Musical Creativity, Brain Structure, and Education

(working paper)

David M. Bashwiner*
Assistant Professor of Music
University of New Mexico

Christopher J. Wertz
Research Assistant
Department of Neurosurgery
University of New Mexico

Ranee A. Flores
Lab Director and Research Assistant
Department of Neurosurgery
University of New Mexico

Rex E. Jung
Assistant Research Professor
Department of Neurosurgery
University of New Mexico

*corresponding author: dbashwin@unm.edu

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Abstract

Public education in the United States is in a state of crisis, with test scores dropping in almost all racial and ethnic groups. The government's response to this crisis has been to make funding conditional upon student outcomes in subjects deemed central to lifelong success—particularly reading and mathematics. The result, however, has been a nationwide reduction in offerings in the creative arts, including music. Given that decades of scientific research link musical training with enhanced cognitive ability, might such a reduction be more hindrance than help?

To address this question, we investigated the brain-structural correlates of creative musical experience. Individuals (N=239) from the STEM fields (science, technology, engineering, and math) were given a "musical creativity questionnaire," in which they reported (among other things) whether and to what extent they had ever improvised or written original music. The same subjects' brains were scanned using sMRI, and positive correlations were found between musical creativity and surface area (or volume) in numerous cortical (or subcortical) brain regions. These regions included higher-cognitive motor and temporal-sequencing regions (planum temporale, dorsal premotor cortex, and supplementary and pre-supplementary motor areas); "default mode" regions (medial prefrontal cortex, orbitofrontal cortex, and lateral temporal cortex); and emotion and motivation regions (orbitofrontal cortex, insula, medial

prefrontal cortex, and amygdala). Thus, experience being musically creative may give rise to—and/or may result from—greater surface area or volume in regions affiliated with higher-cognitive motor operations, default mode activity, and emotion.

Creative behaviors—including musically creative behaviors—are among the most complex that humans engage in. And while the study presented here is not intended to be causal, a possible interpretation of the findings is that the creative fields develop the brain in complex and important ways. Thus, while the U.S. educational crisis is a real one, reducing curricular offerings in music and the arts may be doing more harm than good.

EXECUTIVE SUMMARY

Public education in the United States is in a state of crisis, with test scores dropping in almost all racial and ethnic groups. The government's response to this crisis has been to make funding conditional upon student outcomes in subjects deemed central to lifelong success—namely reading and mathematics. While programs of this sort are no doubt well-intentioned, an unfortunate outcome has been a nationwide reduction in offerings in the creative arts, including music. Importantly, and unfortunately, this reduction in arts offerings has not proven effective, as scores have continued to decline. Reducing music and art offerings, therefore, may even be counterproductive to developing more general cognitive abilities.

Decades of scientific research has demonstrated that musical training and enhanced cognitive ability correlate with one another—and many of these studies further suggest that the relationship is a causal one. The brains of those trained in music at a young age, for instance, reveal profound structural differences when compared with those trained at a later age or not at all. Students taking music lessons, furthermore, often increase in IQ at rates faster than those not taking lessons, even when randomly assigned. Other skills shown to correlate with musical experience include mathematics, visuo-spatial reasoning, reading comprehension, vocabulary, and verbal sequencing. If musical training causes—rather than merely correlates with—these neural and cognitive enhancements, then cutting the former will clearly bring about undesired effects upon the latter.

Creative experiences more generally may also be positively influential upon the brain. Brain scans of a functional nature have revealed that those who perform better on creative tasks show more blood flow in a set of regions collectively known as the "default mode network." These regions are more active when subjects direct attention internally rather than externally, as well as when they defocus the attention or envision future consequences of present actions. Subjects who do engage these regions more fully—and who perform better on creative tasks apparently as a result—consistently reveal far greater experience *practicing* being creative. Thus, being creative—including getting into the brain "mode" associated with creativity—may be as much of a "skill" as any other. If creativity is a kind of skill that is necessarily developed over years of practice; if such practice translates to changes in brain structure and organization; and if such changes are beneficial to intellectual and cognitive performance more generally—then it follows that curricular offerings that develop creative behaviors are likely to be facilitative of general intellectual and cognitive functioning.

In a word: musical and artistic creative experiences, we propose, may not simply be the *fruits* of healthy and intelligent brains—they may be the very *agents* that make those brains as healthy and intelligent as they are.

An issue as complex as this cannot, of course, be resolved in a single study, but we aimed to begin addressing it by investigating the relationship between brain structure (on the one hand) and experience being musically creative (on the other). Individuals (N=239) from the STEM fields (science, technology, engineering, and math), aged 16–32, were given a "musical creativity questionnaire," in which they reported (among other things) whether and to what extent they had ever improvised or written original music. The same subjects' brains were scanned using sMRI, and positive correlations were found between this musical creativity measure and surface area (or volume) in numerous cortical (or subcortical) regions. These regions we interpreted as belonging to three partly-distinct cognitive networks: one representing higher-cognitive motor and temporal-sequencing faculties (planum temporale, dorsal premotor cortex, and supplementary and pre-supplementary motor areas); one representing the "default mode" of brain function (medial prefrontal cortex, orbitofrontal cortex, and lateral temporal cortex); and one representing emotion and motivation (orbitofrontal cortex, insula, medial prefrontal cortex, and amygdala).

Thus, our results indicate that those with more experience being musically creative show greater surface area or volume in regions associated with music-making (motor and temporal-sequencing regions), creativity (default-mode regions), and emotion. While the study presented here is not intended to be causal, a possible interpretation of these findings is that creative experience may develop the brain in complex and important ways. If the aim is to develop healthy and intelligent brains, cutting students' access to artistic and musical creative experiences may ultimately do more harm than good.

RESEARCH REPORT

INTRODUCTION

Focus on New Mexico: Music, the Arts, and General Education

Music, art, and culture are of primary importance to New Mexicans. New Mexico's musical and artistic history is rich and diverse, dating back several centuries, and boasting the achievements of numerous diverse ethnic and language groups. In 1978, Albuquerque was one of the first cities in the nation to devote 1% of its budget to the support of the arts. Today, arts and culture in Albuquerque and Bernalillo County generate $1.2 billion annually, pay $413 million in wages, and provide 19,500 jobs—equivalent to 6% of county employment in total.[1] In Santa Fe, the situation is even more remarkable: the arts and culture industries comprise 22% of total jobs, with 40% of money that enters the county from outside doing so as a result of these industries.[2] New Mexico ranks first in the nation for percentage of artists relative to the entire labor force, fifth for those in theater and dance, and fifteenth for musicians.[3] The artist to non-artist ratio is seven times greater in Santa Fe than it is in the remainder of the

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[1] Jeffrey Mitchell, "The economic importance of the arts & cultural industries in Albuquerque and Bernalillo County" (University of New Mexico Bureau of Business and Economic Research, 2007).

[2] "Arts economy," McCune Charitable Foundation, accessed Sept. 22, 2013, http://www.nmmccune.org/foundation_goals /arts_economy.

[3] "Equal opportunity data mining: National statistics about working artists," NEA Arts Data Profile: Series 1, accessed Sept. 20, 2013, http://www.arts.gov/research/EEO/index.html.

nation.[4] In sum, New Mexico is virtually defined by its involvement in music and the arts.

