Effects of Music Training on the Child's Brain and Cognitive Development

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ABSTRACT: Research has revealed structural and functional differences in the brains of adult instrumental musicians compared to those of matched nonmusician controls, with intensity/duration of instrumental training and practice being important predictors of these differences. Nevertheless, the differential contributions of nature and nurture to these differences are not yet clear. The musician–nonmusician comparison is an ideal model for examining whether and, if so, where such functional and structural brain plasticity occurs, because musicians acquire and continuously practice a variety of complex motor, auditory, and multimodal skills (e.g., translating visually perceived musical symbols into motor commands while simultaneously monitoring instrumental output and receiving multisensory feedback). Research has also demonstrated that music training in children results in long-term enhancement of visual–spatial, verbal, and mathematical performance. However, the underlying neural bases of such enhancements and whether the intensity and duration of instrumental training or other factors, such as extracurricular activities, attention, motivation, or instructional methods can contribute to or predict these enhancements are yet unknown. Here we report the initial results from our studies examining the brain and cognitive effects of instrumental music training on young children in a longitudinal study and a cross-sectional comparison in older children. Further, we present a comparison of the results in these children's studies with observations from our cross-sectional studies with adults.

KEYWORDS: music; instrumental music training; musicians; nonmusicians; brain plasticity; skill learning; longitudinal study; children; development morphometry; fMRI

BRAIN DIFFERENCES BETWEEN ADULT MUSICIANS AND NONMUSICIANS

Instrumental training is a multisensory motor experience, typically initiated at an early age. Playing an instrument requires a host of skills, including reading a com-

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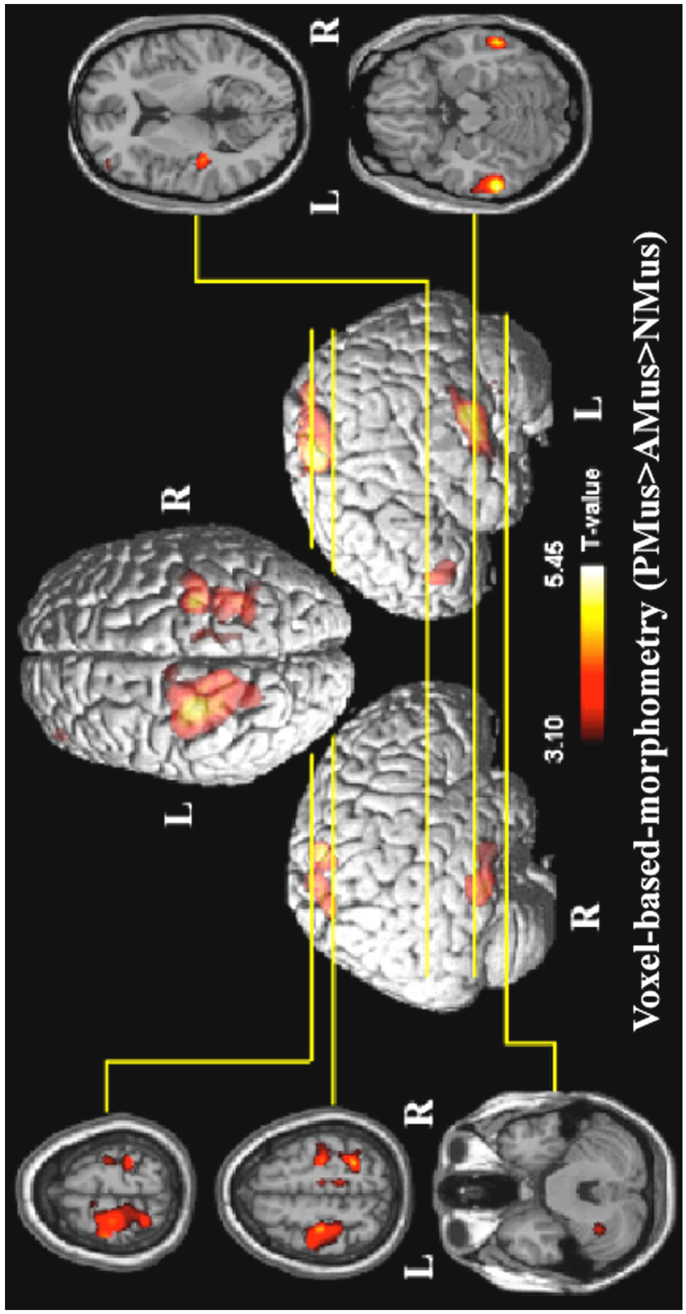

