Journal of Mathematics Education
December 2015, Vol. 8, No. 2, pp. 139-157

Brain Research on the Study of Music and Mathematics: A Meta-Synthesis

Jeff Cranmore
Grand Canyon University
Jeanne Tunks
University of North Texas

Advances in neuroscience and brain imaging techniques now allow researchers to study the brain with greater accuracy and detail than previously imagined. Particularly with education, interest in the brain's processes during learning has been a subject of study. Most recently, there is a growing body of research on the linkage linking musical and mathematic activities in the brain. Numerous studies show physiological changes to the brain both during and after musical processing. Studies on mathematic processing identify brain activation during calculation in the posterior parietal cortex (PPC). Comparing neural images during musical and mathematic tasks offers a venue for researchers to explore any linkage between the two fields. While this meta-synthesis provides compelling evidence to suggest a neurological connection between musical study and math achievement, it is essential to keep in mind the importance of each field independently, and not treat musical study as a mathematical supplement.

Key words: brain-mapping, mathematics, music, neuroscience.

Recent advances in technology have allowed neuroscientists to explore the inner workings of the brain at unprecedented levels. Researchers now explore regions and functions of the brain not imagined 20 years previously; such as affect of emotional attachments, long and short-term memory processing, and regions of the brain activated during specific tasks. Educators in particular use these findings to explain differences in learning and seek to find ways to improve student success. One hypothesis that has intrigued many educators is the idea that by strengthening one region of the brain, all processes associated with that region strengthen as well. This idea of shared usage of the brain manifests itself in the concepts of linkages between musical ability and mathematical achievement.

This paper explores possible theories that link music and mathematical regions in the brain. Additionally, the paper examines the radical changes in technology that have allowed access to the brain as well as a review of recent developments in neuroscience and brain studies and the various findings that have come from these advances. Next, the literature on specific research on both music and mathematic ability in relation to brain imaging are presented. Finally, this paper concludes with an argument for shared usage of regions in the brain related to the study of music and mathematics citing current brain imaging research.

Theoretical Perspectives

Cognitive Perspective

Most literature related to music and mathematics linkages emerges in two fields of study: cognition and neuroscience. Cognitive approaches examine related skill development in both music and mathematics and the relationship to one another (Shore, 2010; Pearce & Rohrmeier, 2012). Strong correlations have been found concerning music students' increases in cognitive aspects of math, specifically logical and spatial areas, over non-musicians, as is seen in many studies relating to standardized test results (Helmrich, 2010; Johnson & Memmott, 2006; Kinney, 2008;). While many authors may imply a direct linkage, where music supports mathematics, too many confounding elements prevent a clear statement of causality. One variation of the cognitive theory is the near transfer theory of relating musical skills to mathematics.

Near transfer theories attempt to connect the cognitive aspects of music and mathematics through shared cognitive skills. Črnčec, Wilson, and Prior (2006) define near transfer theory as "Musical instruction and spatiotemporal reasoning tasks require related cognitive skills. Learning that occurs during music instruction, therefore, may transfer to other tasks. For example, learning to read musical notation and understand spatial relations on the keyboard requires visuo-spatial skills" (p. 584-585).

Neuro-scientific theory

Neuro-scientific models of music and mathematics interaction are based on a concept of shared usage of the brain. Neural theories refer to those that suggest specific regions of the brain are used for both musical and spatial task (Hetland, 2000). New brain imaging techniques leads to a paradigm shift in the understanding of the brain, specifically concerning multiple regions working with one another. Technological advances question prior understanding of the brain, specifically those related to the hemispheric divide of brain functions (Szirony, Burgin, & Pearson, 2008; Olson, 2010; Warren, 2008). Brain imaging shows brain functioning in unison for even simple tasks. The meta-synthesis that follows presents the research evidence that show brain activations in musical and mathematical tasks.

Advances in Brain Mapping Technology

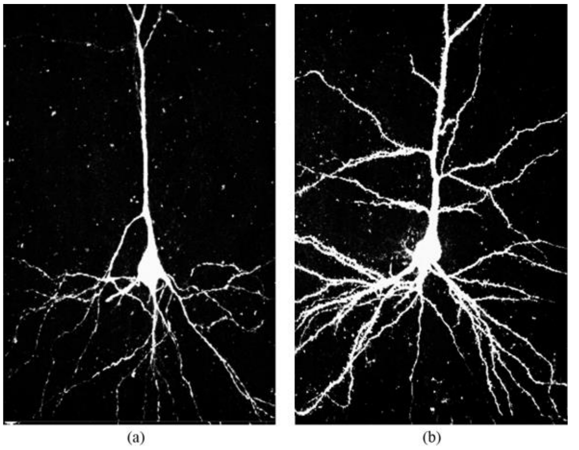
The study of the brain has fascinated humans throughout civilization. From the Egyptian and Greek civilizations through the middle of the 19th century, researchers sought to understand the physiological function and connections of the brain and nervous system. Advances in science and behavioral studies throughout the 20th and beginnings of the 21st centuries have led to an increase in knowledge and new fields of study, previously unimagined, such as the opportunity for scientists to study the actual process as the brain receives information.

In the past 100 years, brain-mapping technology has advanced from early detection of electrical impulses on the scalp to blood flow activation in the cerebral regions to the most current technologies that record blood oxygenation levels in the brain. The current trends in imaging techniques include those based on hemodynamic principles, that monitor blood flow, as well as the electrophysiological approach, which focuses on electric signals from the brain. Neuroimaging based on the hemodynamic approach include functional magnetic resonance imaging (fMRI), positron emission tomography (PET) or single-photon emission computed tomography (SPECT), and near-infrared spectroscopy (NIRS). Magnetoencephalography (MEG) and electroencephalography (EEG) detect neural electric activity through noninvasive monitoring of the brain at high resolutions. Along with transcranial magnetic stimulation (TMS) these constitute electrophysiological approaches (Baillet, Mosher, & Leahy, 2001; Shibasaki, 2008; Singer, 2007). Other techniques include diffusion tensor imaging (DTI) that identifies connections among regions of the brain.