Despite this musical and cultural richness, however, New Mexico remains one of the poorest states in the nation, and it has one of the lowest educational success rates. Educational success tends to be measured according to performance on standardized tests in only a few core subject areas, particularly reading and mathematics. Recent governmental programs such as No Child Left Behind and Race to the Top have aimed to elevate performance in these areas by making funding conditional upon student test performance. While undoubtedly well-intentioned, an unfortunate byproduct of such governmental programs has been the reduction of offerings in virtually all other subjects.[5] Art and music courses have been hit especially hard, being reduced in 75% of schools across the nation[6] by an average of 16% of class time.[7] Some schools have entirely purged offerings in all areas but math, reading, and physical education.[8] Such reductions are a national trend but are especially pronounced in urban and high-risk areas—a fact which has been called

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[4] *Ibid.*, accessed Sept. 20, 2013, http://www.arts.gov/research/EEO/sample-findings.html.

[5] Tina Beveridge, "No Child Left Behind and fine arts classes," *Arts Education Policy Review* 111 (2010): 4–7.

[6] Claus von Zastrow with Helen Janc, "Academic atrophy: The condition of the liberal arts in America's public schools" (Washington, D.C.: Council for Basic Education, 2004).

[7] J. McMurrer, "NCLB year 5: Choices, changes, and challenges: Curriculum and instruction in the NCLB era" (Center on Education Policy, 2007); Joe Onosko, "Race to the Top leaves children and future citizens behind: The devastating effects of centralization, standardization, and high stakes accountability," *Democracy & Education* 19, no. 2 (2011): 1–11.

[8] S. Dillon, "Schools cut back subjects to teach reading and math," (*New York Times*, March 26, 2006).

"troubling," given that "these same students typically benefit the most from a rich and diverse curriculum."[9]

To the best of our knowledge, there is no evidence that reducing music and arts offerings leads to enhanced standardized test performance. What is evident, on the contrary, is that standardized test scores have not been increasing—in New Mexico or elsewhere in the nation—despite the myopic curricular focus on the subjects tested. From 2006 to 2010, SAT scores declined nationally by 2 points for reading, 2 points for math, and 5 points for writing. This statistic is rosier than it appears, since scores by one ethnic group—Asian Americans and Pacific Islanders—has increased by 36 points. All other ethnic groups have shown losses, some by as many as 14 points.[10] ACT results have shown similar trends.

It seems clear from such statistics that purging music and arts curricula is not as effective as hoped. *Doing so may even be detrimental*—we suggest—to the goal of increasing scores in math and reading. Musical training has long been associated in the popular imagination with intellectual capacity, language skills, and mathematics skills, and the last several decades of experimental research strongly supports such associations.[11] In a sample of 144 six-year-olds, for instance, half of whom were given music lessons for a year

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[9] Beveridge, "NCLB and fine arts."

[10] Onosko, "Race to the Top."

[11] Susan Hallam, "The power of music: its impact on the intellectual, social and personal development of children and young people," *International Journal of Music Education* 28 (2010): 269–289.

(according to random assignment), IQs increased by a significantly greater extent for the music group than for the control groups.[12] For a second example, in a statistical analysis of two national datasets—totaling 45,000 students—musical involvement was demonstrated to correlate significantly with achievement in both mathematics and reading, and these findings held up even when prior achievement was taken into account.[13] Numerous studies, reviews, and meta-studies have consistently found positive transfer effects from music to performance on tests of mathematics,[14] visuo-spatial reasoning,[15] reading comprehension,[16] vocabulary and verbal sequencing,[17] intelligence,[18] and creativity.[19] Of particular interest are reading improvements demonstrated for slow learners[20] and those with dyslexia.[21] One researcher[22] has gone so far as to equate the benefits of musical instruction with 84 points on the SAT.

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[12] Glenn Schellenberg, "Music lessons enhance IQ," *Psychological Science* 15, no. 8 (2004): 511–514.

[13] D. E. Southgate & V. J. Roscigno, "The impact of music on childhood and adolescent achievement," *Social Science Quarterly* 90, no. 1 (2009): 4–21.

[14] Jennifer Haley, "The relationship between instrumental music instruction and academic achievement in fourth grade students" (doctoral dissertation, Pace University, 2001).

[15] L. Hetland, "Learning to make music enhances spatial reasoning," *Journal of Aesthetic Education* 34, no. 3/4 (2000): 179-238.

[16] R. Butzlaff, "Can music be used to teach reading?" *Journal of Aesthetic Education* 34 (2000): 167-178.

[17] J. M. Piro & C. Ortiz, "The effect of piano lessons on the vocabulary and verbal sequencing skills of primary grade students," *Psychology of Music* 37, no. 3 (2009): 325-347.

[18] Schellenberg, "Music Lessons Enhance IQ."

[19] M. Kalmar, "The effects of music education based on Kodaly's directives in nursery school children," *Psychology of Music,* Special Issue (1982): 63–68.

[20] D. Nicholoson, "Music as an aid to learning" (doctoral dissertation, New York University, 1972).

[21] Katie Overy, "Dyslexia and music: From timing deficits to musical intervention," *Annals of the New York Academy of Science* 999 (2003): 497-505; E. Flaugnacco, L. Lopez, C. Terribili M. Montico, S. Zoia, and D. Schön, "Music Training Increases Phonological Awareness and Reading Skills in Developmental Dyslexia: A Randomized Control Trial," *PLoS One* (2015): 10, no. 9:e0138715.

[22] Hetland, "Learning to Make Music."

The transfer benefits of music are evident not only in terms of cognition but also with regard to the structure and function of the brain. The brains of musicians tend to be faster, more accurate, and more efficient in responding—not only to music, but also to language.[23] The brains of musicians also demonstrate structural enhancements, and not only in regions associated with audition and motor performance.[24] The arcuate fasciculus, for instance—one of the main fiber tracts connecting the temporal and parietal lobes with the frontal lobe—is larger and has greater structural integrity in musicians compared to nonmusicians.[25] The corpus callosum is also thicker in musicians trained at an early age, and the planum temporale region (at the posterior of the superior temporal gyrus) is often larger on the left compared to the right in trained musicians.[26]

The aim of the present study was to investigate whether structural differences exist in the brains of musicians—particularly in the brains of *creative* musicians. Given that musical experience has been shown to correlate with (and in some cases cause) enhanced cognitive and intellectual skills; and given that musical experience has also been shown to correlate with (and in some cases cause) brain-structural enhancements of numerous sorts; it follows that

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[23] Sylvain Moreno and Mireille Besson, "Musical Training and Language-Related Brain Electrical Activity in Children," *Psychophysiology* 43 (2006): 287–291.
[24] Krista L. Hyde, J. Lerch, A. Norton, M. Forgeard, E. Winner, *et al*., "Musical Training Shapes Structural Brain Development," *The Journal of Neuroscience* 29, no. 10 (2009): 3019 –3025.
[25] Psyche Loui, H. Charles Li, and Gottfried Schlaug, "White matter integrity in right hemisphere predicts pitch-related grammar learning," *NeuroImage* 55, no. 2 (2011): 500–507.
[26] C. J. Steele, J. A. Bailey, R. J. Zatorre, & V. B. Penhune, "Early Musical Training and White-Matter Plasticity in the Corpus Callosum: Evidence for a Sensitive Period," *J Neurosci* 33 (2013): 1282–90.

musical experience may be particularly valuable—if not essential—in the development of healthy and intelligent brains. Even if the ultimate aim of education reform is solely focused on raising reading and math competency levels, it may be the case that cutting musical (and other creative-arts) curriculum would thus be detrimental to this goal.

The fostering of creativity in young students may be particularly important to bringing about the desired "transfer" effects of music and the other arts. For this reason, we now turn the discussion particularly to *creative* musical experience.

