FROM PRACTICE ROOMS TO PRACTICE PROBLEMS: EXPLORING THE COGNITIVE ADVANTAGES OF MUSICAL TRAINING

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Abstract

Music is a powerful tool for learning and enhancing cognitive abilities. Researchers studying neuroplasticity in the brain have taken special interest in this field of study, specifically which cognitive enhancements can be seen with musical education. This paper reviews relevant literature in understanding the connection between musical training and increased cognitive performance. In particular, it evaluates how training in music affects visual attention, auditory processing, memory, and emotional recognition. The paper also recognizes how musical training can result in far-transfer effects that are not directly related to learning music. Important findings from the review include: increased brain matter in certain regions and better performance in a variety of cognitive tests ranging from reaction time to facial recognition.

The report discusses the importance of musical training in schools using the example of the Harmony Project, a partnership between music education programs and schools to promote musical learning and general cognitive enhancement. These programs can catalyze cognitive enhancement and holistic development in students. Through giving underprivileged communities access to music education, the program develops critical thinking abilities that are vital for both academic achievement and lifetime learning. Through the allocation of resources from educational institutions and policymakers, these programs should be extended, especially in areas with adolescents who are at-risk, to ensure that youth and adults in all communities have the chance to enhance their cognitive abilities.

I. Introduction

Like musical instruments, the brain can be 'tuned' to enhance neural development and cognitive abilities. These skills develop over time, often starting from a young age for many musicians. Training as a musician involves numerous components of the brain: the sensory and cognitive domains, auditory cortex, kinesthetic control, visual perception, pattern recognition, and memory.[1] This has become a topic of interest for researchers studying neuroplasticity in the brain, specifically which cognitive enhancements can be seen with education in this field. Musical training directly enhances the skills that are used in practicing music (eg. improved listening and sensorimotor skills), but can also be involved in far-transfer effects.[2] Far transfer refers to the improvement of skills that are not directly related to the activity of interest, or in this case, musical training. Though the specific causal relationship between practicing music and general cognition are still being investigated, there are observable differences in the anatomy of musicians when compared to non-musicians. This includes increased gray matter tissue in areas of the brain that involve the mentioned regions, larger cerebellar volume, and higher motor efficiency. Despite there being documented evidence for these variations between musicians and non-musicians, there have still been reports claiming that the differences are due to ordinary biological diversity, and that there is not an established connection between musical training and cognition.

While specific causal relationships are still under clinical investigation, this report will outline the various correlations that have been shown between training in music and developing cognitive skills beyond the scope of music alone. It will look at how musical training affects cognition, or the forms of knowing and awareness which include perceiving, conceiving, remembering, reasoning, judging, imagining, and problem-solving.[3] To answer this question, the report will review the findings of relevant literature in understanding the connection between musical training and increased cognitive performance, specifically how it affects visual attention, auditory processing, memory, and emotional recognition. Finally, the report will discuss the importance of musical training in schools using the example of the Harmony Project, an existing partnership between musical training programs and schools.

II. Overview of the Brain

A. Anatomical Description

The brain is part of the central nervous system, which is responsible for decision making, regulating major processes like motor skills, vision, and breathing, and monitoring various bodily signals like hunger and thirst. It is composed of gray matter, the darker and outer layer, and white matter, the lighter and inner layer. Gray matter houses the cell bodies of neurons which interpret signals, whereas white matter is made up of axons, or the signal-transmitting component of neurons. The brain is split into three main sections, the cerebrum, cerebellum, and the brainstem.

The brainstem contains three structures: the midbrain, pons, and medulla. The midbrain is critical in the facilitation of hearing and movement, response to environmental changes, and maintaining coordination of different parts of the body.[4] The pons serves as an origin point for several cranial nerves, and conducts activities like focusing vision, balance, and facial expressions. It also connects the midbrain with the medulla, which regulates processes important for survival such as heart rhythm and breathing. The cerebellum, meaning ‘little brain’ is significant in controlling posture and balance.[5] It is also involved in a variety of other functions from learning new skills to depth perception and developing a sense of musical timing. It can also play a role in decision-making and emotional processing.

