects focused on a visual pont. The most important aspect is the comparison of the the participant's score on each exam and their correlated brain scan.

The data gathered from the fNIRS was examined for each subject, and HbO2 and HbR 8-region files were read by a Python script for each task. Within each task, HbO2 and HbR data points along the timeline were squared and divided by the median to be normalized for intersubject comparison. These points were used to find the area under the curve (AUC) for . AUC was found for [HbO2], [HbR], and [HbO2] – [HbR] (the difference between [HbO2] and [HbR]) in each of the eight regions of the brain, this was found using trapezoidal Riemann sum.

A title and legend were added to show subject name, task number, and proper order of lines. This graph was saved, along with a csv file dictating the AUC of [HbO2], [HbR], and [HbO2] - [HbR] for each anatomical region of interest. For each graph, a title and legend were added to show the subject name, task number, and order of lines. This graph was saved into the subject folder under the “results” folder. Then, a csv file was also saved within the same folder, dictating the AUC of [HbO2], [HbR], and [HbO2]-[HbR]. In the csv, column 1 represented the right DLPFC, column 2 represented the right VLPFC, column 3 represented the right FPPFC, column 4 represented the right OFPFC, column 5 represented the left DLPFC, column 6 represented the left VLPFC, column 7 represented the left FPPFC, column 8 represented the left OFPFC.

We analyzed the area under the curve for the difference between oxygenated hemoglobin ([HbO2]), and de-oxygenated hemoglobin ([HbR]). The interpretation of this data is that a larger difference between the two concentrations of [HbO2] and [HbR] means that more oxygen was delivered and consumed in that area.

Statistical Questions

For our analysis, we asked the following statistical questions:

1. Is there a difference in activation of the left hemisphere and right hemisphere during the rhythm, geometry, algebra, and sudoku tasks betweem musicians and non-musicians?

2. Is there a difference in activation of the right and left DLPFC and VLPFC during the geometry, algebra, and sudoku tasks between musicians and non-musicians?
3. Does score on the music assessment or math assessment, or scores on both the music and math assessment predict activation of the right or left hemisphere for the rhythm, geometry, algebra, or sudoku task?
4. Does score on the music assessment or math assessment, or scores on both the music and math assessment predict activation of the right or left DLPFC and VLPFC for the rhythm, geometry, algebra, or sudoku task?
5. What are the correlations in the data between left activation for all music tasks, left activation for all math tasks, right activation for all music tasks, right activation for all math tasks, left and right DLPFC and VLPFC activation during the rhythm task, the geometry task, the algebra task, and the sudoku task?

CHAPTER THREE

Results

Recognizing that we only had 8 subjects we ran non-parametric statistics because we knew that activation of the brain would not be normalized. Statistics were analyzed and interpreted via the following methods:

1. Kendall's tau-b correlation to determine relationships between brain activity seen during the music and math assessment for all participants (n=8).
2. A multiple regression to determine if score on either the music or math assessment or score on both the music and math assessment predict activation during the rhythm, algebra, geometry, or sudoku task for all participants (n=8)
3. Non-parametric Kruskal-Wallis H test to determine if there was statistically different activation in the right and left hemispheres during geometry, algebra, and sudoku tasks between musicians and non-musicians, as well as the difference in right and left activation of the DLPFC and VLPFC during the rhythm, geometry, algebra, and sudoku tasks between musicians and non musicians.

We plotted the [HbO2], [HbR], [HbO2]-[HbR] on a timeline for each anatomical area for each task (example in Figure 14).