With such a wide array of new information, scientists have begun to map regions of the brain and their functionality in a detail not seen previously. Specifically, the field of neuroscience has grown to several distinct branches encompassing all areas of the brain. As brain-imaging technology improves and becomes more readily available to fields other than neuroscientists, it is a valuable resource for research in education. Multiple disciplines in education, including both mathematics and music, have worked to include such brain research into the literature on student learning and achievement.

Shared Usage of the Brain

Researchers have long associated external stimulation with changes in the brain. Neural pathways strengthen through additional stimulation. While the numerous environmental stimuli bombard the brain daily, specific activities such as the study of music or mathematics may further develop these neural pathways. The term brain plasticity refers to this concept of changes and adaptability of the brain (Johansson, 2006). Brain imaging technologies provide a close look at changes in neurons as they experience more stimulation. Figure 1 shows the differences in the neurons of a rat removed from stimulation and again after three weeks of engagement with other rats and a variety of activities in a larger cage. The figure on the right clearly shows the growth of the neuron, with additional branches. This branching fosters communications with other neurons. The more branches in the neurons allows for better communication in the neuropathways.



Exposure to stimulating environments can alter neurons in as few as three weeks. Left (a) is a nerve cell from a rat housed in a standard laboratory cage. To the right (b) the effect of housing in a larger cage with more rats and the opportunity for various activities. From Johansson (2006) Music and brain plasticity, p. 51.
Figure 1. **Effects of stimulation on neural pathways.**

Through the strengthening of neural pathways, communication between regions of the brain increases. It is theorized that the connection between music and mathematics possibly exist due to the neural pathway connections communicating across the brain (Olson, 2010; Warren, 2008).

Musical Regions of the Brain

Music researchers have used brain-mapping techniques in an attempt to explore the role of music in brain development. Early studies that attempted to confine music to one hemisphere of the brain led to current research that indicates music's ability to bridge the hemispheres (Warren, 2008). More importantly than determining specific regions of the brain, that process music is the understanding of musical study's effect on neural pathways. Based on the concept of brain plasticity, research shows that the brain changes through the musical experiences. Numerous studies show the various changes seen in musician's brains (Blood & Zatorre, 2001; Gaser, & Schlaug, 2003; Olson, 2010)

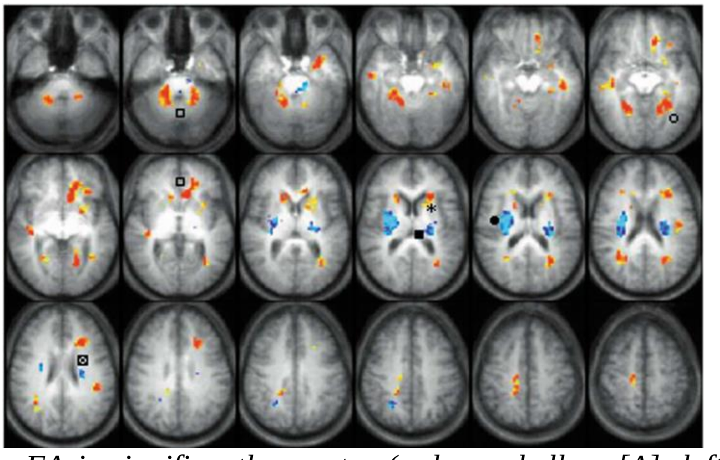
Hodges (2000) notes that as neuroscientists study the effect of musical training, they are "able to discover things about the brain that they cannot know through other cognitive processes. Likewise, through music we are able to discover, share, express, and know about aspects of the human experience" (p. 21). Hodges indentified five basic premises from various neuromusical studies: (a) the human brain has the ability to respond to and participate in music, (b) the musical brain operates at birth and persists throughout life, (c) early and ongoing musical training affects the organization of the musical brain, (d) the musical brain consists of extensive neural systems involving widely distributed, but locally specialized, regions of the brain, and (e) the musical brain is highly resilient. Each of the above represents an understanding of the brain's function in regards to musical responses. In studying specific regions of the brain, Hodges identified each one's relation to music: cognitive, affective, and motor. In all areas, there is evidence of physiological changes in the brain when presented with various musical actives, from listening, and analyzing, and performing.

Blood, Zatorre, Bermudez, and Evans (1999) used positron emission tomography (PET) to map cerebral blood flow (CBF) responses to consonances and dissonances in music. Ten subjects, all with only amateur musical training, listened to a simple melodic pattern with harmonic accompaniment. The melody remained constant as the harmonic structure changed to add increased levels of dissonance. Using regression maps to look at the correlation between dissonance and CBF, the researchers found significant activity in the "parahippocampal and frontal regions" (p. 384).

Olson (2010) identifies changes of brain activity in practicing musicians and non-musicians. After 15 months of instrumental study, the trained musicians showed increases in the motor area, which controls the hands, a larger corpus callosum, the area that connects the two hemispheres of the brain and an enlarged right primary auditory region, the area most responsible for deciphering sounds. Further, the study demonstrated the greatest increases in the musicians who practiced three to five hours a week, over those who practiced less, supporting the theory that extended use of synapses strengthens their processing ability. Musical activities, such as performing or actively listening to music serve to strengthen synaptic response, as with any other sensory, perceptual, or cognitive activities (Schmithorst & Wilke, 2002; Weinberger, 1998; Helmrich, 2010). Additional structural differences in the brains of musicians exist in cerebellum and the frontal, parietal, and temporal lobes. All of these are regions associated with computations, coordination, motor skills, and the discernment of auditory input (Gaser & Schlaug, 2003). Warren (2008) further identifies musical activity as a "whole-brain phenomenon," rather than affecting a single region of hemisphere of the brain (p. 32).