Musical Creativity and the Brain

Creative behaviors are often treated as mysterious—musically creative behaviors perhaps especially. For example, the entire repertoire of Gregorian Chant is reputed to have been sung to Pope Gregory by a dove, while the Devil's Trill Sonata is said to have come to Tartini in a dream, played by the Devil himself. Creative "revelations" of this sort—often called Big C creativity[27]—are no doubt difficult to study scientifically. But everyday creative behaviors—little c—are arguably within reach.

Progress has been made in recent years toward understanding little c creative behavior from the neuroscientific perspective. By definition, "creativity" has been understood to refer to the production of things and ideas that are

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[27] M. I. Stein, "Creativity and Culture," *Journal of Psychology* 36 (1953): 311–322.

both novel and useful.[28] Multiple subprocesses are believed to be involved in creative mentation, including the ability to both focus and defocus the attention,[29] to generate variations and select between them,[30] to regress to primary-process types of consciousness,[31] to search memory stores either deliberately or spontaneously,[32] and to do so using either cognitive or emotional search processes.[33]

One brain network that has been proposed to be especially central to creative functioning is the default mode network (DMN).[34] The DMN is composed of regions such as the dorsomedial prefrontal cortex (dMPFC), ventromedial prefrontal cortex (vMPFC), lateral temporal cortex (LTC), posterior cingulate, and inferior parietal lobule (IPL)—regions which, when a subject is not given an explicit task, tend to increase in activation relative to baseline.[35] The regions of this network also tend to be implicated in a number of cognitive

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[28] *Ibid*.

[29] H. Takeuchi *et al*., "Failing to Deactivate: The Association Between Brain Activity During a Working Memory Task and Creativity" *Neuroimage* 55 (2011): 681–7.

[30] M. Ellamil, C. Dobson, M. Beeman, & K. Christoff, "Evaluative and Generative Modes of Thought During the Creative Process," *Neuroimage* 59 (2012): 1783–9.

[31] C. Martindale, "Creativity, Primordial Cognition, and Personality. *Personality and Individual Differences* 43 (2007): 1777–1785.

[32] Arne Dietrich, "The Cognitive Neuroscience of Creativity." *Psychonomic Bulletin and Review* 11 (2004): 1011–1026.

[33] M. C. Eldaief, T. Deckersbach, L. E. Carlson, J. C. Beucke, & D. D. Dougherty, "Emotional and Cognitive Stimuli Differentially Engage the Default Network During Inductive Reasoning," *Soc Cogn Affect Neurosci* 7 (2012): 380–92.

[34] Rex E. Jung, B. S. Mead, J. Carrasco, & R. Flores, "The Structure of Creative Cognition in the Human Brain," *Front Hum Neurosci* 7 (2013): 330; R. E. Beaty *et al*., "Creativity and the Default Network: A Functional Connectivity Analysis of the Creative Brain at Rest" *Neuropsychologia* 64C (2014): 92–98.

[35] R. L. Buckner, J. R. Andrews-Hanna, & D. L. Schacter, "The Brain's Default Network: Anatomy, Function, and Relevance to Disease," *Ann N Y Acad Sci* 1124 (2008): 1–38.

capacities related to creativity, such as divergent thinking,[36] self-referential thinking,[37] affective reasoning,[38] mind wandering,[39] thinking about the past and future,[40] and mental simulation.[41] It might be expected, therefore, that creative behavior of a musical nature would also implicate the DMN.

The functional imaging literature has indeed implicated the DMN in musically creative behavior—at least improvisation[42] (which, because it is instantaneous, is more easily studied in the scanner than are drawn-out processes like orchestral scoring and songwriting). Limb and Braun,[43] for instance, had professional jazz pianists improvise while in the scanner, finding that improvisation (compared with exact replication of a melody or scale) correlated with enhanced activity in medial prefrontal regions (MPFC) and diminished activity in lateral prefrontal regions (LPFC). In a related study from the same laboratory, Liu *et al*.[44] compared improvised vs. memorized rap performances by professional freestyle artists, again finding significant activation

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[36] Beaty et al., "Creativity and the Default Network"; Jung et al., "The Structure of Creative Cognition"

[37] K. N. Ochsner *et al*., "Reflecting upon Feelings: An fMRI Study of Neural Systems Supporting the Attribution of Emotion to Self and Other. *Journal of Cognitive Neuroscience* 16 (2004): 1746–1772.

[38] Eldaief et al., "Emotional and Cognitive Stimuli"

[39] K. Christoff, A. M. Gordon, J. Smallwood, R. Smith, & J. W. Schooler, "Experience Sampling During fMRI Reveals Default Network and Executive System Contributions to Mind Wandering," *Proc Natl Acad Sci USA* 106 (2009): 8719–24.

[40] D. L. Schacter, *et al*., "The Future of Memory: Remembering, Imagining, and the Brain." *Neuron* 76 (2012): 677–94.

[41] K. D. Gerlach, R. N. Spreng, K. P. Madore, & D. L. Schacter, "Future Planning: Default Network Activity Couples with Frontoparietal Control Network and Reward-Processing Regions During Process and Outcome Simulations," *Soc Cogn Affect Neurosci* 9 (2014): 1942–51.

[42] Roger E. Beaty, "The Neuroscience of Musical Improvisation," *Neurosci Biobehav Rev* 51 (2015): 108–17.

[43] Charles J. Limb & A. R. Braun, "Neural Substrates of Spontaneous Musical Performance: An fMRI Study of Jazz Improvisation," *PLoS ONE* 3 (2008): e1679.

[44] Liu, S. *et al*., "Neural Correlates of Lyrical Improvisation: An fMRI Study of Freestyle Rap," *Sci Rep* 2 (2012): 834.

in the MPFC, which was in turn negatively correlated with activity in dorsolateral prefrontal cortex (dLPFC). Supporting these findings, Pinho *et al*.[45] studied trained pianists with more vs. less experience improvising (compared to playing classically), finding that, during an improvisation, experienced improvisers showed reduced activity in right-hemisphere regions implicated in top-down cognitive control, such as the dLPFC and inferior frontal gyrus (IFG). At the same time, these musicians showed increased functional connectivity in numerous prefrontal, premotor, and motor regions.

These findings suggest that, while regions in the DMN are frequently implicated in studies of musical improvisation and creativity, certain other regions outside of the DMN are also implicated, notably dorsal premotor cortical regions (dPMC) and the supplementary and pre-supplementary motor areas (SMA and pre-SMA). Indeed, all imaging studies of musical improvisation to date implicate at least one of these regions.[46] These regions are highly

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45 A. L. Pinho, O. de Manzano, P. Fransson, H. Eriksson, & F. Ullén, "Connecting to Create: Expertise in Musical Improvisation is Associated with Increased Functional Connectivity Between Premotor and Prefrontal Areas," *J Neurosci* 34 (2014): 6156–63.