The cerebrum is the largest section of the brain and is instrumental in most bodily processes. It manages the five senses, produces and understands language, maintains working memory, governs behavior and personality, supervises movement, and oversees logic and reasoning.[5] This is the region that often changes with the development of new knowledge, skills, and lessons learned from mistakes or injuries. The cerebrum is further divided into two hemispheres, connected by a white matter structure known as the corpus callosum.[6] It refines motor and cognitive skills, and transfers information between the right and left hemispheres; its fibers have also been shown to relay a variety of sensory information coming in from all of the different regions of the cerebrum, known as lobes. Each cerebral hemisphere contains four lobes: frontal, parietal, temporal, occipital.[7] The frontal lobe handles processes related to thinking, like planning, organizing, problem-solving, short-term memory, and movement. In the left frontal lobe, Broca's area serves as an important speech production center for the brain. The parietal lobe interprets signals from sensory nerves, as seen with textural, temperature, odor, and taste cues. Transmission and processing of images from the eyes occurs in the occipital lobe, where it can be used for a variety of skills from memory to pattern recognition. The temporal lobe is important in storing memories as well as interpreting signals relating to olfactory, gustatory, and auditory signals. This lobe also houses Wernicke's area, a critical center in language comprehension.

B. Cognitive Skills

Cognitive skills are those "involved in performing the tasks associated with perception, learning, memory, understanding, awareness, reasoning, judgment, intuition, and language."[8] These skills are used in most every day decision making processes, and are practiced using input from the body's sensorimotor system. Musical cognition is comprised of the cognitive activities that are involved in the mentioned processes relating to the learning and practicing of musical training. Examples of these skills, as discussed in this report, are: visual attention, auditory processing, memory capacity, and logical reasoning. Musical training has the capacity to hone in certain skills through repeated and consistent practice.

The cerebrum, cerebellum, and the brainstem, despite having specialized functions, are all involved in governing both cognitive and motor functions. Movement is not triggered solely through external stimuli (ie. reflexes); motor actions involve a series of mental processes and recall of memories associated with the action to be planned.[9] Additionally, motor actions are planned with a specific outcome in mind: when playing an instrument, this may be reading a line on a score, playing a melody, or listening for accuracy while playing a piece. In any of these scenarios, complex integration of various inputs is needed to continue planning actions.

Oftentimes, all three of these actions are occuring at once, engaging various centers in the brain. The first step, reading the score, involves first identifying information about the overall piece (eg. tempo, dynamics, key signature), and then identifying each note in a given duration of the piece. After this information has been processed, the brain must transmit the information from the occipital lobe to the frontal lobe, where planning how the body will play those notes on the instrument will occur. Once the brain has planned the action, it will send signals to the limbs to execute a series of movements. During the action of playing, the body will receive many signals about the length and position of movement, texture of the instrument, and most importantly, the sound resulting from each movement. This information will then be transmitted once again to the frontal lobes through the temporal, occipital, and parietal lobes so that the brain can make further decisions about the accuracy of the movement and whether to continue playing or to stop and restart.

This back-and-forth exchange between the brain and the body can strengthen certain connections, known as synapses, in the brain, demonstrating neuroplasticity. A popular phrase in neuroscience, “neurons that fire together, wire together” can be used to describe this phenomenon. As certain neurons in the brain, such as those involved in reading a score while planning movement during the sight reading process, continually transmit signals at the same time, their connection with one another strengthens and eventually results in observable structural changes.[10] During the early stages of musical training especially when new techniques or styles are introduced, the brain develops multiple paths of signal circuitry that are used exploratively until the most efficient path is determined with practice. This path stabilizes over time and the change becomes a more permanent part of the cortical circuit structure.[10] Though the specific neurobiological models of how musical training leads to certain anatomical changes in the brain are yet to be fully developed, many correlations highlighting the impact of long-term musical training have already been reviewed.

III. Musical Training and Cognitive Skills

A. Visual Attention

Musicians experience enhanced visual processing in comparison to non-musician groups. Rapid Automatized Naming (RAN) is a test that assesses how quickly an individual is able to name objects, colors, letters, and numbers. As sight reading relies heavily on quickly identifying notes and how to play them on an instrument in the given tempo and key parameters, it has been an area of interest for researchers to investigate how eye movements and visual cue processing times relate to musician ability to transfer skills to general information processing. A study on expert sight readers, non-expert sight readers, and non-musicians investigated the link between sight reading capacity and WordRAN.[11] Results showed that musicians have a higher RAN capacity, with expert sight-readers having a significantly higher RAN capacity compared to non-experts and non-musicians.