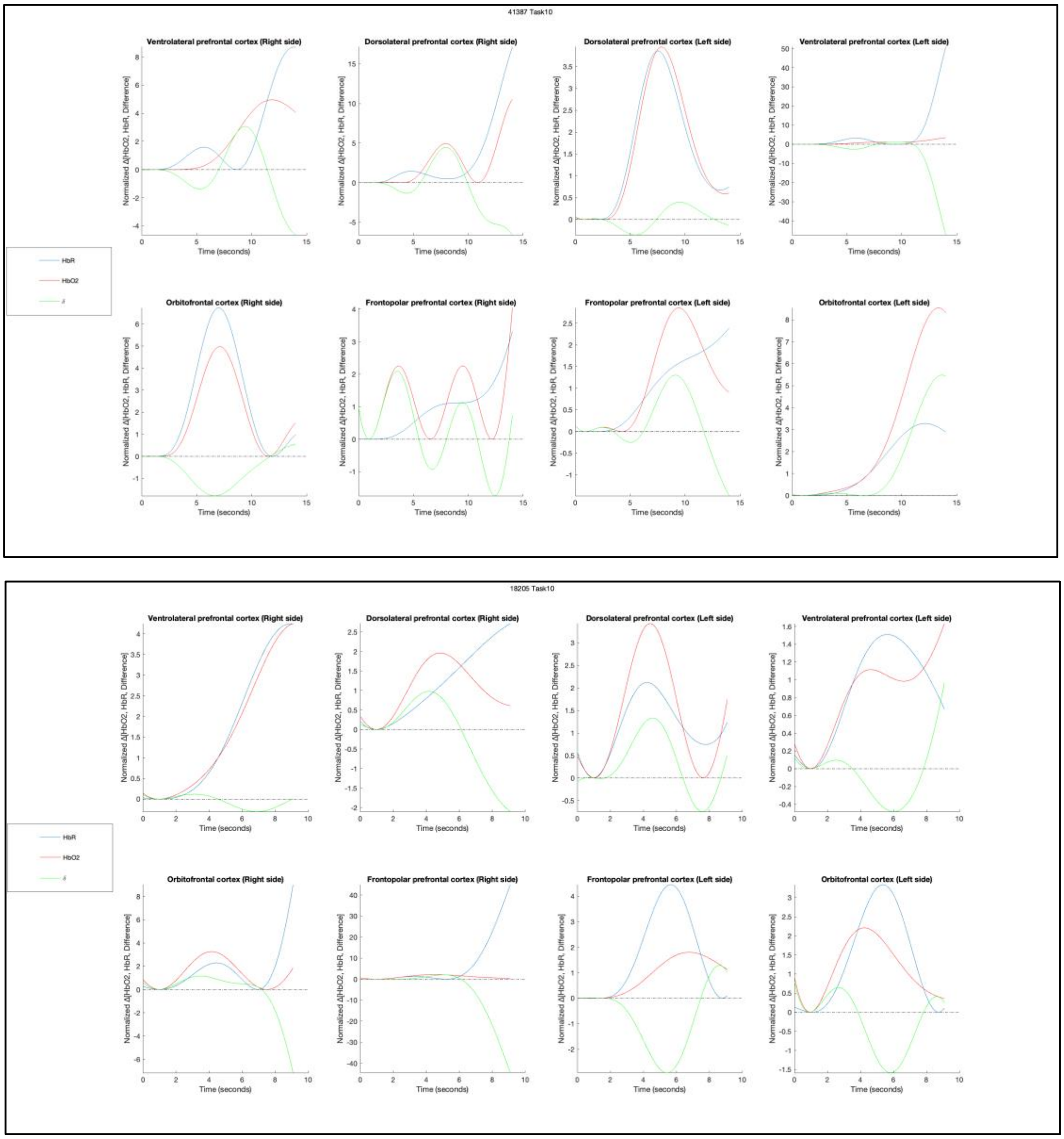

Figure 14. Changes in [HbO2] and [HbR] Within the Prefrontal Cortex for the Geometry Task in a Musician (Top) and Non-musician (Bottom). The area under the curve of the green line represents the difference in [HbO2] and [HbR].

The bar graphs of AUC for Δ[HbO2]- Δ[HbR] were created for the eight areas of the brain measured by the fNIRS (example in Figure 15).