FIGURE 1. A voxel-based morphometric analysis of nonmusicians compared with amateur and professional musicians.

plex symbolic system (musical notation) and translating it into sequential, bimanual motor activity dependent on multisensory feedback; developing fine motor skills coupled with metric precision; memorizing long musical passages; and improvising within given musical parameters. Studies have explored the brain bases of these highly specialized sensorimotor,[1–5] auditory,[6–11] and auditory–spatial[12] skills. As shown in FIGURE 1 (a voxel-based morphometric analysis of nonmusicians compared with amateur and professional musicians), professional keyboard players, who reported approximately twice as much weekly practice time as the amateur musicians,[5] have significantly more gray matter in several brain regions, including the primary sensorimotor cortex, the adjacent superior premotor and anterior superior parietal cortex bilaterally, mesial Heschl's gyrus (primary auditory cortex), the cerebellum, the inferior frontal gyrus, and part of the lateral inferior temporal lobe, than either the amateur musicians or the nonmusicians.

While it may not be as surprising that structural differences are found in those brain regions that are closely linked to skills learned during instrumental music training (such as independent fine motor movements in both hands and auditory discrimination), structural differences outside of these primary regions (e.g., inferior frontal gyrus; see also Ref. 13) are of particular interest since this may indicate that plasticity can occur in brain regions that either have control over primary musical functions or serve as multimodal integration regions for musical skills. Functional correlates of music processing differences between musicians and nonmusicians typically show greater lateralization and stronger activation of auditory association areas in musicians, whereas nonmusicians may show stronger activation of primary auditory

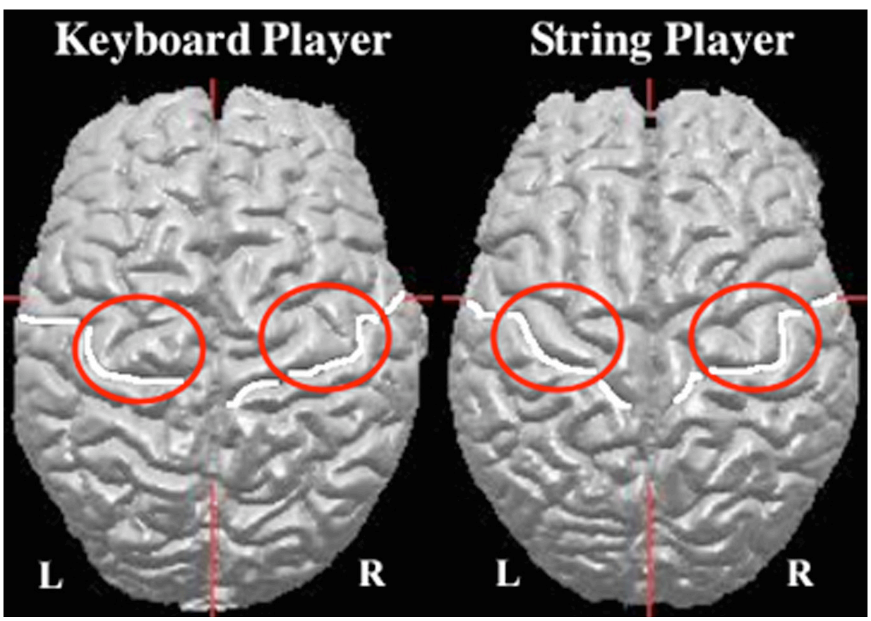

FIGURE 2. Within-musician, instrument-typical, gross-anatomical differences are seen in the precentral gyrus.

regions.[11] These effects have also been found in short-term training studies both in adult nonmusicians and in young children using auditory evoked potentials.[14–16]

Further support for the plasticity hypothesis comes from studies showing within-musician differences. Pantev and colleagues[17] found more pronounced cortical responses to trumpet and string tones in the respective players of those instruments, demonstrating that functional brain differences can be associated with the particular musical instrument played. Similarly, when comparing string and keyboard players, Bangert and colleagues[18] from our group have found within-musician differences in the omega sign (OS), an anatomical landmark of the precentral gyrus commonly associated with representation of hand/finger movement (see FIG. 2). The majority of the adult keyboard players had an elaborated configuration of the precentral gyrus on both sides, whereas most of the adult string players had this atypicality only on the left. There is evidence suggesting that these structural differences in musicians' brains are more pronounced in musicians who began study at a younger age[1,19,20] and who practiced with greater intensity.[5,10,21] Long-term motor training studies in animal studies also support the argument for training-associated brain plasticity.[22]

In order to determine whether the structural and functional differences seen in adult musicians reflect adaptations that occurred as a result of musical training during sensitive periods of brain development, or are instead, markers of musical interest and/or aptitude that existed prior to training, it is necessary to examine children and/or adults before the onset of instrumental music training and compare them to a group of control subjects not planning to study a musical instrument and practice regularly. Thus, we report here our baseline results and preliminary analyses after the first year of our pilot longitudinal study that aims to examine this hypothesis. These results are presented in conjunction with those of our cross-sectional studies of nine- to eleven-year-old children.

