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Brain and Cognition 59 (2005) 124–134

Brain and Cognition

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Are there pre-existing neural, cognitive, or motoric markers for musical ability?

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Accepted 29 May 2005
Available online 28 July 2005

Abstract

Adult musician's brains show structural enlargements, but it is not known whether these are inborn or a consequence of long-term training. In addition, music training in childhood has been shown to have positive effects on visual–spatial and verbal outcomes. However, it is not known whether pre-existing advantages in these skills are found in children who choose to study a musical instrument nor is it known whether there are pre-existing associations between music and any of these outcome measures that could help explain the training effects. To answer these questions, we compared 5- to 7-year-olds beginning piano or string lessons ($n = 39$) with 5- to 7-year-olds not beginning instrumental training ($n = 31$). All children received a series of tests (visual–spatial, non-verbal reasoning, verbal, motor, and musical) and underwent magnetic resonance imaging. We found no pre-existing neural, cognitive, motor, or musical differences between groups and no correlations (after correction for multiple analyses) between music perceptual skills and any brain or visual–spatial measures. However, correlations were found between music perceptual skills and both non-verbal reasoning and phonemic awareness. Such pre-existing correlations suggest similarities in auditory and visual pattern recognition as well a sharing of the neural substrates for language and music processing, most likely due to innate abilities or implicit learning during early development. This baseline study lays the groundwork for an ongoing longitudinal study addressing the effects of intensive musical training on brain and cognitive development, and making it possible to look retroactively at the brain and cognitive development of those children who emerge showing exceptional musical talent.

Keywords: Music; Brain; Cognition; Development

1. Introduction

The study of musical cognition has long fascinated researchers (Altenmueller, 1986; Besson, Faita, & Requin, 1994; Bever & Chiarello, 1974; Clynes, 1982; Deutsch, 1982; Gaab & Schlaug, 2003; Gaser & Schlaug, 2003; Meyer, 1977; Minsky, 1981; Muente, Altenmuller, & Jancke, 2002; Pantev, Oostenveld, & Engelien, 1998; Schlaug, 2001; Schlaug, Jancke, Huang, & Steinmetz, 1995; Schlaug, Jancke, Huang, Staiger, & Steinmetz, 1995; Schneider et al., 2002; Seashore, 1919, 1938; Slum-ing et al., 2002; Zatorre, Perry, & Becket, 1933; Zatorre et al., 1998, 2003). One of the earliest explorations of musical cognition and the origins of musical talent can be found in the work of Franz Joseph Gall, who argued for a special organ of the brain dedicated to "tune"

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doi:10.1016/j.bandc.2005.05.009

(Gall, 1835). Musical performance demands complex cognitive and motor operations. Musicians must translate music notation (visual–spatial–temporal information) into precisely timed sequential finger movements involving coordination of both hands, recall long passages, bring meaning to music through the use of dynamics and articulation, transpose pieces to new keys, and improvise melodies and harmonics based on existing musical pieces. Some musicians are also able to identify pitches without the use of a reference tone (absolute pitch).

Studies have explored the brain bases of these exceptional and highly specialized sensorimotor skills (Amunts, Schlaug, & Jancke, 1997; Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Gaser & Schlaug, 2003; Hund-Georgiadis & von Cramon, 1999; Jancke, Shaw, & Peters, 2000; Jancke et al., 2000; Schlaug, 2001; Sluming et al., 2002), auditory skills (Besson et al., 1994; Gaab & Schlaug, 2003; Keenan, Thangaraj, Halpern, & Schlaug, 2001; Ohnishi et al., 2001; Pantev et al., 1998; Schneider et al., 2002; Shahin, Bosnyak, Trainor, & Roberts, 2003; Tramo, 2001; Zatorre et al., 1998), and auditory–spatial skills (Muente et al., 2002). These studies have shown that in musicians certain regions of the brain are larger or have more gray matter volume (when compared to non-musicians): specifically, the anterior corpus callosum, the medial portion of Heschl's gyrus, the inferior frontal gyrus, the cerebellum, and the intrasulcal length of the precentral gyrus that has been used as a parameter of primary motor cortex size. In addition, musicians with absolute pitch have shown greater left-sided asymmetry of the planum temporale (Keenan et al., 2001; Schlaug et al., 1995). However, it is not yet known whether these atypical brain structures exist prior to musical training (and therefore might predispose the child to develop musical skill if exposed to music, or to develop other kinds of skill subserved by these brain structures given exposure to the appropriate stimuli) or are a product of the long-term, specialized training.