Zatorre (2003) conducted additional studies of musical influences on cognitive development from neurological point of view, suggesting that the study of music may "provide a window onto complex brain functions" (p. 4). Through a set of three independent research studies, related to musical imagery, absolute pitch, and music and emotions, the research explored the influence of music on neural development.

Zatorre first examined music heard compared to an internal imagery of music and the associated increases in the superior temporal gyrus region. Comparing the internal imagery results to a group with brain damage in the same region, Zatorre found that those with the brain injury were less successful in perceiving pitch differences in musical lines. Similarly, participants in a related study listened to popular melodic lines, and then imagined the continuation of the musical phrase. Neural imaging revealed a strong correlation to the right hemisphere, possibly indicating that region is responsible for melodic processing. In the final study, fMRI results of participants imagining the timbre of certain instruments found the greatest level of activity in the right auditory cortex.



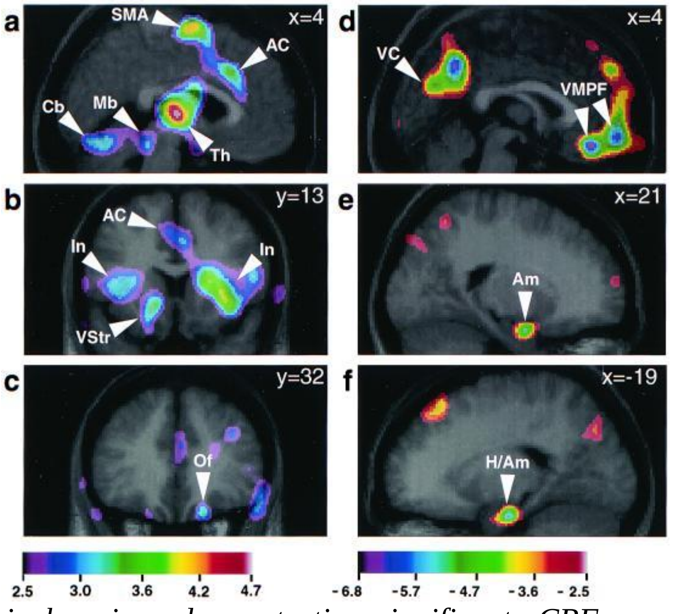
Areas where FA is significantly greater (red: cerebellum [A], left and right inferior longitudinal fasciculi [W], corpus callosum [h], and the left and right caudate and putamen [*]) or smaller (blue: thalamus [B], right external capsule/claustrum [X], left and right internal capsule and corona radiata [ ]) in subjects with musical training since early childhood versus controls. From Schmithorst and Wilke (2002).

Figure 2. **Changes in the brains of musicians.**

Studying absolute pitch, Zatorre revealed that participants with absolute pitch showed an increase of activity in the frontal cortex when listening to random pitch patterns. However, both those without absolute pitch and those with absolute pitch showed activation in this region when listening to chord patterns. Neuroscientists believe the frontal cortex supports memory associations, thus this may indicate that the region categorizes auditory inputs and compares them with previous knowledge.

Zatorre's (2003) third set of studies, involving music and emotion, employed brain-imaging responses to both pleasure and dissonance when listening to musical examples. Increased dissonance appeared in the parahippocampal region, while decreased dissonance caused reaction in the orbitofrontal region. As one region engaged, the other disengaged, suggesting the effect of musical experiences on regions of the brain. Positive responses to musical interactions produced physiological responses showing an overall increase in brain activity when listening to music that produced a positive emotional response. Further, it found that musical exposure lessened negative emotions, such as fear.

Blood and Zatorre (2001) continued to explore pleasant responses to music using positron emission tomography and cerebral blood flow changes. Selections such as the Barber *Adagio for Strings* and the Rachmaninoff *Piano Concerto No. 3 in D minor* produced a sensation of "chills" in musicians with eight or more years of musical study. Additional physiological responses appeared in increases heart rate and respiration. As the pleasurable musical sensation increased, activation also increased in the ventral striatum, midbrain, amygdala, orbitofrontal cortex, and ventral medial prefrontal cortex, all regions noted for activation in response to pleasurable stimulation. Figure 3 shows the activation of regions as subjects listen to pleasurable music.



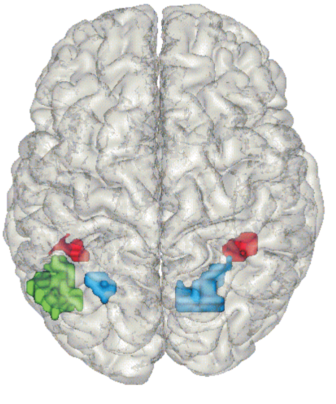
Neuroanatomical regions demonstrating significant rCBF correlations with chills intensity ratings. The t*-statistic ranges for each set of images are coded by color scales below each column, corresponding to* a–c *(positive correlations with increasing chills intensity), and* d–f *(negative correlations). From Blood, A. J. & Zatorre, R. J. (2001).*
Figure 3. **Effects of pleasurable music.**

These images show physiological changes in the brain associated with exposure to pleasurable musical stimuli. In addition, multiple regions of the brain activate in the processing of the various musical experiences. Johansson (2006) noted, "Music is composed of many components that involve both hemispheres as well as sub-cortical regions and the hindbrain. There is probably no other activity that activates so many neuronal networks as music" (p. 53).