A CROSS-SECTIONAL COMPARISON OF FIVE- TO SEVEN-YEAR-OLD CHILDREN PRIOR TO INSTRUMENTAL MUSIC TRAINING

For the past two years we have been conducting a longitudinal study of the effects of music training on brain development and cognition in young children.[23–25] The major questions addressed were (1) whether there are pre-existing differences in brain structure/function and/or cognitive skills in children just beginning to study a musical instrument compared to those who are not; and (2) whether instrumental training initiated between the ages of five and seven leads to cognitive enhancement and stimulates regional brain growth in areas previously shown to be structurally different in adult musicians.[4,5,10,21] We have tested fifty, five- to seven-year-old children at baseline prior to beginning music lessons. Approximately two-thirds of those children chose to take piano, while the other third chose string lessons. We have also tested a smaller, untreated control group (currently $n = 25$) matched to the instrumental group in age, socioeconomic standard (SES), and verbal IQ. Each child underwent a battery of behavioral tests, including the Object Assembly, Block Design, and Vocabulary subtests from either the Wechsler Intelligence Scale for Children (WISC-III) (for children six years and older) or the Wechsler Preschool and Primary Scale of Intelligence (WPPSI-III) (for children under age six); the Raven's Colored Progressive Matrices (CPM) and Raven's Standard Progressive Matrices (SPM); the

Auditory Analysis Test[26] as a measure of phonemic awareness; Gordon's Primary Measures of Music Audiation (PMMA) as a measure of musical skill/aptitude; and two motor tests (an index finger tapping test and a motor sequencing task using four fingers) to measure speed and dexterity in both right and left hands.

Children also underwent structural and functional MR scans of their brains using a specially designed, child-appropriate protocol. MR images were acquired on a 3 Tesla General Electric Magnetic Resonance Imaging (MRI) Scanner. We found no pre-existing cognitive, music, motor, or structural brain differences between the instrumental and control groups at baseline,[25] thereby making it unlikely that children who choose to play a musical instrument do so because they have atypical brains, and suggesting that the brain atypicalities seen in adult musicians are more likely to be the product of intensive music training rather than pre-existing biological markers of musicality. The structural MR sequence had a spatial resolution of $1 \times 1 \times 1.5$ mm. We used a fully automatic technique for computational analysis of differences in local gray and white matter.[5,27] There were no differences in the absolute brain volume, gray matter volume, white matter volume, or the midsagittal corpus callo-