Musical reading has been demonstrated to exhibit a higher level of structural organization compared to reading text, particularly in terms of the complexity and richness of processing involved, filled with cues for pitch, duration, timing, and dynamics of notes. Due to this increase in information, there is more variation in how the eyes move suggesting that reading music thus becomes less mechanical and more cognitive.[12] The measure of saccadic eye movements tracks how rapidly the eyes move and intake sensory information. When reading music, new saccades (movements) do not occur until the information from the previous saccade has been processed. Research comparing these saccades in musicians and non-musicians found that musicians comparatively used their oculomotor senses with extreme efficiency.[13] This was marked by shorter saccade reaction times, higher saccade velocities, and shorter anticipatory delays in movement.

To test reaction times in particular, a study performed a perceptual and mental imagery task involving reporting where a target dot was located in reference to lines that were retained during the reporting period in some trials and taken away in other trials. This same study also conducted a second experiment that reflected a more basic reaction time task (ie. clicking a key when a given stimulus appeared on a screen). Musicians outperformed non-musicians in both experiments, further highlighting their ability to efficiently process visual information.[14] This research uncovers intriguing insights into the interplay between sensory processing, attentional mechanisms, and cognitive performance.

B. Auditory Processing

Undoubtedly, a large component of musical training relies on paying close attention to the intricacies of sounds, such as pitch, timing, and timbre.[15] Pitch refers to the perception of certain frequencies in sound, ranging from low to high. Timing is defined as the specific moments in time in which a sound starts and stops. Timbre is an attribute relating to the quality and color of the sound. These aspects are all critical in many forms of music, whether it is tuning an instrument such as the viola (pitch), maintaining the rhythm of a piece as a conductor (timing), or enhancing emotions through the tones of an instrument (timbre). Increased consideration towards these aspects of sound enhances auditory processing in musicians, as observed in several studies.

Brain imagery of musicians with different levels of expertise (ie. professional, amateur) and non-musicians found that regions in the auditory cortex had larger gray matter volume, specifically Heschl's gyri which house the primary auditory cortex.[16] Another study, one conducted on pianists, found that, in comparison to non-musicians, those who were trained in piano had a 25% increase in brain response to keyboard notes.[17] Additionally, these results were positively correlated with the age at which the musician had begun training, meaning that an increased number in years of study was associated with a higher level of neural response to the sound. Another study investigated the ability of musicians and non-musicians to generate a mismatch negativity response, the brain's response to the violation of a rule.[18] The rule in this scenario was a deviance from a five-note ascending melody played in various keys; the deviance was a change in the last note by a whole tone. Once again, musicians had a significantly higher response compared to non-musicians in recognizing the deviant melody.

To test the ongoing effects of musical training, several longitudinal studies have been conducted. One such investigation consisted of putting a group of children through fifteen months of instrumental training, and compared their brain and behavioral differences to a control group.[19] The results found that the children who practiced instrumental music experienced more growth in their Heschl's gyrus in the auditory cortex and greater improvements in melodic and rhythmic discrimination skills compared to the children in the control group. Another longitudinal analysis of children training in music found that six months of musical training improved pitch processing in music as well as in speech.[20] The findings of these studies contradict claims that anatomical changes seen in musicians are due to innate differences between study participants trained in music and those who are not.

Far transfer effects for musical training in auditory enhancement primarily involve speech processing, as understanding music and speech both involve pitch, timing, and timbre cues. In addition to these physical aspects, both also require the use of memory and attention to distinguish between intricate differences in syntax and acoustics.[21] Musical phrasing follows similar patterns seen in linguistic phrase structures; the Tonal Pitch Space Theory outlines how changes like increases in tension followed by relaxations and chord patterns in reference to a tonic note mimic the tones of speech inflections. Musical expertise has been demonstrated to improve pitch processing in music as well as speech. An inquiry about the ability of musicians and non-musicians to recognize speech and musical sound onset also concluded that musicians had an earlier and increased frequency encoding in the auditory brainstem in response to speech onset, and that the response was correlated with the age at which they began playing.[22]

Transfer effects from musical training are not only useful in recognizing speech patterns, but also better understanding the emotions encoded in alternating pitches during speech. Musicians have been found to better detect minute changes in pitch, specifically at the ends of words and sentences, compared to non-musicians.[23] This can be important in identifying whether a sentence is a statement or a question, and can even be transferred to situations where the musician does not understand the speech. This was measured through the frequency-following response (FFR), which determines whether participants produce stronger and more consistent responses to changes in pitch. Studies have revealed musicians' abilities to better process pitch even in foreign languages compared to non-musicians.[24]

This is all possible through the encoding of sounds into meaning in the brain. When musicians read from a score, for example, they use multi-sensory incorporation to process the tactile quality of the instrument's surface, visual representation of the notes they play, and the movement of their hands to play those notes. This information, along with the ability to distinguish between competing sounds in their vicinity, is all collected and transmitted to various regions of the brain. Sound travels from the cochlea (signal-transmitting organ of the ear) to the auditory cortex through the brainstem, where top-down processing (ie. decisions made from higher level processes in the brain influence lower level regions) strengthens the connection between the cortex and the brainstem.[25] During musical practice, musicians focus more effort towards encoding certain sounds with different meanings, whether that is visually in the form of notes, kinesthetically through movement, or emotionally with the overall sentiment of a piece.