Reimer (2004) further expanded the research on emotional experiences associated with music by comparing brain activity between novice and professional musicians. While each activate "both hemispheres and involve cerebral cortex activity and memory retrieval mechanisms" (p. 23), different patterns in the activation exist in each group. Differences in brain activity appear in both vocal and instrumentally trained musicians while performing, listening, comparing, and evaluating musical selections. This further supports the theory that multiple regions of the brain, acting together, perceive music. The addition of any new information, including any music process, creates new neural connections, prompting Reimer further to postulate "every musical experience that we offer our students affects their brains, bodies, and feelings. In short, it changes their minds permanently, and, if we are conscientious, it does so progressively" (p. 25).

Mathematic Connections in the Brain

Using brain-mapping technology, researchers have a greater understanding of mathematic processing, such as addition, subtraction, division, and multiplication as well as complex issues such as spatial reasoning. Neuroscience sheds a new light on the inner workings of the brain during these mathematic processes. Dehaene, Piazza, Pinel, and Cohen (2003) explored activation in the parietal lobe as it relates to mathematical functions. Using fMRI techniques the researchers observed three regions during number tasks: the horizontal segment of the intraparietal sulcus (HIPS), the left angular gyrus (AG) area and the bilateral posterior superior parietal system (PSPL). Their findings indicate that each of the regions is "thought to be associated with broader functions than mere calculation" (p. 501). The HIPS region does show the greatest level of activation during quantity processes and may be the primary region associated with that line of mathematic functioning. This may indicate that while the HIPS serves as a central processing area, the AG and PSPL support through the verbal manipulation of numbers, with additional spatial reasoning support from the PSPL as seen in Figure 4.

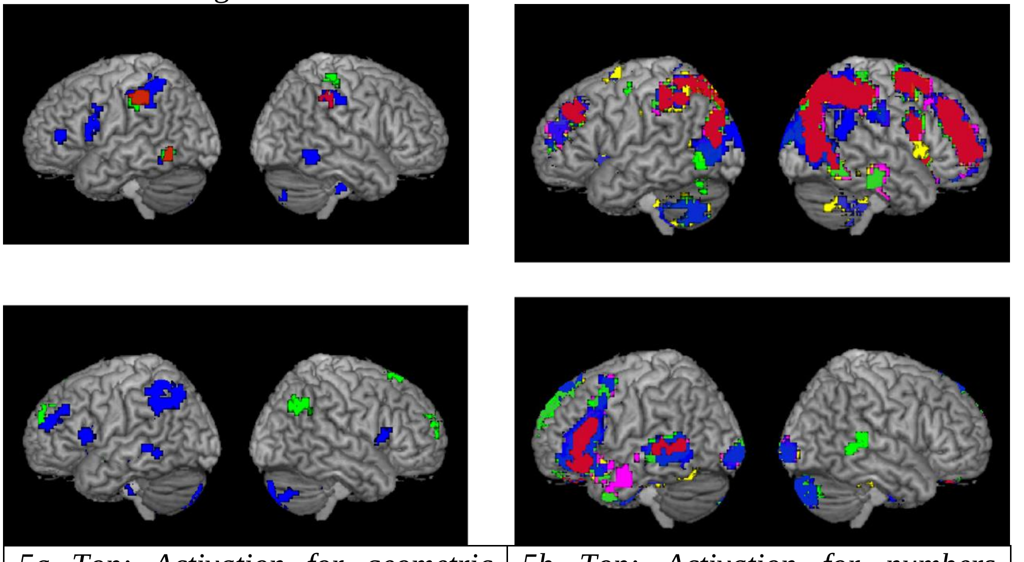


Green- left angular gyrus (ag).Blue-bilateral posterior superiorparietal lobe (PSPL); red-bilateral horizontal segment ofintraparietal sulcus (HIPS). From Dehaene, Piazza, Pinel, and Cohen (2003).

Figure 4. **Parietal regions of the brain related to mathematic processing.**

Using fMRI scans, Hubbard, Piazza, Pinel, and Dehaene (2005) identified regions of the brain that are most responsible for processing the visual representations of numbers. Mathematic tasks, such as word problems shares the same region of the brain used in many other functions: “The neural circuitry that is crucial for abstract representations of quantity is housed in the parietal lobe, in regions that overlap with the neural circuitry involved in spatial representations” (p. 440).

Zhang, Chen, and Zhou (2012) observed that the processing of numbers occurred primarily in the bilateral intraparietal sulcus (IPS) and prefrontal cortex. This is even more evident with specific geometric processes. Regions of the brain associated with language such as the left middle temporal gyrus and the left inferior frontal gyrus showed higher levels of activity in fMRI scans, indicated activation of the regions in interpreting the mathematic problems, seen below in Figure 5.



5a Top: Activation for geometric terms relative to linguistic terms and tool words. Bottom: Activation for algebraic terms relative to linguistic terms and tool words.	*5b Top: Activation for numbers relative to the word materials. Bottom: Activation for word materials relative to numbers. From: Zhang et al., (2012)*

