Neuroscience Letters 354 (2004) 193–196

Neuroscience Letters

www.elsevier.com/locate/neulet

The effect of musical training on the neural correlates of math processing: a functional magnetic resonance imaging study in humans

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Received 18 August 2003; received in revised form 6 October 2003; accepted 8 October 2003

Abstract

The neural correlates of the previously hypothesized link between formal musical training and mathematics performance are investigated using functional magnetic resonance imaging (fMRI). FMRI was performed on fifteen normal adults, seven with musical training since early childhood, and eight without, while they mentally added and subtracted fractions. Musical training was associated with increased activation in the left fusiform gyrus and prefrontal cortex, and decreased activation in visual association areas and the left inferior parietal lobule during the mathematical task. We hypothesize that the correlation between musical training and math proficiency may be associated with improved working memory performance and an increased abstract representation of numerical quantities.

Keywords: Adult; Cognition; Functional magnetic resonance imaging; Neural pathways; Music; Mathematics

The effect of formal musical training on separate cognitive domains such as language, mathematical, and spatial continues to be a subject of debate, with some behavioral studies reporting positive associations [15]. Some neuro-imaging studies have also demonstrated differences between musicians and non-musicians. Increased corpus callosum size was found in musicians [16], as well as increased white matter organization in the genu of the corpus callosum and decreased white matter organization in the corticospinal tract [18]. In a functional magnetic resonance imaging (fMRI) study, differences in cortical representations for a motor task were shown [9].

Based on evidence from previous behavioral and neuroimaging studies, we therefore hypothesized that formal musical training through the developmental period would affect the neural correlates of math processing. We performed a preliminary investigation of this hypothesis using fMRI. The cross-sectional design employed does not allow testing of the alternative hypothesis that differences in neural networks utilized for math processing between subjects with and without musical training were already in place prior to the inception of the musical training. However, the presence of cortical regions displaying activation differences between musicians and non-musicians would still provide supporting, though not probative, evidence of a causal link.

Fifteen normal adults (4F, 11M, mean age = 37.8 ± 15.2 years) were recruited to participate in the study. Institutional review board approval and written informed consent were obtained for all subjects, and each subject was prescreened for any conditions which would prevent an MRI scan from being performed. Seven of the subjects had studied either a musical instrument or voice since early childhood, while eight had not. In order to investigate the effects of formal musical training during the developmental period, our criterion for classifying a subject a 'musician' was that he or she have engaged in musical study continuously since early childhood (age 8 or earlier) throughout adolescence. Since the hypothesized causal link regarding musical training would not be expected to be unique to math processing, but would likely encompass other cognitive domains as well [11], the cross-sectional design precluded the possibility of controlling for any effects due to general intelligence or other cognitive abilities, as the correct control variables to utilize would be the (unavailable) measures of those factors obtained prior to the musical training. Hence, we chose to randomly select our study population from a sample of normal, college-educated adults.

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0304-3940/03/$ - see front matter © 2003 Published by Elsevier Ireland Ltd.
doi:10.1016/j.neulet.2003.10.037

Stimuli were presented by an Apple Macintosh G3 (Apple Computer, Cupertino, CA) using MacStim through an MRI-compatible video system (Magnetic Resonance Technologies, Van Nuys, CA). A block-periodic fMRI paradigm was used. During the active condition, the subjects were presented with three fraction problems (either addition or subtraction) to perform mentally. The fractions all contained single digit numbers in both numerator and denominator. No specific instructions were given to the subjects on how to perform the task except the visual reminder on a board prior to the scanning session that $a/b + c/d = (ad + bc)/bd$. All subjects underwent a practice session outside of the magnet prior to the scanning session to ensure they understood and could perform the task. They were given 10 s to complete each problem, and were instructed to move on to the next one if they did not finish in time. The denominators of the fractions were restricted to five or less; however, improper fractions were used, and the answers were sometimes negative. During the control condition, the subjects were presented with three sets of four numbers at 10 s intervals at the same positions on the screen as the fractions, but without any divisor bars or plus or minus signs. The subjects were given a 3 s visual cue of either 'Perform Math' or 'Rest' prior to the active and control task, respectively. Fifteen seconds of scans were acquired prior to the beginning of the paradigm in order to allow for T1 relaxation, followed by ten alternating active and control conditions of 33 s each (including the 3 s cue), for a total scan time of 5 min 45 s. No performance data was collected, due to the impossibility of the subjects' speaking aloud without introducing uncorrectable motion artifacts. However, the likelihood of any differences in task performance was greatly minimized, due to the task being chosen to have a difficulty level well below the subjects' level of educational attainment, and the 'dry run' performed prior to the scanning session.