46 Beaty, "The Neuroscience of Musical Improvisation,"; Limb & Braun, "Neural Substrates of Spontaneous Musical Performance"; Liu *et al*., "Neural Correlates of Lyrical Improvisation"; Pinho *et al.*, "Connecting to Create"; S. L. Bengtsson, M. Csíszentmihályi, M. & F. Ullén, "Cortical Regions Involved in the Generation of Musical Structures During Improvisation in Pianists," *Journal of Cognitive Neuroscience* 19 (2007): 830–842; A. L. Berkowitz & D. Ansari, "Generation of Novel Motor Sequences: The Neural Correlates of Musical Improvisation," *Neuroimage* 41 (2008): 535–43; Steven Brown, M. J. Martinez, D. A. Hodges, P. T. Fox, & L. M. Parsons, "The Song System of the Human Brain," *Cognitive Brain Research* 20 (2004): 363–75; O. de Manzano & F. Ullén, "Activation and Connectivity Patterns of the Presupplementary and Dorsal Premotor Areas During Free Improvisation of Melodies and Rhythms," *Neuroimage* 63 (2012): 272–80; G. F. Donnay, S. K. Rankin, M. Lopez-Gonzalez, P. Jiradejvong, & C. J. Limb, "Neural Substrates of Interactive Musical Improvisation: An fMRI Study of 'Trading Fours' in Jazz," *PLoS ONE* 9 (2014): e88665.

interconnected with one another, both anatomically[47] and functionally.[48] Furthermore, they connect to one another across the hemispheres by means of a portion of the corpus callosum (CC) that has been demonstrated to be larger in musicians compared to nonmusicians.[49] The dPMC, SMA, and pre-SMA are all implicated in higher-cognitive aspects of motor control,[50] particularly as they extend more rostrally within the frontal lobe.[51] Thus while the DMN appears to be one system frequently recruited in musical improvisation tasks, regions outside of this network might also be expected to be involved.

Finally, because music and emotion are so intertwined,[52] it would not be surprising if musically creative people were more emotionally sensitive to music than controls. While Ulrich *et al*.[53] found reduced activation in the amygdala and MPFC when subjects entered flow states, those flow states were induced by performing mathematical calculations rather than creating music. We hypothesized that we might see brain-behavior associations with musical

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[47] N. Picard & P. L. Strick, "Imaging the Premotor Areas," *Current Opinion in Neurobiology* 11 (2001): 663–672.

[48] S. Narayana *et al*., "Electrophysiological and Functional Connectivity of the Human Supplementary Motor Area," *Neuroimage*, 62 (2012): 250–65; Pinho *et al.,* "Connecting to Create."

[49] C. J. Steele, J. A. Bailey, R. J. Zatorre, & V. B. Penhune, "Early Musical Training and White-Matter Plasticity in the Corpus Callosum: Evidence for a Sensitive Period," *J Neurosci* 33 (2013): 1282–90.

[50] R. J. Zatorre, J. L. Chen, & V. B. Penhune, "When the Brain Plays Music: Auditory-Motor Interactions in Music Perception and Production," *Nat Rev Neurosci* 8 (2007): 547–58.

[51] Picard and Strick, "Imaging the Premotor Areas."

[52] David M. Bashwiner, *Musical Emotion: Toward a Biologically Grounded Theory*. Ph.D. thesis, University of Chicago (2010); David M. Bashwiner, "Lifting the Foot: The Neural Underpinnings of the 'Pathological' Response to Music," In Barbara M. Stafford (ed.), *A Field Guide to a New Meta-Field: Bridging the Humanities-Neurosciences Divide*, 239–266 (University of Chicago Press, Chicago, IL, 2011).

[53] M. Ulrich, J. Keller, K. Hoenig, C. Waller, & G. Gron, "Neural Correlates of Experimentally Induced Flow Experiences," *Neuroimage* 86 (2014): 194–202.

creativity in limbic and paralimbic regions indexing not the *capacity* to create, but the *drive* to do so.

To our knowledge, no previous studies have examined brain structure as it relates to specifically *creative* musical behavior—although numerous studies have examined brain structure as it relates to musical experience more generally. The planum temporale (PT) is larger on the left side of the brain than on the right in humans generally, and this appears to be more the case in musicians compared to nonmusicians.[54] The CC tends to be thicker in musicians who begin their training at an early age, including in regions of the CC that connect the motor and premotor cortices across the hemispheres.[55] Likewise the arcuate fasciculus, which connects the posterior temporal lobe region to the premotor region of the frontal lobe, has been shown to be thicker and more structurally sound in musicians compared to nonmusicians.[56] Finally, cortical gray matter has been found to be thicker in various regions of the brains of trained musicians, including primary auditory and motor regions and numerous prefrontal cortical regions.[57]

The present study reports on the structural correlates of self-reported musical creativity in a sample of 239 subjects with expertise in the STEM fields

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[54] S. Elmer, J. Hanggi, M. Meyer, & L. Jancke, "Increased Cortical Surface Area of the Left Planum Temporale in Musicians Facilitates the Categorization of Phonetic and Temporal Speech Sounds," *Cortex* 49 (2013): 2812–21.
[55] Steele *et al.,* "Early Musical Training."
[56] G. F. Halwani, P. Loui, T. Rüber, & G. Schlaug, "Effects of Practice and Experience on the Arcuate Fasciculus: Comparing Singers, Instrumentalists, and Non-Musicians, *Frontiers in Psychology* 2, Article 156 (2011): 1–9.
[57] Hyde, *et al*., "Musical Training."

(science, technology, engineering, and mathematics). On the assumption that regions shown to be functionally active during musically creative tasks are candidates for structural enhancement, we hypothesized that subjects reporting high levels of musical creativity would show greater surface area in regions affiliated with the DMN (such as dMPFC and LTC), higher-cognitive motor regions (such as dPMC, SMA, and pre-SMA), and limbic and paralimbic regions (such as amygdala and OFC).

METHODS

This study was conducted in accordance with the principles in the Declaration of Helsinki. The study was approved by the Institutional Review Board of the University of New Mexico (IRB 11-531). All subjects provided written informed consent before collection of any data and subsequent data analysis.

Subjects

Two hundred and thirty-nine subjects working or studying in the STEM fields were recruited for the present study. Subjects ranged from 16 to 32 years of age (21.9 +/- 3.5 years) and were well-matched by gender (123 males, 116 females). They were recruited through postings in departments and classrooms at the University of New Mexico, at local high schools, and at various STEM-related places of business. Prior to entry into the study, subjects were screened by a questionnaire and met no criteria for neurological or psychological disorders that would impact experimental hypotheses (e.g., learning disorders, traumatic brain injury, major depressive disorder). Subjects were also screened for conditions that would prohibit undergoing an MRI scan (e.g., metal implant, orthodontic braces, claustrophobia). Subjects were compensated 100 dollars for their participation in the study.

Behavioral Measures

Subjects were administered a musical creativity questionnaire consisting of four sections inquiring about different aspects of their musical background (see Appendix). The first set of questions asked whether the subject had ever practiced a musical instrument daily or several hours per day, and if so, which instruments were practiced, for how many years, for how many hours per day, whether such study was formal or informal, and whether the dominant mode of learning was through written notation or by ear. A second set of questions was borrowed from the Creative Achievement Questionnaire[58] and asked whether the subject had written a piece of original music, whether it had been performed, whether it had been published or recorded, and so on. The third set of questions asked whether the subject had composed or improvised original music, and, if so, how frequently, for how many years, and whether such activity was best described as improvising, writing songs, composing on paper,

[58] S. H. Carson, J. B. Peterson, & D. M. Higgins, "Reliability, Validity, and Factor Structure of the Creative Achievement Questionnaire," *Creativity Research Journal* 17 (2005): 37–50.

composing electronic music, or other. A final set of questions gauged general listening behaviors and preferences.

For this study, only the third set of questions was addressed, specifically the question as to how frequently subjects had improvised or written original music. Subjects responded on a scale from 1 to 6, with 1 representing never, and 6 representing several hours per day.