The increased connectivity between these regions contributes to greater subcortical encoding of sounds, as seen in the results of studies where musicians had stronger responses to certain tones.

In a pragmatic sense, this knowledge is valuable for musicians to understand how their practice can improve not only their music, but also other aspects of their learning. Possessing a strong ability to discriminate between and memorize pitches as well as quickly process tonal and temporal qualities of sounds has profound effects in literacy skills: it manifests in enhanced reading ability, better vocabulary, and verbal fluency.[26] Understanding how to extract certain tonal clues in music can also translate into better performance in auditory selective attention (known as stream segregation), and in voice tagging, which is the ability to focus on one particular auditory stimulus in a cacophonous environment.[27] Examining the relationship between auditory perception, cognitive processing, and musical expertise allows for insights into how musicians' heightened sensory acuity extends into broader cognitive domains.

C. Memory

The body continually faces an abundance of varying auditory, tactile, and visual cues. Its ability to pay selective attention to one of those components and identify it involves the capacity to retrieve the cue from working memory. This is so that attention can be diverted to the "input of highest interest" while maintaining awareness of changes in the surrounding for a stimulus that may need to be immediately attended to.[27] Thus memory is a critical aspect of auditory processing, not just for general use but especially in musical training.

To understand the impact of musical experience in memory, it is important to distinguish between the different types of memory: long-term, short-term, and working. Short-term memory has a limited capacity to hold information and is the most temporary of the three, but holds information in the most accessible manner.[28] These memories are not always in conscious awareness, and are thus more easily forgotten. For musicians, short term memory may be active in the first sight read of a certain piece where the goal is to listen to how the piece sounds rather than learn the notes and commit them to memory. Here, the musician will likely be able to recall a few bars from memory immediately after playing them, but may not recall specific notes from the beginning after completing a page.

Working memory makes use of short-term memory to plan and carry out actions.[28] It is a more conscious action, meaning that both storage and processing of the memory take place concurrently and is dependent on the ability to focus attention to particular stimuli. Using the previous example, while short-term memory is used in a simple preview of the notes in a piece, working memory can use that knowledge to then focus on other dimensions of sound. A working memory process could include playing two bars, noting the musicality associated with that section (in terms of tempo and dynamics), and then practicing that section until the desired musicality is achieved. The pattern that is held in memory during this practice is called a phonological loop.[29] Working memory specifically is an important cognitive enhancement that is improved with musical training.

Long-term memory consists of a vast array of knowledge and memories from past experiences, and greatly shapes how individuals develop unique thought processes and worldviews. This memory has a greater lifespan in that, once encoded, does not have to be frequently revisited to be able to recall (though this recall may contain some flaws). In musical training, a musician may practice a certain piece numerous times over a span of months in preparation for a recital, and very rarely revisit the song after the recital is over. However, even after many months, they may be able to play the song with few errors due to its encoding in long-term memory.[30]

Research suggests that the enhancement of memory capacity takes place in the cerebellum, which makes predictions about what consequences will result from an action based on past experiences. The past experiences serve as patterns to draw from and recognize in other situations, and musical training improves the cerebellum's capacity to function by providing the brain with new patterns to learn from.[31] Other observable effects are larger volumes of gray matter found in the hippocampus of musicians, an area highly associated with memory encoding activity.[32] This finding is further supported by other studies that determine the specific aspects of training that alter memory capacities in musicians. For instance, musical notation represents certain spatial cues and practice with the translation between these two concepts allows them to retain better visuospatial memory.[33]