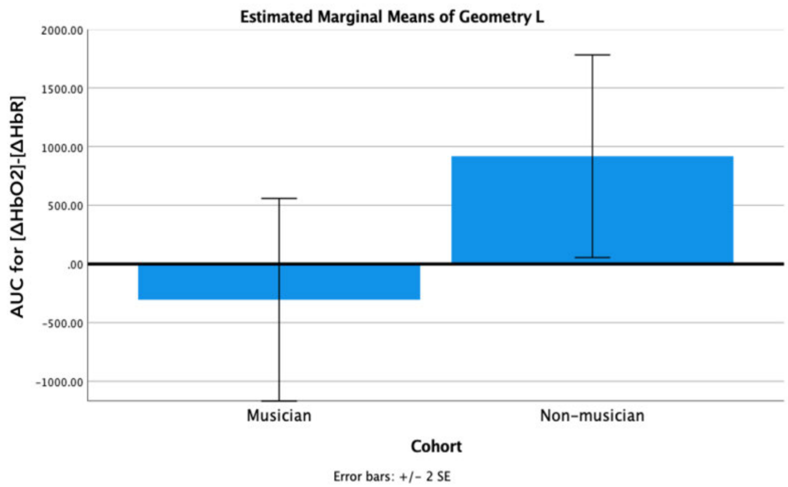

Figure 15. Comparison of Area Under the Curve Measured by the fNIRS for the Geometry Task in Musicians versus Non-musicians. Difference in the mean concentration of oxygenated hemoglobin and deoxygenated hemoglobin in the left hemisphere was compared for musicians and non-musicians. Musicians show a greater difference in concentration of HbO2 and HbR than non-musicians.

Significant Correlations

A kendall's tau-b correlation was run to determine relationships between brain activity seen during the music and math assessment for all participants (n=8). Activation of the right hemisphere during the math assessment is significantly correlated with activation of the right VLPFC, $p<0.006$, and left DLPFC, $p<0.048$, during the sudoku task. Activation of the left hemisphere during the math assessment is significantly correlated with activation of the right DLPFC during the algebra task, *p*<0.048, and the right VLPFC during the sudoku task, *p*<0.001. The green boxes indicate significant correlations and the yellow box indicates a trend towards significant correlation of activation in the left hemisphere for all math tasks and activation of the right DLPFC during the sudoku task, *p*<0.083.

Table 2 shows correlations between activation of the right and left hemisphere during the math assessment, with activation seen for specific tasks within both the music and math assessment in all participants (both musicians and non-musicians) (Table 2).

			95% Confidence Intervals (2-tailed)[a]	
	Kendall's tau_b	Significance(2-tailed)	Lower	Upper
Right Hemisphere Activation for all Math Tasks - Right VLPFC Sudoku	0.786	0.006	0.390	0.936
Right Hemisphere Activation for all Math Tasks - Left DLPFC Sudoku	0.571	0.048	0.002	0.861
Left Hemisphere Activation for all Math Tasks - Right DLPFC Algebra	0.571	0.048	0.002	0.861
Left Hemisphere Activation for all Math Tasks - Right DLPFC Sudoku	0.500	0.083	-0.098	0.833
Left Hemisphere Activation for all Math Tasks - Right VLPFC Sudoku	0.929	0.001	0.762	0.980

Table 2. Analysis of Correlations Associated with the Mathematical Tasks. Correlations found between right and left hemisphere activation during the math assessment and activity during specific tasks within both asssesments for all participants (n=8). Yellow boxes indicate a trend towards significance and green boxes indicate statistically significant correlations at *p*<0.05.

Non-musicians were not able to complete the task that required the three sequences to be played back, and so these tasks were excluded from this analysis so that the data for both musicians and non-musicians could be compared. The green boxes indicate significant correlations and the yellow box indicates a trend towards significant correlation of activation in the right hemisphere for all music tasks and activation of the right VLPFC during the sudoku task, $p<0.083$.Table 3 reports significant correlations between activation of the right and left hemisphere during all tasks of the music assessment except playing the three sequences back, with activity seen during specific tasks of both the music and math assessment.