Image Acquisition and Processing

Sructural imaging was obtained at a 3 Tesla Siemens scanner using a 32-channel head coil to obtain a T1 5 echo sagittal MPRAGE sequence [TE = 1.64 ms; 3.5 ms; 5.36 ms; 7.22 ms; 9.08 ms; TR = 2530 ms; voxel size = 1.0x1.0x1.0 mm3; FOV = 256 mm; slices = 192; acquisition time = 6:03]. For all scans, each T1 was reviewed for image quality. Cortical reconstruction and volumetric segmentation were performed with the FreeSurfer-v5.3.0 image analysis suite, which is documented and freely available for download online (http://surfer.nmr.mgh.harvard.edu/). The methodology for FreeSurfer is described in full in several papers, and summarized by Reuter.[59] Briefly, this process includes motion correction and averaging of volumetric T1 weighted images, removal of non-brain tissue, automated Talairach transformation, segmentation of the subcortical white matter and deep gray matter volumetric structures, intensity normalization, tessellation of the gray matter, white matter boundary identification, automated

[59] M. Reuter, N. J. Schmansky, H. D. Rosas, & B. Fischl, "Within-Subject Template Estimation for Unbiased Longitudinal Image Analysis," *Neuroimage* 61 (2012): 1402–1418.

topology correction, and surface deformation following intensity gradients to optimally place the gray/white and gray/cerebrospinal fluid borders. Segmented data were then parceled into units based on gyral and sulcal structure, resulting in values for cortical thickness, surface area, and volume. The results of the automatic segmentations were quality-controlled, and any errors were manually corrected. FreeSurfer morphometric procedures have been demonstrated to show good test-retest reliability across scanner manufacturers and across field strengths\cite{Reuter:2012}.

Statistical Analysis

A general linear model was used to assess correlations with musical creativity scale scores and cortical pial surface area. This type of group analysis was done by the Query, Design, Estimate, Contrast (QDEC) interface within FreeSurfer. QDEC is a single-binary application used to perform group averaging and inference on the cortical morphometric data created by the FreeSurfer processing stream (http://surfer.nmr.mgh.harvard.edu/fswiki/Qdec). First, the subject's surface was smoothed using a full-width/half-maximum Gaussian kernel of 10 mm. This smoothing was done so that all subjects in this study could be displayed on a common template, which is an average brain. The design matrix consisted of musical creativity measures as the independent variable and age and sex as covariates, and the slope used was different offset/intercept, different slope (DODS). Correction for multiple comparisons was performed using a Monte Carlo Null-Z simulation method for cortical surface analysis available within QDEC. For these analyses, a total of 10,000 simulations were performed for each comparison, using a threshold of P = 0.05. This is the probability of forming a maximum cluster of that size or larger during the simulation under the null hypothesis and presents the likelihood that the cluster of vertices would have arisen by chance.

RESULTS

Any deviations from the initial sample were due to missing behavioral data and were excluded before analysis was conducted. While the "Musical Creativity Questionnaire" we designed for this study collected data on many aspects of subjects' past musical experiences (see Appendix), the number of subjects in our pool with experience playing music and being musically creative was relatively small (N=113 of 239), and we therefore chose to restrict our study of the data to one very general question about the subjects' self-rated degree of musical creativity (**Table 1**; see Methods section for discussion).

(N=239)	***Males** (N=123)*	***Females** (N=116)*	*(t)*	*p*
Age	22.05 (3.6)	21.79 (3.5)	.5	ns
Background[1]	3.46 (1.5)	3.78 (1.6)	1.5	.12
Achievement[2]	2.67 (4.2)	2.30 (5.1)	.6	ns
Creativity[3]	1.84 (1.0)	1.59 (.9)	1.9	.05*
General[4]	2.83 (1.5)	2.51 (1.3)	1.8	.08
General[5]	5.33 (.73)	5.47 (.62)	-1.6	.11

Table 1. Responses to Musical Creativity Questionnaire. [1]Have you ever practiced a musical instrument? [2]Musical Creative Achievement. [3]Have you ever improvised or written original music? [4]How musically creative would you rate yourself to be? [5]How frequently do you listen to music? Values for males and females represent Mean and Standard Deviation (in parentheses.) (t) = Student's statistic; p = significance level.

Our measure of musical creativity was weakly but significantly correlated with other measures of creativity such as the Creative Achievement Questionnaire (r = 0.28, P = 0.001) and the personality trait Big Five Aspects Scale Openness-Intellect (r = 0.19, P = 0.0103; **Table 2**), both of which have been shown to be correlated with behavioral creativity measures.[60]

In both hemispheres, we found significant clusters of greater cortical surface area at P<0.05, corrected for multiple comparisons, that had a positive correlation with higher musical creativity ratings (**Figure 1** and **Table 3**). These include bilateral dorsomedial superior frontal gyrus (SFG) (P = 0.00010), bilateral OFC (left, P = 0.00010; right P = 0.01900), left planum temporale region (PT) (P = 0.03840), and right middle temporal gyrus (MTG) (P = 0.00510). Musical creativity ratings were also found to correlate significantly with subcortical volume in left amygdala (F = 3.4, p = .02, Beta = .17).

(N=182)	***Musical Creativity***	***CAQ - Total***	***CAQ - Music***	***DT Originality***
CAQ - Total	.31***			
CAQ - Music	.56***	.44***		
DT Originality	.17*	.23**	.15*	
Openness/Intellect	.20**	.16*	.20**	.26***

Table 2. Partial correlations, controlling for age and sex, between behavioral assessment measures commonly associated with creativity and subject scores on MCQ question III ("Have you ever improvised or written original music?") MCQ—Musical Creativity Questionnaire; CAQ—Creative Achievement Questionnaire; DT—Divergent Thinking (Torrance Test of Creative Thinking); Openness/Intellect—Big Five Aspect Scale. *p<.05; **p<.01; ***p<.001.

[60] Rex E. Jung, *et al*., "Neuroanatomy of Creativity," *Human Brain Mapping* 31 (2010): 398–409.