Such brain differences may well be due to learning. Functional and structural brain changes are associated with acquiring and practicing new skills (Karni et al., 1995; Maguire et al., 2000; Pascual-Leone, Dang, & Cohen, 1995; Stewart et al., 2003; Toni, Krams, Turner, & Passingham, 1998), and differences in brain structure covary with behaviors demanded by the environment (Emmorey, Allen, Bruss, Schenker, & Damasio, 2003; Hamzei et al., 2001; Penhune, Cismaru, Dorsaint-Pierre, Petitto, & Zatorre, 2003). Animal and human studies have shown that long-term practice of skills can lead to small, structural brain changes or regional enlargements (Anderson, Eckburg, & Relucio, 2002; Draganski et al., 2004; Hutchinson, Lee, Gaab, & Schlaug, 2003; Kleim, Lussnig, & Schwarz, 1996).

Further evidence for learning comes from studies showing that these differences are even greater among musicians who began musical training at an early age (Elbert et al., 1995; Hutchinson et al., 2003; Schlaug et al., 1995). Similarly, differences between musicians and non-musicians correlate with intensity of musical training throughout life (Gaser & Schlaug, 2003; Hutchinson et al., 2003; Schneider et al., 2002). Furthermore, auditory training studies (Jancke, Gaab, Wustenberg, Scheich, & Heinze, 2001; Menning, Roberts, & Pantev, 2000) as well as motor training studies (Karni et al., 1995; Toni et al., 1998; Van Mier, Tempel, Perlmutter, Raichle, & Peterson, 1998) have shown that functional brain differences are associated with the particular musical instrument played (Pantev, Roberts, Schulz, Engelien, & Ross, 2001). Violin training is associated with adaptations in brain regions controlling fine finger movements of the left hand; piano training is associated with adaptations in brain regions controlling finger movements of both the hands (Amunts et al., 1997; Bangert, Nair, & Schlaug, 2005; Elbert et al., 1995).

These findings provide support for plasticity and learning as the explanation of musicians' brain atpyicalities. However, the critical test has not yet been carried out. To determine whether the structural and functional differences seen in musicians reflect adaptations due to musical training during sensitive periods of brain development, or are instead markers of musical interest and/or aptitude existing prior to training, it is necessary to examine children before the onset of instrumental music training and compare them to a group of children not planning to play and practice regularly on a musical instrument. We report the results of such a study here.

Music training may not only affect neural development but also non-musical cognitive skills. Previous research has demonstrated that music training enhances visual–spatial abilities in young children (Costa-Giomi, 1999; Graziano, Peterson, & Shaw, 1999; Hassler, Birbaumer, & Feil, 1987; Hetland, 2000; Rauscher & Zupan, 2000; Rauscher, Shaw, & Key, 1993; Rauscher et al., 1997). Music training appears to enhance performance on the WISC-III Object Assembly, a task that requires mental rotation, but has no effect on Raven's Progressive Matrices, a task considered non-spatial. The ability to copy geometric forms (WISC-III Block Design), which requires coordination between visual perception and motor planning, has also been found to be enhanced by music training (Miller & Orsmond, 1999). There is some evidence for a relationship between music instruction and mathematics, but the findings are inconsistent (see Vaughn, 2000 whose meta-analysis of six studies showed an overall modest effect, but with only two of the studies showing a significant positive effect of music on mathematics). Music training enhances verbal memory in both adult musicians (Chan, Ho, & Cheung, 1998; Kilgour, Jakobson, & Caddy, 2000) and children (Ho, Cheung, & Chan, 2003). Music training has also been shown to raise IQ modestly