MRI images were obtained using a 3T Bruker Medspec system (Bruker Medical Instruments, Karlsruhe, Germany). For the functional imaging scans, a 24-slice blipped echo-planar imaging (EPI) sequence was used with the following parameters: $\text{matrix} = 64 \times 64$, $\text{BW} = 125$ kHz, $\text{FOV} = 25.6 \times 25.6$ cm, $\text{TE} = 38$ msec, $\text{TR} = 3$ s, slice thickness = 5 mm. In addition, a whole-brain T1-weighted scan was acquired for anatomical coregistration.

FMRI post-processing was performed with routines written in IDL (Research Systems Inc., Boulder, CO). During reconstruction, the EPI data was corrected for geometric distortion and Nyquist ghost artifacts via the multiecho reference method [17]. The images were corrected for motion via a pyramid iterative algorithm [19] and transformed into stereotaxic coordinates using landmarks found from the whole-brain anatomical images. The fMRI data was smoothed with a Gaussian filter of width 2 mm and then post-processed using the general linear model [20], with a set of cosine basis functions used as covariates to account for possible signal drift and aliased respiratory and cardiac signals. Voxelwise random-effects analyses [5] for musicians, non-musicians, and all subjects combined, were performed in order to determine clusters of significant group activation, based on extent threshold of activated voxels and Gaussian Random Field theory. Separate analyzes were performed on the subset of voxels determined to be active in either musicians or non-musicians (with corrected $P < 0.001$) in order to determine regions with significant group differences.

The task paradigm involves a combination of multiplication, thought to be primarily moderated by language and rote processes, and addition or subtraction, thought to be primarily moderated by visuo-spatial processes [3]. In addition, a working memory component would be expected as it is necessary to retain intermediate results. Accordingly, activation was found in visual association areas, the fusiform gyrus, and the inferior frontal gyrus (Fig. 1); as well as the inferior parietal lobules, prefrontal areas, and the medial frontal gyrus (data not shown). The results are in agreement with previous imaging studies involving arithmetic processing, in which activation has been found in the prefrontal and parietal cortices [2,4], and the fusiform gyrus [13].

Significantly greater activation was found (Table 1) in regions including the left fusiform gyrus and left prefrontal cortex for musicians; and the right inferior occipital gyrus, left medial occipital gyrus, right orbital gyrus, and left inferior parietal lobule for non-musicians. The increased activation seen in the left fusiform gyrus (Fig. 1, top) is likely associated with increased proficiency in the processing of shape information [14] and visual perceptual