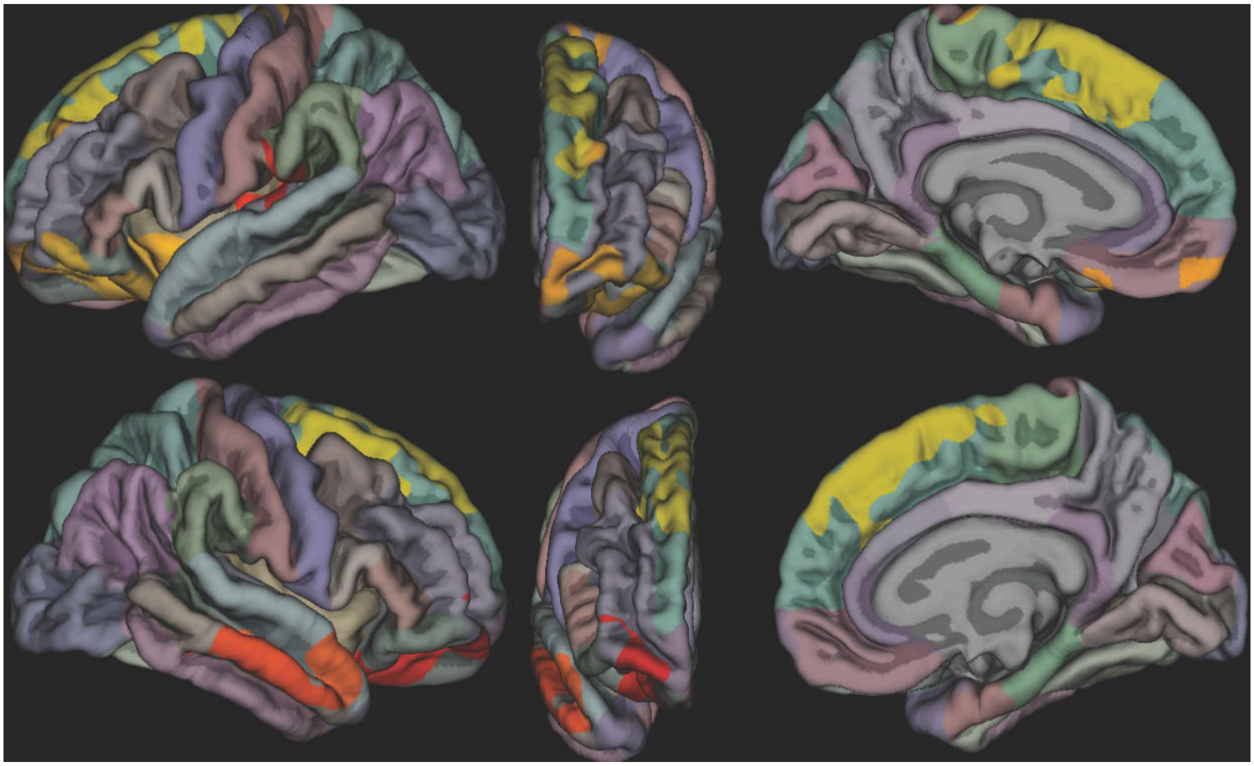

Figure 1. Regions in which surface area correlated significantly (yellow, orange, red) with musical creativity ratings across the entire sample (N=239).

DISCUSSION

Our results indicate that several brain regions show increased surface area in subjects reporting high levels of musical creativity (i.e., high levels of having "improvised or written original music"). These regions include a) bilateral dorsomedial SFG, extending from the dPMC and SMA posteriorly (BA 6) to well anterior of the rostral portions of these regions in BAs 8 and 9; b) bilateral OFC, with greater representation in the left hemisphere, extending to the medial wall of the frontal pole (in the left hemisphere) as well as posteriorly as far back as anterior insula (in both hemispheres); c) right MTG, extending into the superior

Hem	Max	Size(mm2)	TalX	TalY	TalZ	P-Value	Vtxs	Gyrus
Left	4.915	3495.73	-10.4	-0.3	58.7	0.00010	6750	superior frontal
	4.114	1043.91	-34.6	-26.1	21	0.03840	2590	planum temporale
	3.617	2320	-26	16.7	-9.5	0.00010	4321	orbitofrontal
Right	5.883	2883.28	8.3	18.4	51.6	0.00010	5440	superior frontal
	4.567	1487.19	61.8	-15.6	-16.2	0.00510	2448	middle temporal
	2.912	1218.92	18.7	32.8	-17.4	0.01900	2008	lateral orbitofrontal

Table 3. Musical Creativity Questionnaire: Regions surviving Monte Carlo simulation (P<0.05).

temporal gyrus (STG) at the pole; and d) left planum temporale region (PT). We also examined subcortical volume, finding increased volume in e) left amygdala.

A main finding of this study is that high creativity correlated with enhanced surface area in three out of four nodes of the dMPFC subsystem of the DMN,[61]—namely, dMPFC, LTC, and temporal pole (TP). The DMN has been frequently implicated in studies of creativity generally,[62] as well as in studies specifically focused on musical creativity.[63] The dMPFC subsystem of the DMN in particular has been implicated in reflecting on one's own internal state and that of others,[64] making aesthetic judgments,[65] and emotional reasoning.[66] Thus our findings suggest that this subsystem of the DMN may be integral to musical

[61] J. R. Andrews-Hanna, J. S. Reidler, J. Sepulcre, R. Poulin, & R. L. Buckner, "Functional-Anatomic Fractionation of the Brain's Default Network, *Neuron* 65 (2010): 550–62; Buckner *et al.*, "The Brain's Default Network."

[62] Beaty et al., "Creativity and the Default Network"; Jung et al., "The Structure of Creative Cognition."

[63] Limb and Braun, "Neural Substrates"; Liu *et al*., "Neural Correlates"; Pinho *et al*., "Connecting to Create."

[64] Andrews-Hanna *et al.,* "Functional-Anatomic Fractionation"; Ochsner *et al.,* "Reflecting Upon Feelings."

[65] Ellamil *et al.,* "Evaluative and Generative Modes," E. A. Vessel, G. G. Starr, & N. Rubin, "The Brain on Art: Intense Aesthetic Experience Activates the Default Mode Network," *Front Hum Neurosci* 6 (2012): 66.

[66] Eldaief *et al.,* "Emotional and Cognitive Stimuli."

creativity—more precisely that musico-creative experiences may either lead to, or result from, enhanced brain surface area in the DMN's dMPFC-subsystem.

Though medial within the prefrontal cortex, the SMA and pre-SMA, along with the dPMC on the dorsal surface, are not frequently included in the DMN\cite{Buckner:2008}. Instead, these regions tend to be implicated in active tasks, particularly tasks related to motor performance and event sequencing. As noted, all imaging studies on the subject of musical improvisation of which we are aware have implicated at least one of these three regions,[67] and studies of music perception and production more generally implicate these regions, particularly for tasks related to rhythmic perception,[68] rhythmic motor imagery,[69] and rhythmic motor production.[70] These regions have been reported to be implicated in higher-cognitive aspects of motor sequencing, particularly so in their more rostral extents.[71] The pre-SMA has been linked to the perception[72] and

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[67] Beaty, "The Neuroscience of Musical Improvisation,"; Limb & Braun, "Neural Substrates of Spontaneous Musical Performance"; Liu *et al*., "Neural Correlates of Lyrical Improvisation"; Pinho *et al.*, "Connecting to Create"; Bengtsson *et al.*, "Cortical Regions"; Berkowitz & Ansari, "Generation of Novel Motor Sequences"; Brown *et al.*, "Song System"; de Manzano & Ullén, "Activation and Connectivity Patterns"; Donnay *et al.*, "Neural Substrates of Interactive Musical Improvisation."

[68] J. L. Chen, V. B. Penhune, & R. J. Zatorre, "Listening to Musical Rhythms Recruits Motor Regions of the Brain, *Cereb Cortex* 18 (2008): 2844–54; Zatorre *et al*., "When the Brain Plays Music."

[69] R. Harris & B. M. de Jong, "Cerebral Activations Related to Audition-Driven Performance Imagery in Professional Musicians, *PLoS ONE* 9 (2014): e93681.

[70] J. L. Chen, Robert J. Zatorre, & Virginia B. Penhune, "Interactions Between Auditory and Dorsal Premotor Cortex During Synchronization to Musical Rhythms," *Neuroimage* 32 (2006): 1771–81; J. L. Chen, Robert J. Zatorre, & V. B. Penhune, "Moving on Time: Brain Network for Auditory-Motor Synchronization is Modulated by Rhythm Complexity and Musical Training," *Journal of Cognitive Neuroscience* 20 (2008), 226–239.

[71] Picard and Strick, "Imaging the Premotor Areas."

[72] Chen *et al*., "Listening to Musical Rhythms."

production[73] of greater complexity in music; it has also been implicated in freely chosen motor activities, particularly when timing is an issue.[74] The SMA proper is less implicated in studies of musical production than in musical perception; it has been proposed, however, to be involved in executing the movements that are planned in the pre-SMA,[75] and Narayana *et al*.[76] report that it coactivates with MTG and the transverse temporal region (including PT) specifically for cognitive aspects of motor tasks. The dPMC is implicated in most music perception and production tasks, and has been proposed to be involved in "extracting higher-order features of the auditory stimulus...in order to implement temporally organized actions."[77] Thus all three regions are implicated in higher-cognitive motor processing, and collectively they may represent enhancements less general to creativity and more specific to musical creativity.