Figure 5. **Activation of the brain during mathematic process.**

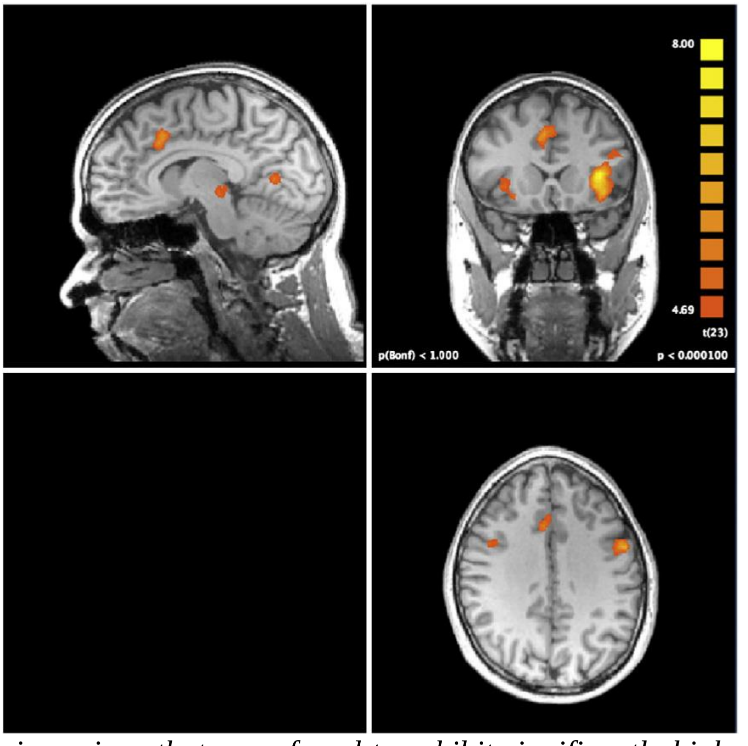
Using fMRI, neuroscientists identified the posterior parietal cortex (PPC) as a major center for mathematical functions. The exact location of the specific functions of addition, subtraction, multiplication, and division remain a topic of some debate. Within the PPC, the intraparietal sulcus (IPS), superior parietal lobule (SPL) and angular gyrus (AG) each activate through number identification and task controlling. There are some differences in the process of addition and multiplication, specifically with retrieval “multiplication evoked significantly greater activation in right posterior IPS, as well as the prefrontal cortex, lingual and fusiform gyri, demonstrating that addition and multiplication engage different brain processes” (Rosenberg-Lee, Chang, Young, Wu, & Menon, 2011, p. 2592). Further, the arithmetic operations of retrieval, calculation, and inversion activate the IPS, SPL and AG at different rates, specifically during inverse functions, such as multiplication versus division or addition versus subtraction. This suggests, "The four basic arithmetic operations rely on a complex profile of distributed responses within the PPC" (p 2606).

Grabner et al. (2007) investigated activation patterns in the brain during mental calculations, based on individual mathematic proficiency. The researchers analyzed fMRI scans of 25 adults as they identified correct or incorrect responses in single and multiple-digit multiplication tasks. The more complex multiplication tasks, such as single digit by multiple digits, "was accompanied by a stronger and more widespread brain activation primarily comprising a network of frontal and parietal cortices. These regions have been repeatedly found to be involved in mental calculation" (p. 352). Participants with higher mathematical ability showed a higher level of usage in the left angular gyrus during both single and multiple digit multiplication, suggesting, "a stronger reliance on language mediated processes during arithmetic problem solving in mathematically more competent individuals" (p. 354).

Ansari, Grabner, Koschutnig, Reishofer, and Ebner (2011) studied error detection in mathematics. Neuroscientists commonly accept that the parietal cortex, including the left inferior parietal lobe and the angular gyrus (AG), is an essential part of numerical calculation; however, the authors used fMRI scans on 24 adults to identify areas associated with error detection. Both medial and lateral regions of the prefrontal cortex showed activation during error detection as well as the right dorsolateral prefrontal cortex. These areas in the brain seem to form a network associated with comparing correct and incorrect solutions to mathematical functions suggesting, "that arithmetic errors are associated with very robust neural correlates of regions that have been associated with errors in other domains" (p. 642). Additionally, the individual level of mathematical ability seems to influence the activation pattern during the error detection phase.

> These findings therefore suggest that individual differences in mathematical competence do not only modulate the processing of correctly solved problems in parietal areas associated with calculation but also modulate the brain processes associated with responses to errors and suggest that mathematical competence affects the way in which brain regions associated with error processing are activated when individuals make calculation mistakes (p. 642).

This opens the possibility for neuroscientists to reconsider the existing model for error detection, based on individual learning and cognitive development. Figure 6 shows the activation of the brain during error detection.



Map of brain regions that were found to exhibit significantly higher levels of activation during arithmetic problems that were solved incorrectly compared to problems where participants chose the correct solution (incorrect vs. correct). From Ansari, D., Grabner, R. H., Koschutnig, K., Reishofer, G., & Ebner, F. (2011).
Figure 6. **Brain activity during error detection.**

Rocha, Rocha, Massad, and Menezes (2005) further defined differences in brain activation in adults and children during mathematical operations. Using EEG measurements in groups of children and adults, the authors identified a larger level of activation in children during mathematical computation. This is most likely due to a generalized approach in calculation in children, while the adults showed a more focused approach. Higher levels of adult circuit development show a higher level of activation in certain regions, versus a lower level of general activation; however, both older children and adults with greater mathematic training showed more activation in the left angular gyrus region.

Musical and Mathematical Brain Connections

Spelke (2008) found correlations between intense musical study and geometric thinking, based on increases in neural connections through cognitive development. Mathematic thinking relies on three core systems of reasoning relating to (a) representing small exact numbers, (b) representing large and approximate numbers, and (c) representing geometric relationships and properties. While each of the core systems are independent of each other, they "become linked over the course of human cognitive development, and the most important linkages emerge before children begin their formal education" (p. 19). While previous studies examined linkages between music and IQ or other cognitive measures, they are dependent on a variety of abilities and factors. Spelke sought to isolate the effects of musical training on one of the three core mathematical systems, by using tasks specifically designed to measure just those areas. In three separate studies, students with music training outperformed their non-musically trained peers, on geometric tasks relating to core systems. The author further identified three aspects of the relationship between geometrical thinking and musical study: (a) it is not dependent on other factors such as intelligence, income or academic ability, (b) it does not relate to other mathematical skills, such as numerical reasoning, and (c) it is not related to the study of all of the arts, as students with music and dance training outperformed students with theater, writing or visual arts training.

Schmithorst and Holland (2004) identify linkage between musical study and mathematic skill due to increases in working memory and improvement in representing abstract quantities of numbers. The researchers performed fMRI scans on 15 adults, seven with extensive musical training, and eight without. The participants mentally added and subtracted fractions. Those with musical training saw an increase in the left fusiform gyrus and prefrontal cortex, while there was decreased activity in the visual association areas and the left inferior parietal lobule. Figure 7 shows this activation.