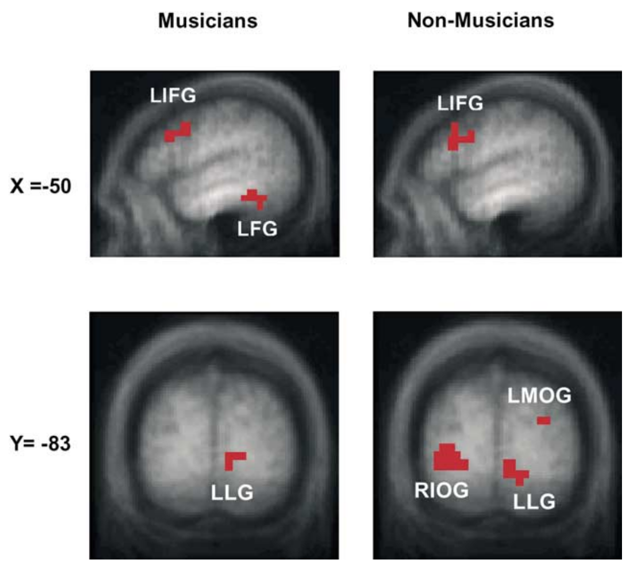

Fig. 1. Composite activation maps for seven musicians (left) and eight non-musicians (right) performing the mental addition and subtraction of fractions. Slices selected for display are sagittal at $X = -50$ and coronal at $Y = -83$ (Talairach coordinates). Activated pixels have $P < 0.001$ (corrected). (Labels: LIFG = left inferior frontal gyrus; LFG = left fusiform gyrus; LLG = left lingual gyrus; LMOG = left medial occipital gyrus; RIOG = right inferior occipital gyrus).

Table 1
Regions with significant differences in activation between musicians and non-musicians ($P < 0.05$, corrected) performing mental addition or subtraction of fractions (BA = Brodmann's Area, X, Y, Z = Talairach coordinates)

Area	BA	X, Y, Z	T
Musicians > non-musicians			
Fusiform gyrus	20/37	−54, −37, −20	3.57
Medial frontal gyrus	9/46	−34, 51, 25	5.30
Musicians < non-musicians			
Inferior occipital gyrus	18	30, −85, −10	−6.44
Medial occipital gyrus	19	−18, −77, 5	−3.81
Thalamus		18, −13, 10	−3.43
Orbital gyrus	19	26, −77, 25	−2.79
Inferior parietal lobule	40	−46, −41, 50	−4.12

semantic processing [12], generated by years of experience reading and interpreting musical notation. This would also account for the decreased activation seen in visual association areas (Fig. 1, bottom), which has been related to practice or habituation effects in studies investigating visuospatial working memory [7], and the presentation of repeated visual stimuli relative to novel objects [8].

An intriguing alternative hypothesis [8], however, is that the left fusiform gyrus may be involved in processes involving a more 'abstract' level of visual form. Thus, musicians would be employing a more 'abstract' representation of numbers and especially fractions. This hypothesis is corroborated by the decreased activation seen in the left inferior parietal lobule, previously implicated in differences in processing strategy during a serial subtraction task [1]. Subjects who used a 'visual' strategy, involving the mental lining up of the numerals and their subtraction through rote processes, displayed increased activation in the left inferior parietal cortex relative to those who used a 'verbal' strategy, involving approximation. If musicians actually are using a more 'abstract' representation of fractions, they would be expected to employ rote calculation procedures to a lesser extent than non-musicians.

The increased activation in the left prefrontal cortex (BA 46) in musicians suggests that the hypothesized link between musical training and improved math performance may also be associated with improved performance of semantic working memory [6], related to improved conflict resolution. A recent fMRI study [10] has shown differential activation in the left prefrontal cortex during the processing of incorrect equations as compared to correct equations, interpreted as maintaining results in working memory while resolving the conflict between the externally presented (incorrect) answer and the internally computed (correct) response. Musical training would be expected to generate increased proficiency at this type of conflict resolution. For instance, a trained musician will instantaneously detect the playing of a wrong note during a practice session. A skilled pianist must be able to quasi-instantaneously detect if his left hand is not exactly in time with his right one, even by a very small amount, and a violinist must be able to detect and correct for extremely minute variations in pitch in order to maintain correct intonation with the other members of the ensemble.

In conclusion, the statistically significant differences found in the neural correlates of math processing between musicians and non-musicians, even with the small sample size used, provide a strong motivation for a future longitudinal study performed on children in order to probe for a possible causal relationship between musical training and any differences in the neural architecture used for math processing, and to associate those differences with any differences seen in math ability.

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