Another region showing increased surface area and implying plasticity of a domain-specific nature is the left PT region. This region has been called a "computational hub"[78] and is believed to perform complex computations upon sounds, translating spectrotemporal sonic information into inferences about

[73] Chen *et al.*, "Interactions Between Auditory and Dorsal Premotor Cortex": Chen *et al.* "Moving on Time."
[74] Bengtsson *et al.*, "Cortical Regions"; I. H. Jenkins, M. Jahanshahi, M. Jueptner, R. E. Passingham, & D. J. Brooks, "Self-Initiated versus Externally Triggered Movements," *Brain* 123 (2000): 1216–1228.
[75] Jenkins *et al.*, "Self-Initiated versus Externally Triggered Movements."
[76] Narayana *et al.*, "Electrophysiological and Functional Connectivity."
[77] Zatorre et al., "When the Brain Plays Music," 554.
[78] Timothy D. Griffiths & J. D. Warren, "The Planum Temporale as a Computational Hub, *Trends in Neurosciences* 25 (2002): 348–353.

objects and their locations in space.[79] The PT is highly asymmetrical in humans, with larger surface area in the left hemisphere, especially in musicians[80]—who additionally show enhanced processing of speech sounds that occur at extremely rapid rates (up to 40 Hz).[81] Trained musicians tend to use the left PT region more than nonmusicians do when listening to music,[82] suggesting to Meyer and colleagues that "highly proficient musicians scan the incoming acoustic signal with higher temporal resolution in order to process the music in a more fine-grained mode."[83] Chen *et al.*[84] further report enhanced functional connectivity between the PT and the dPMC, on the left in particular, for trained musicians. Taken together, these findings can be interpreted to indicate enhanced coordination of sound processing in the temporal lobe with higher-cognitive motor sequencing in the frontal lobe in the brains of musically creative individuals.

The MTG and TP also showed enhanced surface area in musically creative individuals. Both regions are frequently implicated in the default mode network, particularly the dMPFC subsystem,[85] and Wei *et al*.[86] report that resting state

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[79] Griffiths and Warren, "The Planum Temporale"; Zatorre *et al*., "When the Brain Plays Music."
[80] Elmer *et al.,* "Increased Cortical Surface Area."
[81] M. Meyer, S. Elmer, & L. Jancke, "Musical Expertise Induces Neuroplasticity of the Planum Temporale," *Ann N Y Acad Sci* 1252 (2012): 116–23.
[82] T. Ohnishi *et al.,* "Functional Anatomy of Musical Perception in Musicians, *Cerebral Cortex* 11 (2001): 754–760.
[83] Meyer *et al*., "Musical Expertise," 118.
[84] Chen *et al*., "Moving on Time."
[85] Andrews-Hanna *et al.*, "Functional-Anatomic Fractionation"; Buckner *et al.*, "The Brain's Default Network."
[86] D. Wei, *et al.,* "Increased Resting Functional Connectivity of the Medial Prefrontal Cortex in Creativity by Means of Cognitive Stimulation, *Cortex* 51 (2014): 92–102.

functional connectivity between MTG and MPFC is higher among more creative individuals. The MTG has been implicated in the perception of the semantic content of music,[87] and the temporal pole has been implicated in the experience of emotion in music.[88] Both regions have been found to be more responsive to musico-structural violations in musicians compared to nonmusicians.[89] Brown *et al*.[90] report that the temporal pole is active when singers harmonize spontaneously with another voice—suggesting to the authors that the superior part of the temporal pole may be a type of "tertiary auditory cortex specialized for higher-level pitch processing related to complex melodies and harmonies, including the affective responses that accompany such processing" (p.371). In sum, both MTG and TP are implicated in both default-mode processing and in music perception, particularly semantic and affective types of music perception. The enhanced surface area seen in these regions in musically creative individuals, therefore, may represent a neural link between default-mode processing, music perception, and emotion.

The OFC is another region in which we saw enhanced surface area bilaterally, and which has been frequently implicated in emotional responses to

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87 Stefan Koelsch *et al*., "Music, Language and Meaning: Brain Signatures of Semantic Processing," *Nature Neuroscience* 7 (2004): 302–307.

88 Steven Brown, M. J. Martinez, & L. M. Parsons, "Passive Music Listening Spontaneously Engages Limbic and Paralimbic Systems," *Neuroreport* 15 (2004): 2033–2037; S. Koelsch, T. Fritz, K. Müller, & A. D. Friederici, "Investigating Emotion with Music: An fMRI Study," *Human Brain Mapping* 27 (2006): 239–250.

89 Stefan Koelsch, Thomas Fritz, K. Schulze, D. Alsop, & Gottfried Schlaug, "Adults and Children Processing Music: An fMRI Study," *Neuroimage* 25 (2005): 1068–76; M. S. Oechslin, D. Van De Ville, F. Lazeyras, C. A. Hauert, & C. E. James, "Degree of Musical Expertise Modulates Higher Order Brain Functioning, *Cereb Cortex* 23 (2013): 2213–24; Ohnishi *et al*., "Functional Anatomy of Music Perception."

90 Brown *et al*., "Song System."

music.[91] Damage in this region has been reported to impair creativity,[92] and our laboratory reports elsewhere[93] that cortical thickness in left OFC correlates with enhanced divergent thinking and openness. As explained by Kringelbach,[94] the OFC is particularly implicated in integrating sensory input with reward value, and Bechara *et al*.[95] have demonstrated that the OFC is integral to incorporating emotional and somatosensory input into decision-making processes. Brown et al.[96] note that the OFC, TP, and amygdala are all highly interconnected, suggesting a role for their involvement in musico-affective experience. For our subjects, enhanced surface area in the OFC may therefore be interpreted to indicate enhanced emotional engagement with music—perhaps undergirding the drive to create.

Further support for this interpretation comes from our finding of increased left-hemisphere amygdala volume correlating with musical creativity. The amygdala is perhaps the most frequently implicated brain structure in studies of musical emotion, correlating with emotional responses related to fear, joy,

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[91] Anne J. Blood and Robert J. Zatorre, "Intensely Pleasurable Responses to Music Correlate with Activity in Brain Regions Implicated in Reward and Emotion," *Proceedings of the National Academy of Sciences* 98 (2001): 11818–11823; Brown *et al.,* "Passive Listening"; Valerie Salimpoor *et al*., "Interactions Between the Nucleus Accumbens and Auditory Cortices Predict Music Reward Value," *Science* 340 (2013): 216–9.
[92] S. Shamay-Tsoory, N. Adler, J. Aharon-Peretz, D. Perry, & N. Mayseless, "The Origins of Originality: The Neural Bases of Creative Thinking and Originality," *Neuropsychologia* 49 (2011): 178–185.
[93] Rex E. Jung *et al*., "Quantity Yields Quality When it Comes to Creativity: A Brain and Behavioral Test of the Equal-Odds Rule," *Frontiers in Psychology* 6 (2015): 1–8.
[94] Morten L. Kringelbach, "The Human Orbitofrontal Cortex: Linking Reward to Hedonic Experience," *Nature Reviews Neuroscience* 6 (2005): 691–702.
[95] A. Bechara, Hanna Damasio, & Antonio Damasio, "Emotion, Decision Making and the Orbitofrontal Cortex," *Cerebral Cortex* 10 (2000): 295–307.
[96] Brown *et al*., "Song System."

pleasure/displeasure, sadness, tension, and unexpectedness.[97] Liu *et al*.[98] report enhanced functional connectivity between pre-SMA and left amygdala during improvisation, and further enhanced connectivity between left amygdala and numerous other regions involved in music perception and execution, such as insula, IFG, IPL, and anterior cingulate. In a study by Salimpoor *et al*.,[99] the amygdala and OFC also showed increased functional connectivity with the nucleus accumbens—the brain's "reward center"—correlated with the degree to which subjects liked pieces of music. Collectively, these results situate the amygdala within a "hedonic evaluation network"—in which music is perceived and parsed in the STG and PT, is engaged with at higher levels via dPMC, SMA, and pre-SMA, and finally is evaluated via the coordination and enhanced functional connectivity of OFC, TP, and amygdala.