An analysis of study results for the effects of musical training on memory classified memory tasks based on whether they involved delayed recall (long-term memory), tasks with temporary retainment of knowledge (short-term memory), or recall tasks with a secondary recall task (working memory). Overall, musicians seemed to outperform non-musicians in all three categories.[34] Examples of how this is tested in study participants include N-back, reading span, and operation span assessments.[35] The N-back task involves presenting a sequence of visual and auditory stimuli and asking the participant to decide whether each stimulus matches the stimulus that was displayed in *N* letters before. When this exam was conducted on musicians, they performed better than non-musicians, and produced greater brain activity in response to more difficult memory tasks. Specific regions where higher activity was observed were the lateral prefrontal cortex and anterior cingulate cortex, where control, attention, and error prediction skills are linked.[36] High scores on the other assessments further show the increased capacity of musicians' working memory. For tasks pertaining to tonal discrimination, musicians had increased memory capacity and duration compared to non-musicians. For atonal tasks, musicians did not display increased duration, but still outperformed in working memory capacity.[35]

Moreover, the influence of musical training on memory extends beyond working memory, encompassing short-term enhancements in facial recognition and improved verbal memory in both the short and long term. In an investigation into whether musicians can retain memory of faces better than non-musicians, results showed that training in musical rhythm could enhance facial memory by encouraging activity in the parietal lobe, thereby aiding the encoding and retention of memories.[37] Studies have also shown that musicians with extensive musical training at a young age, in comparison to non-musicians, have better verbal memory in both the working and long-term periods.[38] It is important to note that these results were primarily observed in children and adult populations, and that the effect of memory decline in older adults is still under investigation with regards to musical training. Exploring the dynamic relationship between memory and musical proficiency unveils new understandings of how musical training enriches diverse memory systems.

D. Emotional Recognition

Music holds incredible power in humans to convey and elicit emotions. This has been documented in several different means of altering emotions: a caregiver's speech and singing to infants, adolescent and adult listening to music to regulate emotions, and the promotion of social behavior through dancing or other group musical activities.[39] Music also transcends niche cultural and regional values, and can be universally recognized under three basic emotions:

happy, sad, and scared or fearful.[40] It has also shown to alter the activity of important brain processes that control emotion particularly in the amygdala, nucleus accumbens, and the hippocampus.[41] The amygdala, a critical driver in fear response, is very sensitive to both joyful and unpleasant or sad music; music evokes a strong response in the region of the amygdala that is responsible for processing auditory information, and places an emotional reward value on music. Activation of the nucleus accumbens during rewarding musical experiences is associated with increased dopamine availability. The hippocampus is one of the regulators in the hypothalamus-pituitary-adrenal axis-mediated stress response, and also exhibits changes in activity levels in response to music.

As such, musical practice has been newly theorized as connected to emotional recognition. A study manipulating attributes that are open to the interpretation of the performer, like timing and volume, surveyed pianists indicated their emotional sensitivity to certain alterations that were intended to elicit a more emotional response. In every experiment conducted, musical experience was closely correlated with an increased sensitivity to alterations.[42] Another study asking musician and non-musician participants to identify emotional prosodies based on the tone with which semantically neutral sentences were conveyed found that musically trained adults had higher performance in accurately identifying emotions.[43] This study also conducted another experiment where children were randomly assigned to be part of a control group or participate in musical training lessons (eg. keyboard, vocals, drama), and noted that once again, participants who received musical training were more likely to accurately identify emotions.

Furthermore, the emotional recognition skills gained do not apply only to music. An investigation was conducted on the ability of musically trained and untrained adults to recognize emotional prosody in sentences expressing varied emotions (anger, disgust, fear, happiness, sadness, surprise). It found that musicians had a higher accuracy rate in identifying the emotion in comparison to the control group.[44] Another interesting benefit of musical training is an increased ability to display feelings of empathy. One analysis of looking at this ability in children randomly assigned participants to groups where they would participate in empathy-promoting activities, though one group also had a musical element. The results revealed that the children in the group with musical activities had notably higher empathy scores compared to the other group.[45] The dynamic relationship between music and the brain's emotional processing regions highlights music's remarkable ability to evoke, convey, and enhance emotional experiences across diverse contexts and stages of life.

IV. Musical Training Implementation in Schools- The Harmony Project

The mentioned improvement of cognition in visual attention, auditory processing, memory, and emotional recognition all provide compelling arguments for adoption of musical training in schools. Many of the studies conducted on these topics used children as their population demographic, highlighting the importance of music education at a young age for a variety of cognitive benefits that build on one another as time goes on. Nina Kraus, a neuroscientist and advocate of increasing musical education in schools, offers three arguments for the implementation of such programs: indirect, incentive, and intangible.[46]

The indirect argument contends that investing in music education will indirectly facilitate success in school; this can be seen through increased attention even in distracting environments. This argument would also expand potential for research to conduct longitudinal studies that further the understanding of causal relationships in the discovered correlations. The incentive argument posits that music education can, in the long run, lead to increases in standardized testing scores, grade point averages, and college matriculation rates. The Harmony Project is a current initiative focused on raising these statistics for under-resourced families, and boasts a 97% college admittance rate for students involved in the program.[47] Lastly the intangible argument views the effects of musical training as difficult to quantify, but still useful in long-term academic success. Such benefits include increased social relationships from connections in musical programs, discipline resulting from years of practice, and confidence from regular stage performances.