(Schellenberg, 2004), consistent with a report by Gardiner, Fox, Knowles, and Jeffrey (1996) that children receiving both art and music instructions improved on standardized test scores. Further, children with dyslexia have been found to improve on phonemic awareness and spelling tests after only 15 weeks of rhythm-based music training (Overy, 2000, 2003). And reading skills have been demonstrated to correlate with global acoustic pattern perception (Foxton et al., 2003). Less surprisingly, perhaps, studies have also shown that music training can have positive effects on motor skills. The tapping rate of both the right and the left index fingers was shown to be faster in musicians than in non-musicians, and the tapping rate of the non-dominant hand was found to increase with training (Jancke, Schlaug, & Steinmetz, 1977). This higher tapping rate in keyboard players also correlated with a greater intrasulcal length of the posterior precentral gyrus (a gross marker of primary motor cortex size) (Amunts et al., 1997; Schlaug, 2001). Taken together, the research suggests that music training may have positive effects on spatial, mathematical, verbal, and motoric ability.

There are plausible explanations for why music training could lead to transfer effects in other areas. Spatial reasoning might be enhanced by music training because music notation itself is spatial (specific pitches are indicated by their particular position on a series of lines and spaces). Mathematical skill might be enhanced because understanding rhythmic notation requires pattern recognition and understanding of proportion, ratio, fractions, and subdivision (i.e., a half note is twice as long as a quarter note). Phonemic awareness skills and reading ability might be enhanced because both music and language processings require the ability to segment streams of sound into small perceptual units (Overy, 2003), and because language processing depends on processing the global (intonational) pitch patterns of spoken language (Foxton et al., 2003). Consistent with this claim are findings showing that music and language share some neural substrates (Koelsch et al., 2004; Patel, 2003). The suggestion that instrumental training improves finger-tapping speed is understandable since developing technique on an instrument involves fine motor coordination.

In this study, our first aim was to investigate whether children who choose to participate in instrumental training (string or piano) show neural differences prior to training when compared to a control group of children not seeking music lessons. An answer to this question can help resolve the question of whether the atypicalities in adult musicians' brains are innate markers of musical ability, products of long-term training, or both. We also sought to lay the groundwork for a longitudinal study, now ongoing, examining the effects of music training on brain development.

Our second aim was to determine whether children choosing to participate in instrumental training have innately superior visual–spatial, verbal, and/or motor skills prior to training when compared to a control group of children not seeking music lessons. An answer to this question can help resolve the question of whether pre-existing differences partially account for positive effects of music training on non-musical outcomes that have been reported earlier.

Our third aim was to determine whether musical skill as measured by a music perception test correlates (prior to music training) with any of the cognitive, motoric, or neural outcomes that have been shown to be associated with music training. An answer to this question would also shed light on whether the positive effects of music training on non-musical outcomes shown in previous studies are due in part to pre-existing associations between musical and non-musical skills, or are solely an outcome of training.

2. Methods

2.1. Participants

Seventy 5- to 7-year-olds were recruited from public elementary schools and community music schools in the greater Boston area. Thirty-nine children (15 girls and 24 boys, mean age 6.6 years ($SD = 0.8$, range = 5.0–7.6) were about to begin weekly half-hour private lessons on a keyboard or string instrument (Instrumental group). Thirty-one children (13 girls and 18 boys, mean age 6.1 years ($SD = 0.7$, range = 4.8–7.6) formed the control group. Children in the control group were to be exposed to music in school but would not be undertaking study of a musical instrument. Eighteen of the control children were entering a kindergarten or first-grade classroom that included one half-hour music class per week consisting primarily of singing (Control Subgroup 1), and 13 were entering a class which included four half-hour music classes per week that featured singing along with experimentation with a variety of classroom instruments such as drums, bells, etc. (Control Subgroup 2).

2.2. Materials and procedure

Children were tested individually in two to three sessions completed over the course of 3–4 weeks. Sessions took place at the child's academic or music school or at our laboratory. Imaging sessions took place in the MR research facility at Beth Israel Deaconess Medical Center.