There are several limitations to the conclusions drawn here. First, though we examined only brain structure, we interpreted our findings based in part upon the functional imaging literature. It remains uncertain to what extent function and structure in the brain are correlated. Second, we examined surface area of the brain rather than volume or thickness. Surface area can index the size either of intracortical elements or of local subcortical factors,[100] and thus should be interpreted with caution. Nevertheless, surface area is the

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[97] David Bashwiner, "On Scary Music: The Amygdala in Music Theory," (Submitted).
[98] Liu *et al*., "Neural Correlates of Lyrical Improvisation."
[99] Salimpoor *et al.*, "Interactions Between the Nucleus Accumbens and Auditory Cortices."
[100] H. Lemaitre *et al.,* "Normal Age-Related Brain Morphometric Changes: Nonuniformity Across Cortical Thickness, Surface Area and Gray Matter Volume?" *Neurobiol Aging* 33 (2012): 617e1–9.

most stable of the three measures across time,[101] making it potentially the most valid for a cohort of subjects spanning almost two decades of age difference. Third, because our subjects were all young adults, these results might not generalize to children and older adults. Nevertheless, we chose to examine subjects at a point in time when their brains were for the most part fully formed but had not yet begun to demonstrate the structural effects of aging. Fourth, our subjects had (for other reasons) been selected for expertise in the STEM fields, and it would be important to replicate this study using subjects drawn from fields more associated with the arts and humanities. Fifth, this study is correlational and not causal, and it is therefore not possible to determine whether the brain morphometry patterns found for more musically creative individuals led them to create more, or whether creating more led to the brain morphometry patterns seen here. All that can be deduced is that the patterns found correlate with enhanced musical creativity (as indicated by self-report). Sixth, the method used for assessing musical creativity relied entirely on self-report, which is always of questionable reliability, although the correlation of this measure with other well-validated measures of creativity—namely the Creative Achievement Questionnaire and the Big Five Aspects Scale for Openness-Intellect—increases our confidence in its construct validity. Finally, we were not able to distinguish between different types of musical creativity, such as

[101] Lemaitre *et al.,* "Normal Age-Related Brain Morphometric Changes."

improvisation vs. orchestral composition vs. songwriting—which may involve very different sets of cognitive processes, and hence very different neural processes.

By way of outro, it may be of value to reflect upon the creative process as described by composer Johannes Brahms. Brahms stated that, when truly inspired, a "finished product" would often be "revealed" to him "measure by measure." Notably, he had to be "in a semi-trance condition to get such results—a condition when the conscious mind is in temporary abeyance and the subconscious is in control, for it is through the subconscious mind...that the inspiration comes."[102] However anachronistically, we may interpret this description as referring to what we now call the default mode of brain activity. Nevertheless, we should not assume this to be the entirety of musical creativity, for, as Brahms pointed out, "a composer must have mastered the technic [*sic*] of composition, form, theory, harmony, counterpoint, instrumentation."[103] He insisted, "my compositions are not the fruits of inspiration alone, but of severe, laborious and painstaking toil."[104]

Creative behaviors—of both big C and little c types—are among the most complex that humans engage in. They involve not only domain-general capacities, such as the ability to defocus the attention and let ideas "reveal" themselves into consciousness seemingly of their own accord, but also highly intricate, domain-specific knowledge and skill—developed over years of

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[102] A. M. Abell, *Talks with Great Composers* (Philosophical Library, New York, 1955).
[103] *Ibid.*, 6.
[104] *Ibid.*, 59

practice—all motivated by the affective drive to create. This study highlights structural imaging data indicating that self-reported experience being musically creative correlates with greater cortical surface area or volume in a) domain-general creative-ideation regions organized around the default mode network (dMPFC, MTG, TP), b) domain-specific regions frequently recruited for musical tasks (dPMC, SMA, pre-SMA, PT), and c) emotion-affiliated regions (OFC, TP, and amygdala). These findings suggest that default-mode cognitive processing style, domain-specific musical expertise, and intensity of emotional experience are likely coordinated to both facilitate and motivate the drive to create music.

Appendix (Next Two Pages): Musical Creativity Questionnaire

The questionnaire on the next two pages was written and designed specifically for this study. See Table 2 for correlations with other measures of creativity, such as the Creative Achievement Questionnaire and the Big Five Aspects Scale Openness/Intellect.

SUBJECT ID: _____________

MUSICAL CREATIVITY QUESTIONNAIRE

I. Musical Background

Have you ever practiced a musical instrument? Circle one option. (Please include "voice" as an instrument if you are a singer.)

1	2	3	4	5	6
Never	*Rarely*	*Monthly*	*Weekly*	*Daily*	*Several Hours/Day*

If 5 or 6, please indicate for each instrument:

a. The instrument played;
b. The number of years you played the instrument on a daily or almost daily basis;
c. The number of hours you practiced/played the instrument per day *averaged over the whole duration of the period indicated in (b);*
d. Whether study was predominantly formal (with a teacher), informal (for example, learning from recordings, self study from books, playing in a rock band), or an equal amount of both;
e. Whether such study predominantly involved reading music, playing by ear, or an equal amount of both.

(a) Instrument	**(b)** Years Played (Daily Basis)	**(c)** Average Number Hours Played	**(d)** Formality of Study (check one box only)			**(e)** Reading Music vs. Playing by Ear (check one box only)		
			Formal	Informal	Equal Amt. Both	Reading Music	Playing by Ear	Equal Amt. Both
1.								
2.								
3.								
4.								
5.								
6.								
7.								

II. Creative Musical Achievement

Place a check mark beside sentences that apply to you. For "recordings," consider both professional and semi-professional.

_____ I have composed an original piece of music.
_____ An original piece of music that I have composed has been published or recorded.
_____ I have performed on a recording of someone else's composition.
_____ I have performed on a recording of my own composition.
_____ Recordings of my composition have been sold publicly.
_____ My musical talent has been critiqued in a local publication.
_____ My compositions have been critiqued in a national publication.

III. Musical Creativity

Have you ever improvised or written original music? Circle one option.

1	2	3	4	5	6
Never	*Rarely*	*Monthly*	*Weekly*	*Daily*	*Several Hours/Day*

Please indicate for each behavior:

a. The number of years you have spent doing the specified behavior (enter 0 if none);
b. Whether your engagement with the behavior was daily, weekly, or infrequent.

	(a) Number of Years	(b) Degree of Engagement		
		Daily	Weekly	Infrequent
Improvising				
Writing songs (specifically the *musical* portions of songs—not lyrics				
Composing on paper (or in a notation program, such as Finale or Sibelius)				
Composing electronic music				
Other (specify): ____________________				

IV. General Questions

a. On a scale of 1 to 6 (6 = very creative), how musically creative would you rate yourself to be? (circle one number)

1	2	3	4	5	6
not creative					*very creative*

b. How frequently do you listen to music? (circle one)

1	2	3	4	5	6
Never	*Rarely*	*Monthly*	*Weekly*	*Daily*	*Several Hours/Day*

c. What type of music do you listen to most frequently? (circle one)

rock/pop jazz classical electronic folk rap other: _________