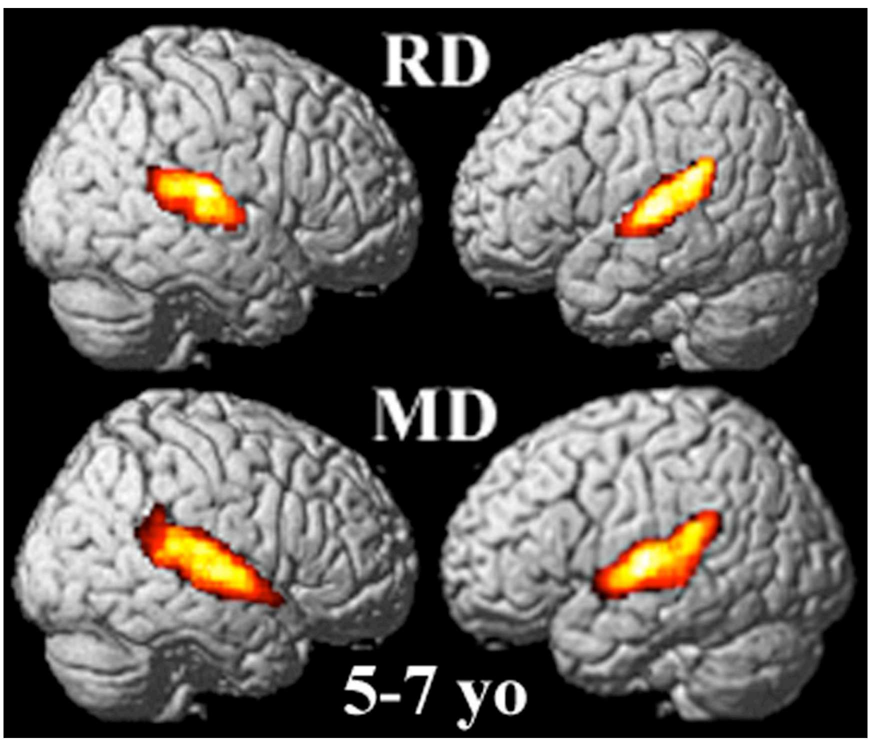

FIGURE 3. Statistical parametric images superimposed on surface renderings of a standardized anatomical brain depict significant group activations during rhythmic and melodic discrimination tasks in five- to seven-year-old children, naive for instrumental music training.

sum size (for more details, see Ref. 25). A voxel-based analysis[5,27] showed no significant differences in regional gray matter volume between the two groups.

Our fMRI scanning protocol, specifically for young children, uses short scanning runs, a sparse temporal sampling data acquisition technique,[28] simple rhythmic (RD) and melodic discrimination (MD) tasks with a button press response to indicate *same/different* judgments for pairs of short musical phrases, and a child-oriented MRI preparation session to overcome the challenges of scanning such young children. The functional images from each musical condition (RD and MD) were contrasted with the images from the silence condition (baseline) at a significance threshold of $P < .05$, using a family-wise error (FWE) correction for multiple comparisons. Both musical conditions led to strong bilateral activation of the superior temporal gyrus (STG; FIG. 3). A region in the right STG (slightly anterior and inferior to Heschl's gyrus) was found to show significantly higher activation during melodic discrimination than during rhythmic discrimination (for more details, see Ref. 23).

AFTER ONE YEAR OF INSTRUMENTAL MUSIC TRAINING

In our preliminary analyses (so far, only half of the children have completed their second round of testing) of the effects of one year of music training, we found significantly greater change scores in the instrumental group compared to the control group in behavioral tests directly linked to instrumental music training: fine motor skills (mean of 10% for the instrumental group compared to 5% for the control group) and auditory discrimination skills, as measured by Gordon's PMMA (1986) (9% vs. 6%). Although we have not yet found evidence for transfer effects in domains such as verbal, visual–spatial, and math after 14 months of observation, the instrumental group showed trends in the anticipated direction. Brain data also support this trend. In the groups used for the preliminary analyses, there was a nonsignificantly greater increase in gray matter volume in the instrumental group than in the control group, but as yet, no significant change in corpus callosum size has emerged. Since these between-group differences are likely to change as more subjects are added to the analyses, we are also investigating the influence of practice intensity on our behavioral outcomes and brain data within the instrumental music group. Preliminary analyses of the fMRI data suggest that functional changes during the melodic and rhythmic discrimination tasks occur after one year of instrumental music learning in both the right and left hemisphere, mainly in auditory association areas in the temporal lobe and temporal-parietal junction. No significant changes were seen when the control group's baseline was compared with their second set of results 14 months later.

A CROSS-SECTIONAL COMPARISON OF NINE- TO ELEVEN-YEAR-OLD CHILDREN: INSTRUMENTALISTS VERSUS NONINSTRUMENTALISTS

We recently added a new cross-sectional comparison between a group of nine- to eleven-year-old instrumentalists with an average of four years of training and a