	Kendall's tau_b	Significance(2-tailed)	95% Confidence Intervals (2-tailed)[a] Lower	Upper
Right Hemisphere Activation for all Music Tasks (except playing music back) - Right DLPFC Algebra	-0.571	0.048	-0.861	-0.002
Right Hemisphere Activation for all Music Tasks (except playing music back) - Right VLPFC Sudoku	-0.500	0.083	-0.833	0.098
Left Hemisphere Activation for all Music Tasks (except playing music back) - Right DLPFC Rhythm	-0.643	0.026	-0.888	-0.115

Table 3. Analysis of Correlations Associated with the Music Tasks. Correlations found between right and left hemisphere activation during the math assessment and activity during specific tasks within both asssesments for all participants (n=8). Yellow boxes indicate a trend towards significance and green boxes indicate statistically significant correlations at $p < 0.05$.

There was a trend towards a significant correlation in activity of the right DLPFC during the rhythm task and activation of the left hemisphere of the geometry task ($p<0.083$), and a significant correlation between activity of the right hemisphere during the rhythm task and activation of the left DLPFC during the geometry task ($p<0.026$). There is a significant correlation between activation of the left DLPFC during the rhythm task and activation of the left DLPFC during the sudoku task ($p<0.048$) as well as activation of the left hemisphere overall during the sudoku task ($p<0.048$). There is a trend towards a significant correlation between activation of the left VLPFC during the rhythm task and the right DLPFC during the geometry task ($p<0.083$).

Table 4 reports correlations between activity seen during the rhythm task and activity seen during specific tasks in both the music and math assessment for all participants.

	Kendall's tau_b	Significance(2-tailed)	95% Confidence Intervals (2-tailed)[a] Lower	Upper
Right DLPFC Rhythm - Geometry Left	-0.500	0.083	-0.833	0.098
Rhythm Right- Left DLPFC Geometry	0.643	0.026	0.115	0.888
Rhythm Left - Left VLPFC Sudoku	0.571	0.048	0.002	0.861
Left DLPFC Rhythm - Left DLPFC Sudoku	0.571	0.048	0.002	0.861
Left DLPFC Rhythm - Sudoku Left	0.571	0.048	0.002	0.861
Left VLPFC Rhythm - Right DLPFC Geometry	-0.500	0.083	-0.833	0.098

Table 4. Analysis of Correlations Associated with the Rhythm Task. Correlations found between right and left hemisphere activation during the math assessment and activity during specific tasks within both asssesements for all participants (n=8). Yellow boxes indicate a trend towards significance and green boxes indicate statistically significant correlations at *p*<0.05.

Scores on the Music and Math Assessment as Predictors for Brain Activity on Certain Tasks

A multiple regression was run to determine if score on either the music or math assessment or score on both the music and math assessment predict activation during the rhythm, algebra, geometry, or sudoku task. We found that the total score on the music assessment predicts activation of the left hemisphere during the geometry task for all participants[$F(1,5)=16.956$, $p<0.009$, $R^2=0.695$]. The total score on the math assessment was also found to predict left hemisphere activation during the geometry task [$F(1,5) = 7.805$, $p<.038$, $R^2=.695$]. The total score on the math assessment was also found to predict left hemisphere activation during the geometry task [$F(1,5)=7.805$, $p<.038$, $R^2=.695$]. Analysis of the between- subjects effects revealed that the total score on the music assessment predicts both activation of the right DLPFC during the geometry task [$F(1, 5) = 7.584$, $p<.020$, $R^2=.451$] and of the right DLPFC during the sudoku task [$F(1, 5)=11.420$, $p<.038$, $R^2=.57$] for all participants. Total score on the math assessment significantly predicts activation of the right DLPFC during the sudoku task [$F(1,5)=7.613$, $p<.040$, $R^2= .574$], and trends towards significantly predicting activation of the right DLPFC during the geometry task [$F(1, 5) =6.182$, $p<.055$, $R^2=.451$].