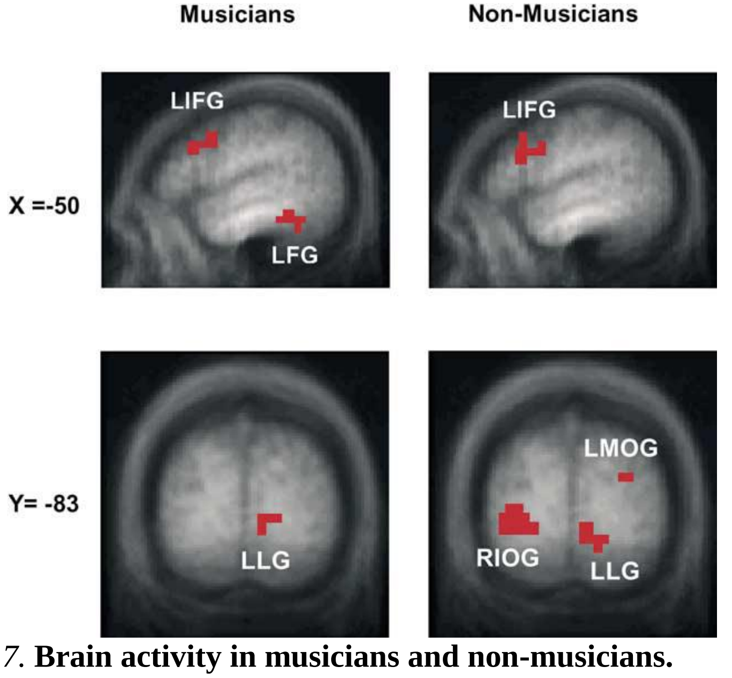


Figure 7. **Brain activity in musicians and non-musicians.**
Composite activation maps for seven musicians (left) and eight non-musicians (right) performing the mental addition and subtraction of fractions. From Schmithorst and Holland (2004).

The researchers propose that the increased activity in the left fusiform gyrus in musicians is due to the years of musical notation reading and interpretation, as this region has been associated with visual perception, shape interpretation, and abstract representations of numbers. This use of abstract visual representations may give the musician group a distinct advantage:

> Subjects who used a "visual" strategy, involving the mental lining up of the numerals and their subtraction through rote processes, displayed increased activation in the left inferior parietal cortex relative to those who used a 'verbal' strategy, involving approximation. If musicians actually are using a more 'abstract' representation of fractions, they would be expected to employ rote calculation procedures to a lesser extent than non-musicians…The increased activation in the left prefrontal cortex in musicians suggests that the hypothesized link between musical training and improved math performance may also be associated with improved performance of semantic working memory, related to improved conflict resolution (p. 195).

Trained musicians regularly activate this conflict resolution system as they are constantly engaged in self-evaluation. When a wrong note, intonation problem, or tempo inaccuracy is detected, immediate corrections are made. Untrained or non-musicians, do not have similar experiences.

The area of the prefrontal cortex shows activation in both musical and mathematical studies. This area of the brain is most associated with executive functions and memory, as well as emotional responses. "The prefrontal association cortex is important for cognitive functions and for organizing behavior, including memories and motor plans that are necessary for interacting with our environment" (Martin, 1996, p. 75). As both music and mathematics are cognitive functions, changes in the brain seem it is logical, especially the prefrontal region, as learners study both of these subjects.

Critiques of Mathematics/Music Connections

This theory of shared usage of the brain is not without criticism. Many neural theories continue to subscribe to the idea of the brain working in hemispheres, with differing functions, independent of each other. This theory of hemispheric laterality continues to hold that certain regions of the brain control specific cognitive function, and that the communication or lack of between the two hemispheres is a great influence in human behavior. Early research (Szirony, Burgin & Pearson, 2008; Radocy & Boyle, 2003) links left-brain dominance with structure, organization, logic and an analytic approach while those with a dominant right brain are often describes as creative, artistic, spatial, and holistic. Concerning musical activity, the specifics of the musical task (e.g., performance, active listening) and the level of musical training of the subject often determine the specific hemisphere.

Szirony, Burgin, and Pearson (2008) note that such "early research tended to oversimplify laterality, placing entire processes within a particular brain hemisphere; although a clear division of function was not always evinced"

(p. 170). Further, certain brain functions may involve either right and left hemispheres, or a complex integration of the two. While the greater part of the population has a preference or dominance in hemispheres, some individuals use the two hemispheres equally. Rather than focus on the specific locations in the brain that certain information is processed, it is more important to understand "that two fundamentally different modes of processing can be handled in two fundamentally different ways and that brain hemispheres can work together in complex ways" (p. 171). Comparing the results of the Human Processing Information Survey (HIPS) of 101 university students, the researchers then asked that the participants provide their own evaluation of their musical and mathematical skills. The results found a correlation between right-brain preference and self-described musical ability however, the relationship between mathematics and left-brain preference were not significant. Even though there was a small sample size and disproportional distribution of males and females, the researchers contend that this study does continue to uphold theories of "the relationship between laterality and musical ability...Understanding more about modes of hemispheric processing and brain hemisphere preference may be helpful in learning, training, teaching, and in understanding more about human development." (p. 177).

Further, Hyde et al. (2009) noted changes in auditory and motor areas of the brains of children with musical training. They additionally found structural differences in frontal areas, not associated with motor skills or auditory processing. This suggested that musical training might increase brain plasticity, or the ability to move more easily between hemispheres. Specifically instrumental music may play a role in increased placidity in primary control regions of the brain, suggesting that, "These results provide new evidence for training-induced structural brain plasticity in early childhood" (p. 185). The plasticity may allow for greater movement between regions of the brain, thus strengthening abilities in these regions.