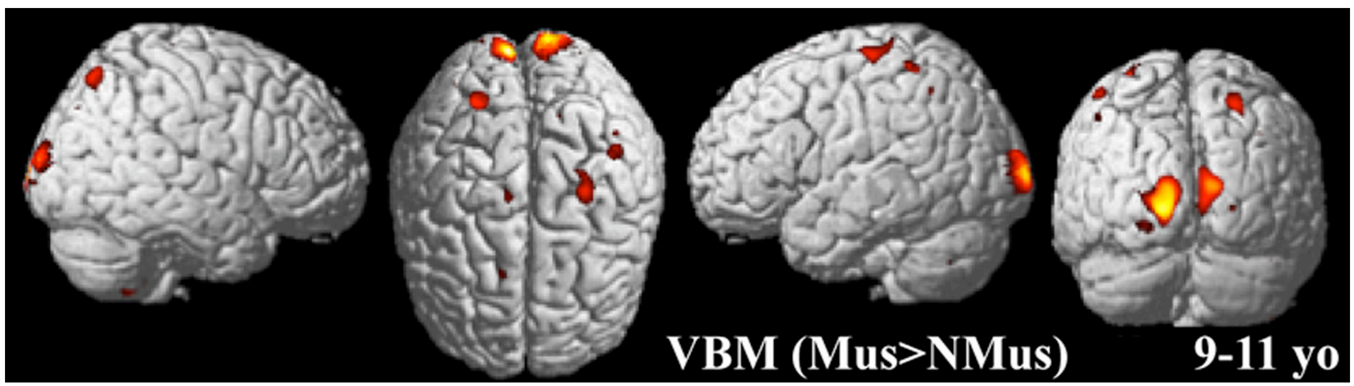

FIGURE 4. Voxel-based morphometry study comparing nine- to eleven-year-old instrumentalists with matched nonmusician controls.

group of noninstrumentalists (matched in age, handedness, and SES) to our ongoing longitudinal study. This group of children underwent the same battery of behavioral tests and imaging studies as the children in our longitudinal group of five to seven year olds did. The instrumental group performed significantly better than the well-matched control group on the Gordon's Intermediate Measures of Music Audiation (primarily due to their superior performance in the tonal subtest), the maximal left hand index finger tapping rate, and the Vocabulary subtest of the WISC-III. Strong, nonsignificant trends were seen in the phonemic awareness test (Auditory Analysis), the Raven's Progessive Matrices, and the Key Math test. We did not find any significant differences in the Object Assembly or Block Design tests. Because the tasks of reading music and playing an instrument call upon a wide variety of skills, there are plausible explanations for why music training could lead to transfer effects in other areas. For example, music training might enhance spatial reasoning because music notation itself is spatial. Mathematical skills may well be enhanced by music learning because understanding rhythmic notation actually requires math-specific skills, such as pattern recognition and an understanding of proportion, ratio, fractions, and subdivision (e.g., a half note is twice as long as a quarter note, and a quarter note can be evenly subdivided into four sixteenth notes). Phonemic awareness skills may be improved by music training because both music and language processing require the ability to segment streams of sound into small perceptual units.

The instrumentalists had significantly more gray matter volume (mean [SD] of 747 [75] cc compared to 661 [82] cc for the noninstrumental group) that was regionally pronounced not only in the sensorimotor cortex, but also in the occipital lobe bilaterally (FIG. 4). FIGURE 4 shows the regional distribution of gray matter volume differences when the instrumental group was compared with the noninstrumental group on a voxel-by-voxel basis.[29]

The nine- to eleven-year-old children participated in the same functional imaging experiments as the five to seven year olds in our longitudinal study (FIG. 5). Functional images from each musical condition (RD and MD) were contrasted with the images from the silence (control) condition at a significance threshold of $P < .05$, using a FWE correction for multiple comparisons. Preliminary analysis of all group comparisons revealed that both the instrumental and noninstrumental groups showed strong bilateral activation of the STG. However, the instrumental group showed more activation of the STG, particularly on the right, and also more activation of the posterior inferior and middle frontal gyrus in both hemispheres (more so in the MD than in the RD task). This trend of additional extratemporal lobe activation was found to be further increased in a group of adult subjects with long-term, intensive instrumental music training who also performed these functional tasks. This data is not reported in detail here, although FIGURE 6 shows the pattern of activation for the RD tasks in two adult groups (professional musicians vs. nonmusicians). Further, by comparing FIGURE 6 with FIGURES 5 and 3, the increase in extratemporal lobe activation with maturity and greater length of instrumental training becomes apparent.

The inferior and middle frontal regions that are activated by these rhythmic and melodic discrimination tasks may play a role in the integration of auditory events into larger units, or the sequential ordering of behaviorally relevant auditory events. The frontal and, in particular, the inferior frontal activations seen in auditory tasks should be considered in the context of the discussion on mirror neurons. "Mirror" neurons respond both when an action is observed and when that same action is per-