2.2.1. Socio-economic status

Parents indicated their highest level of education on a questionnaire, and responses were scored on a 6-point scale: (1) some high school; (2) high school diploma or GED; (3) some college, vocational degree, and associate's degree; (4) 4-year college degree (BA, BS); (5) master's degree (MA, MS, MBA); (6) doctoral degree (PhD, MD, JD, EdD, ThD). Final socio-economic status (SES) score was the mean of each parent's education score (except for single-parent families). While education alone is not a complete measure of SES, it is considered to be an acceptable indicator (Hollingshead & Redlich, 1958).

2.2.2. Handedness

Handedness was assessed by measures adapted from Annett (1970). Children were asked to write their name, scoop goldfish crackers out of a bag with a spoon, throw a ball through a hoop made by the experimenter's arms, and hammer four tacks on a picture. Children were classified as right- or left-handers if they used either their right or left hand for at least three of the four tasks. They were classified as mixed-handers if they used either their right or left hand for only two of the tasks. In the Instrumental group, there were two left-handed boys, two left-handed girls, and one mixed handed boy (who wrote and hammered with his left hand, ate with his right, and threw a ball with either hand). In the non-instrumental group, there were two left-handed boys and one left-handed girl.

2.2.3. Wechsler Scales

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) were administered (Wechsler, 1991, 2002). In the Object Assembly test, the child sees an array of puzzle pieces and puts the pieces together to form a particular image (e.g., a face). This test is considered to be spatial–temporal because it requires the formation of a mental image and the manipulation of that image over time. In the block design test, the child sees a design and attempts to recreate the model (which remains present) using a duplicate set of blocks. This test is considered to be a spatial recognition task (Rauscher et al., 1997) because there is a physical model present to be copied, and therefore, does not require the formation of a mental image. In the vocabulary subtest, the child is given up to 30 words, presented orally, and is asked to define each one.

2.3. Raven's Progressive Matrices

The Raven's Colored Progressive Matrices (CPM) and Raven's Standard Progressive Matrices (SPM) were given in succession, and a composite score was used for analysis (Raven, 1976a, 1976b). The test, considered to be a non-verbal test of reasoning with some visual–spatial elements Hetland, 2000, requires children to look at a design or pattern with a piece missing, then select from a group of six (CPM) or eight (SPM) pieces the one that completes the pattern.

2.3.1. Auditory Analysis test

The Auditory Analysis test (Rosner & Simon, 1971) is a measure of phonemic awareness. Children hear 40 words and after each are asked to repeat the word and then to say the word again while omitting a particular part such as its beginning or ending sound (e.g., say "Cowboy"; now say it again, but without the "boy").

2.3.2. Finger tapping

The finger-tapping task required children to use their index finger to tap the spacebar of the computer keyboard as many times as possible in 20 s (Peters & Durding, 1977). Children performed this task twice with each index finger, beginning with their non-dominant hand, and tapping rates were averaged.

2.3.3. Gordon's primary measures of music audiation (Gordon, 1998)

The Gordon's primary measures of music audiation (PMMA) requires children to listen to a recording of 40 pairs of simple rhythms and 40 pairs of 2-, 3-, 4-, or 5-tone sequences and make a same/different judgment for each pair by circling a pair of same or different faces. Whether this test is a measure of innate aptitude or a measure of learning and achievement is a matter of debate.

2.3.4. Magnetic resonance imaging

Children underwent a structural and functional magnetic resonance (MR) scan of their brain (the functional imaging component of this study is reported by Overy et al., 2004). MR images were acquired on a 3 T MRI Scanner. We designed a child-friendly scanning protocol that included a training session held approximately 1 week prior to the actual scanning session. Children learned about the scanning experience by having a story about the scanner (illustrated with cartoons) read to them, listening to the noises made by the scanner, practicing the task they would perform in the scanner (with scanner noise included), and looking at actual brain images on the computer. During scanning, one of the investigators remained in the scanner room and children who wished could hold the experimenter's hand.