Hudziak et al (2014) examined the longitudinal effect of playing a musical instrument on cortical thickness. Using MRI data from 232 youth, from the National Institutes of Health's MRI study of Normal Brain Development, the researchers looked at thickness in terms of years of playing and the age of the participant. While there were no noticeable changes in the cortical thickness when compared to years playing, there was a change in the prefrontal and parietal regions when looking at the scans in terms of participant age versus years of playing an instrument. This thickness in cortical regions was associated with increased motor skill, visuospatial perception, and coordination. However, the researchers caution that these results may have been influenced by confounding variables. Therefore, while musicians' brains may be different from those of non-musicians, it may be impossible to state that music study is the sole cause of these differences.

Cranmore and Tunks (2015) found that in a study of 24 high school age students, the students were not able to identify major linkage between their study of music and mathematics. Through a series of interviews, the students revealed that while music and mathematics were important, they could not easily identify a specific linkage between the two, other than their own pre-conceived notions of such a connection. This study sought to study the relationship between mathematics and music learning from the perspective of lived experiences of students who had extensive experience learning both.

Conclusion

Opportunities abound in new technologies showing the structural pathways of the brain and their relationship to academic study. There is evidence to support some level of interaction between differing regions of the brain. As specific areas develop in mathematical regions, musical regions are also developing. Student work in both areas strengthens these regions and more importantly the pathways between regions. In essence, the overlap of the two brain functions becoming one, hence, potentially supporting each other. These interactions give credence to the idea of improving brain functioning through external stimuli.

Brain mapping studies in both music and mathematics show an overlap in processing areas of the brain associated with each independent task. The studies identified have focused on the use of fMRI for all math studies listed, while some musical studies use this method, and others use PET. A search of similarity across the multiple studies in both music and math suggest that there are multiple areas activated, but in different regions of the brain, not just in one hemisphere or the other, or in a direct overlap of one over the other. The regions might be next to each other, but they are not always the same regions. However, those regional increases in neural pathway development, due to development in one field or the other, could potentially affect other regions of the brain, and cognitive abilities associated with those regions (Rauscher, 2002). This is true for all cognitive fields (e.g., language, mathematics) leading Rauscher to propose the existence of cognitive connections between mathematics and musical study, specifically related to spatial reasoning. However, the author cautions against the idea of using music only to support mathematic achievement: “It seems clear that children derive measurable educational benefits from musical training beyond those directly related to music…nevertheless…care must be taken to ensure scientific goals do not displace developmentally appropriate instruction” (pp. 274-275). Further, as was previously noted, many confounding variable exist in this type of research, making it impossible to establish causation.

While the debate over correlation between music and other intelligences may never reach a satisfactory conclusion, the continued exploration of this area of study may yet shed new light on the understanding of interactions of all learning and brain activity. Continuing advances in brain mapping research offer the possibility to test hypothesis on these connections. Future research may choose to focus on monitoring the brain in individuals as they perform both musical and mathematical task. While waiting for such research, classroom teachers can focus their teaching on supporting multiple learning styles and points of entry that provoke interest. Teachers of mathematics, and all subjects, may benefit from models that engage multiple aspects of the brain.

One approach that may be beneficial to consider is Gardner's Multiple Intelligences model, based on Gardner's eight areas found in all people. Two of these key areas of intelligence are music and mathematic-logical. Gardner (2000) noted, "Taking off from the theory of multiple intelligences, in a rough-and-ready rather than a slavish way, one can find at least seven powerful entry points to diverse concepts" (p.188). Through different points of entry, students can explore any number of subjects, including both music and math by seeking multiple representations of core ideas. One prime example found in both music and mathematics is the concept of proportion. Mathematically, proportions are represented in numeric terms or shapes, while musically; proportions can be represented in note value and intervals. The Spelke (2008) study explored geometric relations and music study can be built upon by a collaborative effort in music and math teachers to explore proportional relationships. For such an elaboration to engage both musical and mathematical learning, each subject must be treated as equals. Proportional relationships can be explained in both mathematical and musical terms, so that students can experience the concepts in numerous ways, to support the learning of the core idea. By interchanging the correct terms and examples, music and mathematics teachers can support each other in teaching this core concept.

Care must be used when approaching a true multiple intelligence approach to learning. All too often the theory of multiple intelligences has been evoked to convey trivial examples or to present important examples in an offbeat or anecdotal way…"Let's sing our times tables children!" says the teacher; and the observer claims that musical intelligence has been used to teach mathematical thinking (Gardner, 2000, p.188). A multiple intelligence approach to learning should involve collaboration between the mathematic and musical teachers, to best support the instructional needs in both subjects for all students.

Using musical examples in the math classroom, as well as mathematic examples in the music classroom is one possible approach. However, music should not be treated as solely a mathematical support, just as mathematics should not be expected to solely support musical instruction. Instruction in both fields have a profound effect on the brain structure, and should be accorded the proper time and respect in the school curriculum.

References

Ansari, D., Grabner, R. H., Koschutnig, K., Reishofer, G., & Ebner, F. (2011).

Individual differences in mathematical competence modulate brain responses to arithmetic errors: An fMRI study. *Learning and Individual Differences, 21*(6), 636–643.

Baillet, S., Mosher, J.C., & Leahy, R.M. (2001). Electromagnetic brain mapping. *Signal Processing Magazine, IEEE,* 18 (6), 14-30.

Blood, A. J. & Zatorre, R. J. (2001). Intensely pleasurable responses to music correlate with activity in brain regions implicated in reward and emotion. *Proceedings of the National Academy of Sciences of the United States of America, 98*(20), p. 11818 – 11823.