The Harmony Program is structured to include after school, school partnership, in-school, and online programs where all participants receive an instrument, are given opportunities to perform locally and globally, regular music lessons from professionals with assessments, and college scholarship opportunities. A research query followed a specific age cohort (ages 7-10) of children and measured their neural responses to speech before and after training. Results after one year of program participation saw faster neural coding of consonants, robust encoding of high frequency spectral speech content, and strengthened auditory processing.[48] Authors note that further study will be conducted on these populations to standardize variables such as sex differences, the specific musical activities that participants completed (ie. making music versus studying music), and how learning changes between age groups.

The Harmony Project serves as an excellent foundation for schools to implement music education programs that both enhance cognitive skills and foster holistic development in students. It empowers students who are from lower socioeconomic backgrounds or deemed ‘at-risk’ to explore their musical interests as well as improve their cognitive skills. As schools seek to enrich their educational offerings and support the diverse needs of students, musical education programs provide a compelling model for integrating music into academic curricula and promoting academic success, social-emotional growth, and lifelong learning.

V. Conclusion

The evidence presented in this report highlights the correlations between musical practice and enhancements in visual attention, auditory processing, memory, and emotional recognition. These findings not only shed light on the neuroplasticity of the brain but also offer valuable insights into the broader implications of musical training beyond the realm of music itself. The literature reviewed in this report document correlations between musical training and cognitive skills and underscore the transformative power of music training on the human brain.

Notably, studies suggest that musicians display superior auditory processing skills, with enhanced neural responses to musical stimuli and improved speech processing, indicating the transfer effects of musical training to broader auditory tasks. Research findings also illustrate that musical training correlates with improved visual attention, evidenced by enhanced rapid automatized naming (RAN) and increased efficiency in oculomotor senses. Furthermore, musical training has been linked to enhancements in memory, with musicians showing improved short-term, working, and long-term memory capacities. Musicians have also been shown to exhibit heightened emotional recognition skills, better detecting subtle emotional cues in music and speech.

The Harmony Project exemplifies how music education programs can serve as a catalyst for cognitive enhancement and holistic development in students. By providing access to musical training for under-resourced communities, the program fosters essential cognitive skills that are invaluable for academic success and lifelong learning. These programs should be expanded, particularly in communities with at-risk youth, through the allocation of resources from educational institutions and policymakers so that youth and adults in all communities have the opportunity to improve their cognition through musical education.

Many of the benefits associated with musical training have been correlated with four determinants in terms of their influence on neuroplasticity: the age of onset for musical training, the number of years with continued training, the amount of practice during training, and aptitude for music learning.[15] Strong indicators that musicians' enhanced cognitive abilities are due to their training and not regular biological variation come from a plethora of evidence showing that performance on research examinations are closely correlated with years of experience and consistency of practice. However, to better understand the connection between training and skill transfer, there is still research that must be conducted to discover more specific neural pathways. This research should extend beyond simply identifying enhanced brain regions and instead determine the causal, rather than correlative, mechanisms underlying the effects of musical training on cognitive abilities.

References

1. Barrett KC, Ashley R, Strait DL, Kraus N. Art and science: How musical training shapes the brain. *Frontiers in Psychology.* 2013;4. doi:10.3389/fpsyg.2013.00713
2. Bigand E, Tillmann B. Near and far transfer: Is music special? *Memory & Cognition.* 2021;50:339-347. doi:10.31234/osf.io/gtnza
3. APA Dictionary of Psychology. American Psychological Association. Accessed April 28, 2024. https://dictionary.apa.org/cognition.
4. Brain anatomy and how the brain works. Johns Hopkins Medicine. July 14, 2021. Accessed April 28, 2024. https://www.hopkinsmedicine.org/health/conditions-and-diseases/anatomy-of-the-brain.
5. Professional CC medical. Cerebellum: What it is, Function & Anatomy. Cleveland Clinic. Accessed April 28, 2024. https://my.clevelandclinic.org/health/body/23418-cerebellum.
6. Goldstein A, Covington BP, Mahabadi N, Mesfin FB. Neuroanatomy, Corpus Callosum. In: *StatPearls.* Treasure Island (FL): StatPearls Publishing; April 3, 2023.
7. How your brain works. Mayo Clinic. March 2, 2024. Accessed April 28, 2024. https://www.mayoclinic.org/diseases-conditions/epilepsy/in-depth/brain/art-20546821.
8. APA Dictionary of Psychology. American Psychological Association. Accessed April 28, 2024. https://dictionary.apa.org/cognitive-ability.
9. Leisman G, Moustafa AA, Shafir T. Thinking, Walking, Talking: Integratory Motor and Cognitive Brain Function. *Front Public Health.* 2016;4:94. Published 2016 May 25. doi:10.3389/fpubh.2016.00094