Significant Differences in Activation Between Musicians and Non-Musicians

A Kruskal-Wallis H test was run to determine if there was a statistically significant difference in activation of the left and right DLPFC and VLPFC for the math tasks (geometry, algebra, and sudoku) between musicians and non-musicians. Analysis showed that there was a statistically significant difference in [HbO2] and. [HbR] in the left VLPFC during the algebra task between musicians and non musicians [$\chi^2(1)= 4.083$, $p= 0.043$], with the ranked difference greater for musicians at 6.25 compared to musicians at 2.75. In examining the difference in activation between the left and right hemispheres during the rhythm, algebra, geometry, and sudoku tasks, a significant difference between musicians and non-musicians in activation of the left hemisphere during the geometry task was found [χ^2 (1)= 5.333, p= 0.021] with the ranked difference greater for musicians at 6.50 compared to non-musicians at 2.50. A trend towards significantly different activation of the left hemisphere between musicians and non-musicians during the rhythm task was also found [χ^2 (1)= 3.000, p= 0.083], with the ranked difference greater for musicians at 6.00 compared to non-musicians at 3.00. A higher ranked difference means that there was a higher mean difference of oxygenated hemoglobin and deoxygenated hemoglobin, and therefore for more oxygen consumption. A trend towards significantly different activation of the left hemisphere during the rhythm task for musicians compared to non-musicians [χ^2 (1)= 3.000, p=.083].

Discussion

Our first question was whether there is there a difference in activation of the left hemisphere and right hemisphere in musicians vs. non-musicians for the geometry, algebra, sudoku, and rhythm tasks. Our analysis of the data showed that there is a significant difference in activation of the left hemisphere during the geometry task for musicians (p=0.021), as well as a trend towards significant difference in activation of the left hemisphere during the rhythm task for musicians (p=0.083). We then examined if there was a difference in activation of the right and left DLPFC and VLPFC during geometry, algebra, and sudoku tasks between musicians and non-musicians. We found that there was a statistically significant difference in activation of the left VLPFC for the algebra task in musicians compared to non-musicians (p=0.043). Previous research has found evidence for increased use of the left hemisphere in musicians than non-musicians

(Limb 2006). Music is thought to be primarily a right sided activity, and these findings suggest that increased left hemispheric activation due to note labeling and encoding of musical patterns dependent on extent of musical training. Musical training inherently changes musical perception, and this process is found to be similar to the mechanism of learning a language, primarily seen in the left hemisphere of the PFC (Onishi 2015). Our results agree with the findings of previous research and support our hypotheses of differential activation of the left hemisphere compared to the right when completing the algebra task, geometry task, sudoku task, and possibly the rhythm task.

We then examined whether score on either the math or music assessment, or the scores on both the music and math assessment predicted activation of the right and left hemisphere as a whole during the geometry, algebra, or sudoku task. We also examined whether they could predict activation of the right and left DLPFC and VLPFC during the rhythm, geometry, algebra, or sudoku tasks. We found that scores on the music assessment (p=0.009) and the math assessment (p=0.038) predict activation of the left hemisphere during the geometry task. Higher scores on both of the assessments show increased music or mathematical abilities, and these results are interpreted to be that enhanced musical and mathematical abilities predicts activation of the left hemisphere when completing geometry problems. These results agree with previous research that musicians show more left sided activation in visuo-spatial tasks that would typically be considered right sided (Limb 2006). We also found that score on the music assessment predicted activation of the right DLPFC during the geometry task (p=0.040) and the sudoku task (p=0.020), and that score on the math assessment predicted activation of the right DLPFC for the sudoku task (p=0.040). Score on the music assessment also trended towards significantly predicting activation of the right DLPFC during the geometry task (p=0.055). These results agree with our hypothesis that there would be different activation of the right hemisphere when completing tasks that require visuo-spatial processing and mental manipulation of numbers. Results from this multiple regression can appear as though they contradict results found from the Kruskal-Wallis H test, that found significantly more activation of the left hemisphere during the geometry task for musicians. One explanation for this is that while musicians display more activation primarily in the left hemisphere when compared to non-musicians, the right DLPFC is more developed in manipulating the schemas stored in memory to solve the problem from experience in musical training.