Blood, A. J., Zatorre, R. J., Bermudez, P. & Evans, A. C. (1999). Emotional responses to pleasant and unpleasant music correlate with activity in paralimbic brain regions. *Nature Neuroscience 2*(4), 382-387.

Črnčec, R., Wilson, S., & Prior, M. (2006). The cognitive and academic benefits of music to children: Facts and fiction. *Educational Psychology, 26*(4), 579-594.

Cranmore, J. and Tunks, J. (2015). High school student's perceptions of the relationship between music and math. *Mid-Western Educational Researcher 27*(1), 51-69.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20* (3-6), 487-506.

Gardner, H (2000). *The disciplined mind: Beyond facts and standardized tests, the K-12 education that every child deserves.* New York, NY: Penguin Books.

Gaser, C., & Schlaug, G. (2003). Brain structures differ between musicians and nonmusicians. *Journal of Neuroscience, 23*(27), 9240-9245.

Grabner, R. H., Ansari, D., Reishofere, G., Stern, E., Ebner, F. & Neuper, C. (2007). Individual differences in mathematical competence predict parietal brain activation during mental calculation. *NeuroImage, 38*(2), 346–356.

Helmrich, B. H. (2010). Window of opportunity? Adolescence, music, and algebra. *Journal of Adolescent Research, 25*(4), 557–577.

Hetland, L. (2000) Learning to make music enhances spatial reasoning. *Journal of Aesthetic Education*, *34*(3/4), 179-238.

Hodges, D.A. (2000). Implications of music and brain research. *Music Educators Journal*, *87*(2), 17-22.

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interaction between number and space in parietal cortex. *Nature Reviews Neuroscience*, *6*(6), 435-448.

Hudziak, J.J., Albaugh, M.D., Ducharme, S. et al, (2014). Cortical thickness maturation and duration of music training: health-promoting activities shape brain development. *Journal of the American Academy of Child & Adolescent Psychiatry*, *53*(11), 1153–1161.

Hyde, K. L., Lerch, J., Norton, A., Forgeard, M., Winner, E., Evans, A. C., &

Schlaug, G. (2009). The Effects of Musical Training on Structural Brain Development. *Annals of The New York Academy Of Sciences*, *1169*, 182-186.

Johannson, B. B. (2006). Music and brain plasicity. *European Review, 14*(1), 49–64.

Johnson, C. M., & Memmott, J. E. (2006). Examination of relationships between participation in school music programs of differing quality and standardized test results. *Journal of Research in Music Education*, *54*(4), 293–307.

Kinney, D. (2008). Selected demographic variables, school music participation, and achievement test scores of urban middle school students. *Journal of Research in Music Education, 56*(2), 145-161. Retrieved from Research Library.

Martin, J. (1996). *Nueroanatomy: Text and atlas*, 2nd Edition. Ney York, NY: McGraw-Hill Education/Medical

Olson, C. A. (2010). Music training causes changes in the brain. *Teaching Music 17*(6). Retrieved from Education Research Complete database.

Pearce, M., & Rohrmeier, M. (2012), Music cognition and the cognitive sciences. *Topics in Cognitive Science*, *4*(4), 468–484.

Radocy, R. E., & Boyle, J. D. (2003). *Psychological foundations of musical behavior* (4th Ed.). Springfield IL: Charles C. Thomas Publications.

Reimer, B. (2004). New brain research on emotion and feeling: Dramatic implications for music education. *Art Education Policy Review, 106*(2), 21-27.

Rocha, F.T., Rocha, A.F., Massad, E., & Menezes, R. (2005). Brain mappings of the arithmetic processing in children and adults. *Cognitive Brain Research, 22*(3), 359– 372.

Rosenberg-Lee, M., Chang, T.T., Young, C.B., Wu, S., & Menon, V. (2011). Functional dissociations between four basic arithmetic operations in the human posterior parietal cortex: A cytoarchitectonic mapping study. *Neuropsychologia*, *49*(9), 2592– 2608.

Schmithorst, V. J. & Wilke, M. (2002). Differences in white matter architecture between musicians and non-musicians: A diffusion tensor imaging study. *Neuroscience Letters, 321*(1-2), 57-60.

Schmithorst, V. J. & Holland, S. K. (2004).The effect of musical training on the neural correlates of math processing: A functional magnetic resonance imaging study in humans. *Neuroscience Letters, 354* (3), 193-196.

Shibasaki, H. (2008). Human brain mapping: Hemodynamic response and electrophysiology. *Clinical Neurophysiology*, *119* (4), 731-743.

Shore, R. (2010). Music and cognitive development: From notes to neural networks. *NHSA Dialog*, *13*(1), 53-65.

Singer, E. (2007). Fueling brain research. Retrieved from http://www.technologyreview.com/biomedicine/18137/?a=f

Spelke, E. (2008). Effects of music instruction on developing cognitive systems at the foundations of mathematics and science. *Learning, Arts and the Brain: The Dana consortium Report on Arts and Cognition, 1*, 17–49.

Szirony, G., Burgin, J., & Pearson, L. (2008). Hemispheric laterality in music and math. *Learning Inquiry*, *2*(3), 169-180.

Warren, J. (2008). How does the brain process music? *Clinical Medicine, Journal of the Royal College of Physicians, 8*(1), 32-36.

Weinberger, N. M. (1998). The music in our minds. *Educational Leadership*, *56*(3), 36-40.

Zatorre, R. J. (2003), Music and the brain. *Annals of the New York Academy of Sciences, 999*, 4–14.

Zhang, H., Chen, C., & Zhou, X. (2012) Neural correlates of numbers and mathematical terms. *NeuroImage*, *60* (1), 230-240.

Authors:

Jeff Cranmore
Grand Canyon University
Email: Jeffcranmore.consultant@gmail.com

Jeanne Tunks
University of North Texas
Email: Jeanne.Tunks@unt.edu