10. Olszewska AM, Gaca M, Herman AM, Jednoróg K, Marchewka A. How musical training shapes the adult brain: Predispositions and neuroplasticity. *Frontiers in Neuroscience.* 2021;15. doi:10.3389/fnins.2021.630829

11. Arthur, P., Khuu, S., & Blom, D. (2021). Visual processing abilities associated with piano music sight-reading expertise. *Psychology of Music,* 49(4), 1006-1016. https://doi.org/10.1177/0305735620920370

12. Rauscher FH, Zupan MA. Classroom keyboard instruction improves kindergarten children's spatial-temporal performance: A field experiment. *Early Childhood Research Quarterly*. 2000;15(2):215-228. doi:10.1016/s0885-2006(00)00050-8

13. Rodrigues, A., Loureiro, M., Caramelli, P. (2013) Long-term musical training may improve different forms of visual attention ability, *Brain and Cognition*, 82(3), 229-235. https://doi.org/10.1016/j.bandc.2013.04.009

14. Brochard R, Dufour A, Després O. Effect of musical expertise on visuospatial abilities: Evidence from reaction times and mental imagery. *Brain and Cognition*. 2004;54(2):103-109. doi:10.1016/s0278-2626(03)00264-1

15. Kraus N, Chandrasekaran B. Music training for the development of Auditory Skills. *Nature Reviews Neuroscience.* 2010;11(8):599-605. doi:10.1038/nrn2882

16. Gaser, C. & Schlaug, G. Brain structures differ between musicians and non-musicians. *J. Neurosci*. 23, 9240–9245 (2003).

17. Pantev, C. et al. Increased auditory cortical representation in musicians. *Nature* 392, 811–814 (1998)

18. Fujioka, T., Trainor, L. J., Ross, B., Kakigi, R. & Pantev, C. Musical training enhances automatic encoding of melodic contour and interval structure. *J. Cogn. Neurosci.* 16, 1010–1021 (2004).

19. Hyde, K. L. et al. Musical training shapes structural brain development. *J. Neurosci.* 29, 3019–3025 (2009).

20. Moreno, S. et al. Musical training influences linguistic abilities in 8-year-old children: more evidence for brain plasticity. *Cereb. Cortex* 19, 712–723 (2009).

21. Patel, A. D. Language, music, syntax and the brain. *Nature Neurosci.* 6, 674–681 (2003).

22. Musacchia, G., Sams, M., Skoe, E. & Kraus, N. Musicians have enhanced subcortical auditory and audiovisual processing of speech and music. *Proc. Natl Acad. Sci. USA* 104, 15894–15898 (2007)

23. Magne, C., Schon, D. & Besson, M. Musician children detect pitch violations in both music and language better than nonmusician children: behavioral and electrophysiological approaches. *J. Cogn. Neurosci.*18, 199–211 (2006).

24. Wong, P. C., Skoe, E., Russo, N. M., Dees, T. & Kraus, N. Musical experience shapes human brainstem encoding of linguistic pitch patterns. *Nature Neurosci*. 10, 420–422 (2007)

25. Tallal, P. & Gaab, N. Dynamic auditory processing, musical experience and language development. *Trends Cogn. Sci.* 29, 382–390 (2006)