In examining the significant correlations between right and left hemispheric activation for the mathematical task in all participants, we found that there was a significant correlation between right hemispheric activation and left DLPFC activation during the sudoku task, as well as a trend towards significant correlation of left hemispheric activation and right DLPFC activation during the sudoku task. Although the latter finding was not significant, these results indicate that bilateral use of the DLPFC is important in solving sudoku puzzles. We expect that with more participants, this finding would be significant and is an interesting opportunity for further research. We hypothesized that musicians would display more use of the left hemisphere on the musical and mathematical assessment and with the finding that score on both of these assessments predict activation of the left hemisphere for the geometry task, began to examine correlations associated with this prediction. There was a significant correlation between activation of the left DLPFC during the geometry task and right hemispheric activation during the rhythm task ($p<0.026$), as well as a trend towards significant correlation of activation of the right DLPFC during the rhythm task, and left hemispheric activation during the geometry task ($p<0.083$). Given that music abilities predict activation of the left hemisphere for geometry, these results imply that the rhythm task is associated with the right DLPFC in musicians. Furthermore, a correlation was found between left hemispheric activation during all music tasks and activation of the right DLPFC during the rhythm task ($p<0.026$). This finding is of interest because previous research found that in musicians, rhythm processing is seen in the left hemisphere while pitch and melody processing are seen in the right hemisphere (Limb 2006). Results from our study agree with the finding that musicians display left hemispheric dominance, however we did not expect to see activation of the right DLPFC for rhythm in musicians. A study done by Limb in 2006 found that with metric rhythms (subdivision of measures into equal units marked by a tempo), musicians displayed left PFC activation while in non-metric rhythms (measures played without the constraints of a set tempo), musicians displayed right PFC activation. For our study, musicians were not given a set tempo to follow when clapping the rhythm back and so the rhythms are considered non-metric, explaining these results.

From the results of this study we concluded that musicians display left hemispheric dominance in solving geometry problems, algebra problems, and sudoku puzzles with specialized use of the right DLPFC. The right DLPFC is widely responsible for working memory and manipulating information, as required in geometry, sudoku, and music. This is further supported by our finding that musicians showed significantly different activation of the left VLPFC for the algebra task that involves simple arithmetic and numerical schemas.

Limitations and Further Research

This was a pilot study meant to produce results that would guide further research into this field. The results of this study found significant relationships between activity of the PFC and abilities in music and mathematics, and inspire a more in depth analysis of the prefrontal cortex's role on these cognitions. One proposed reason for insignificant results is a small sample of four participants in each cohort, for a total of eight participants. With more participants, some of the insignificant results are promising for future significant data.

This study aimed to find the connection between the EF cognitions developed through musical training within the prefrontal cortex and how they subsequently mediate performance in mathematics. Educational and occupational background were determined for each participant so that gaps in education could be accounted for in the interpretation of our results, however, there could be other reasons for some participants having higher baseline EF skills than others. One example of this is the role of language processing on cultivating EF's. There is evidence that being bilingual promotes cognitions that fall within executive functions. Moreover, music and mathematical processing are related to language acquisition in the requirement of phonological awareness, phonics, and rapid automized naming; proven to be associated with success in reading acquisition (Janurik et al. 2022). Expanding this research to include the role of language on music and mathematical abilities would be useful to better understanding this connection. Another aspect of this study that could account for insignificant results is that the type of musical training given (voice, piano, etc.) was not assessed individually. Certain instruments require different cognitions than others, such as the requirement of motor coordination in playing an instrument versus singing, or the requirement of precise finger placement to obtain a desired pitch in a string instrument versus a piano.

The variables mentioned above are specific and would require further research to better understand their effects on EFs, a common limitation in this avenue of research is the confounding effect of socioeconomic status on education. Children with low socioeconomic status develop academic skills more slowly, enter the education system with less of these skills already in place, and are less likely to be involved in extra-curricular activities that may further these academic skills (Janurik 2022). While no major differnces in levels of education was seen between the participants in this study, better understanding how EF's are enhanced by musical training and implementing music programs in academic curriculum could bridge this gap in the future.

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