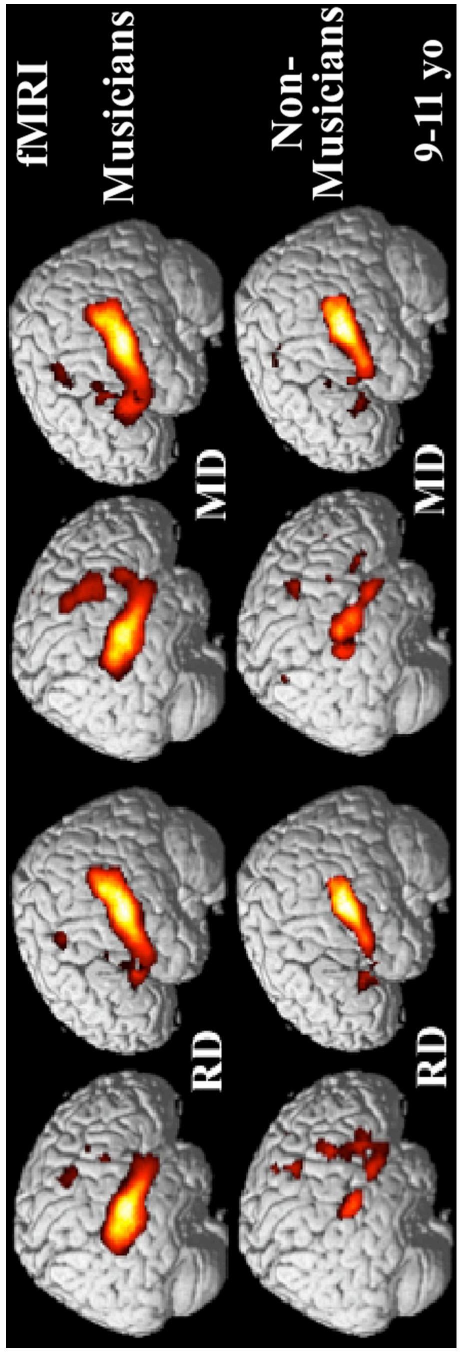

FIGURE 5. Statistical parametric images superimposed on surface renderings of standardized anatomical brains depict significant group activations during rhythmic and melodic discrimination tasks in nine- to eleven-year-old children with and without instrumental music training.

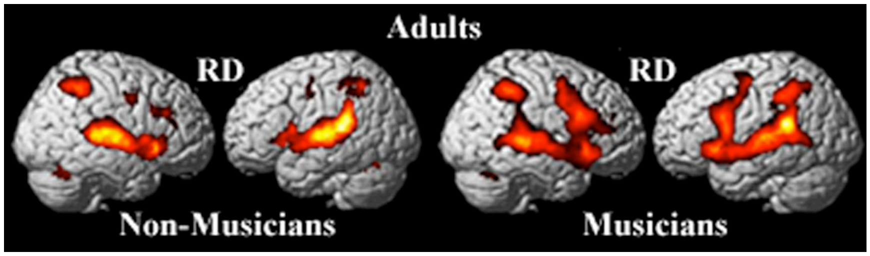

FIGURE 6. Statistical parametric images superimposed on standardized anatomical brains show significant activations during a melodic discrimination task in a group of professional musicians and a matched group of nonmusicians.

formed. In addition to the sight and performance mirror neurons, a subset of mirror neurons in monkeys also responds to the sound of an action.[30,31] These "auditory–visual" mirror neurons exemplify high-level abstraction in the representation of action—an identical neural system becomes activated regardless of whether a particular action is heard, seen, or performed. This may have implications for music learning over time. As musical skills are acquired, the same kinds of action–sound mappings occur.[32] The student learns by watching the teacher and/or conductor, by listening to the sounds that are produced by particular types of movement, by evaluating self-produced sounds either in isolation or in combination with sounds produced by other musicians, and by translating visual symbols into sound. Thus, it is likely that mirror neurons may play an important role in instrumental music learning. This notion is supported by the frontal activation that emerges in the nine- to eleven-year-old group and becomes more prominent in the adult musician group.

SUMMARY

Preliminary results of our longitudinal study in five- to seven-year-old children suggest that cognitive and brain effects from instrumental music training can be found. After 14 months of observation, these effects are still small and in domains such as fine motor and melodic discrimination that are closely related to the instrumental music training. Data from our cross-sectional study of nine- to eleven-year-old children with an average of four years of musical training suggest that the predicted effects become stronger, and that transfer effects begin to emerge in addition to those strong effects in closely related motor and auditory domains. Nevertheless, our nine- to eleven-year-old cross-sectional study is correlational, and although it supports the general trends seen across all three groups (from small, nonsignificant trends in five- to seven-year-olds after 14 months of observation, to prominent musician–nonmusician differences in adults), only an experimental study such as our longitudinal study can prove causality and test the role of other predictors such as intensity of training, skill at reading musical notation, and level of musical achievement.

[Competing interests: The authors declare that they have no competing financial interests.]

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