26. Chandrasekaran, B. & Kraus, N. Music, noise-exclusion, and learning. *Music Percept.* 27, 297–306 (2010).

27. Strait D, Kraus N. Playing Music for a Smarter Ear: Cognitive, Perceptual and Neurobiological Evidence. *Music Percept.* 2011;29(2):133-146. doi:10.1525/MP.2011.29.2.133
28. Cowan N. What are the differences between long-term, short-term, and working memory?. *Prog Brain Res.* 2008;169:323-338. doi:10.1016/S0079-6123(07)00020-9
29. Chai WJ, Abd Hamid AI, Abdullah JM. Working Memory From the Psychological and Neurosciences Perspectives: A Review. Front Psychol. 2018;9:401. Published 2018 Mar 27. doi:10.3389/fpsyg.2018.00401
30. Groussard M, La Joie R, Rauchs G, et al. When music and long-term memory interact: effects of musical expertise on functional and structural plasticity in the hippocampus. *PLoS One*. 2010;5(10):e13225. Published 2010 Oct 5. doi:10.1371/journal.pone.0013225
31. Vandervert L. How music training enhances working memory: A cerebrocerebellar blending mechanism that can lead equally to scientific discovery and therapeutic efficacy in neurological disorders. *Cerebellum & Ataxias.* 2015;2(1). doi:10.1186/s40673-015-0030-2
32. Gaser C, Schlaug G. Brain structures differ between musicians and non-musicians. *J Neurosci.* 2003;23(27):9240-9245. doi:10.1523/JNEUROSCI.23-27-09240.2003
33. Suárez L, Elangovan S, Au A. Cross‐sectional study on the relationship between music training and working memory in adults. *Australian Journal of Psychology.* 2016;68(1):38-46. doi:10.1111/ajpy.12087
34. Talamini F, Altoè G, Carretti B, Grassi M. Musicians have better memory than nonmusicians: A meta-analysis. *PLOS ONE.* 2017;12(10). doi:10.1371/journal.pone.0186773

35. Yurgil KA, Velasquez MA, Winston JL, Reichman NB, Colombo PJ. Music training, working memory, and neural oscillations: A Review. *Frontiers in Psychology*. 2020;11. doi:10.3389/fpsyg.2020.00266

36. Pallesen KJ, Brattico E, Bailey CJ, et al. Cognitive control in auditory working memory is enhanced in musicians. *PLoS One.* 2010;5(6):e11120. Published 2010 Jun 15. doi:10.1371/journal.pone.0011120

37. Zanto TP, Johnson V, Ostrand A, Gazzaley A. How musical rhythm training improves short-term memory for faces. *Proceedings of the National Academy of Sciences.* 2022;119(41). doi:10.1073/pnas.2201655119

38. Rodrigues AC, Loureiro MA, Caramelli P. Musical training, neuroplasticity and cognition. *Dement Neuropsychol.* 2010;4(4):277-286. doi:10.1590/S1980-57642010DN40400005

39. Martins M, Pinheiro AP, Lima CF. Does music training improve emotion recognition abilities? A critical review. *Emotion Review.* 2021;13(3):199-210. doi:10.1177/17540739211022035

40. Fritz T, Jentschke S, Gosselin N, et al. Universal recognition of three basic emotions in music. *Curr Biol.* 2009;19(7):573-576. doi:10.1016/j.cub.2009.02.058

41. Koelsch S. Brain correlates of music-evoked emotions. *Nat Rev Neurosci.* 2014;15(3):170-180. doi:10.1038/nrn3666

42. Bhatara A, Tirovolas AK, Duan LM, Levy B, Levitin DJ. Perception of emotional expression in musical performance. *J Exp Psychol Hum Percept Perform*. 2011;37(3):921-934. doi:10.1037/a0021922

43. Thompson WF, Schellenberg EG, Husain G. Decoding speech prosody: do music lessons help?. *Emotion.* 2004;4(1):46-64. doi:10.1037/1528-3542.4.1.46

44. Lima CF, Castro SL. Speaking to the trained ear: musical expertise enhances the recognition of emotions in speech prosody. *Emotion*. 2011;11(5):1021-1031. doi:10.1037/a0024521

45. Rabinowitch T-C, Cross I, Burnard P. Long-term musical group interaction has a positive influence on empathy in children. *Psychology of Music*. 2012;41(4):484-498. doi:10.1177/0305735612440609

46. Kraus N, White-Schwoch T. The Argument for Music Education. *Am Sci.* 2020;108(4):210-213. https://ezproxy.library.arizona.edu/login?url=https://www.proquest.com/scholarly-journals/argument-music-education/docview/2432561787/se-2

47. Harmony project. Harmony Project. Accessed April 28, 2024. https://www.harmony-project.org/.

48. Kraus N, Slater J, Thompson EC, et al. Auditory learning through active engagement with sound: Biological impact of community music lessons in at-risk children. *Frontiers in Neuroscience.* 2014;8. doi:10.3389/fnins.2014.00351