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 (Ashburner & Friston, 2000; Gaser & Schlaug, 2003), and subjected the high-resolution anatomical images to further analysis. This method involves: (1) spatial normalization of all images to a standardized anatomical space through the removal of differences in overall size, position, and global shape; (2) extraction of gray and white matter from the normalized images; (3) analysis of differences in local gray and white matter volume across the whole brain (Ashburner & Friston, 2000).

The mid-sagittal area of the corpus callosum was determined as previously described (Lee, Chen, & Schlaug, 2003; Schlaug et al., 1995) by one person blinded to subject identity. Intraobserver reliability in corpus callosum measurements was 0.94; interobserver reliability determined in a subset of 40 brains was 0.95.

3. Results

The control subgroups did not differ significantly on any cognitive, musical, or motoric outcome variable ($p > .05$) and were therefore combined. Preliminary ANOVAs revealed no sex differences on any of our tasks, and we therefore did not include sex as a factor in any of our subsequent analyses. A MANOVA, Group × Age × SES, showed that the Instrumental and Control groups differed in both age [$F(1,69) = 6.527$, $MES = 3.934$, $p = .013$] and SES [$F(1,69) = 5.014$, $MSE = 4.553$, $p = .028$]. The mean age of the Instrumental group was slightly higher (as reported above) as was their mean SES (Instrumental = 4.92, $SD = 1.04$; Control = 4.40, $SD = 0.83$). A series of ANCOVAs were then carried out with age and SES as covariates. There was a significant effect of age on all outcomes but Object Assembly and Block Design, as shown in Table 1. SES had a significant effect only on Vocabulary (Table 1). However, when age and SES were controlled, there was no significant effect of group (nor were there any trends even approaching significance) on any cognitive, musical, or motor outcome (Table 2).

We next matched the two groups on age by eliminating the 11 oldest children in the Instrumental group and the five youngest in the Control group. This resulted in 28 children in the Instrumental group (mean age = 6.2, $SD = 0.67$) and 26 in the Control group (mean age = 6.2, $SD = 0.67$ (Table 3). A one-way ANOVA confirmed that the groups did not differ significantly in age. However, a one-way ANOVA revealed that the groups still differed in SES [$F(1,53) = 5.792$, $MSE = 5.727$, $p = .02$] because the mean SES of the Instrumental group was slightly higher than that of the Control group ($M = 4.9$, $SD = 0.85$, range = 2.0–6.0 vs. $M = 4.25$, $SD = 0.76$, range = 2.5–5.5).

We then analyzed the age-matched sample data in two ways, once with a series of univariate ANOVAs with group as the independent factor, and once with a series of univariate ANCOVAs in which group was the independent factor and SES was controlled. Neither the ANOVAs nor the ANCOVAs revealed significant (or even near significant) differences between groups on any cognitive, musical, or motor outcome. These findings are summarized in Table 4, with the top line for each outcome showing the ANOVA results, and the second line showing the ANCOVA results.

Table 1
Effects of age and SES on each outcome as shown by MANOVA using full sample

	Effect of age on outcomes	Effect of SES on outcomes
Object Assembly	$F(1,69) = 0.098$, $MSE = 1.083$, $p = .755$	$F(1,69) = 0.833$, $MSE = 0.495$, $p = .833$
Block Design	$F(1,69) = 2.337$, $MSE = 48.597$, $p = .12$	$F(1,69) = 2.102$, $MSE = 43.697$, $p = .15$
Vocabulary	*$F(1,69) = 7.429$, $MSE = 60.439$, $p = .008$	*$F(1,69) = 4.171$, $MSE = 33.937$, $p = .045$
Raven's	*$F(1,69) = 24.875$, $MSE = 2733.682$, $p = < .001$	$F(1,69) = 0.932$, $MSE = 102.386$, $p = .338$
Auditory Analysis	*$F(1,69) = 27.087$, $MSE = 2364.070$, $p = < .001$	$F(1,69) = .544$, $MSE = 47.496$, $p = .463$
RH tapping	*$F(1,69) = 23.926$, $MSE = 2949.827$, $p = < .001$	$F(1,69) = 1.627$, $MSE = 200.603$, $p = .207$
LH tapping	*$F(1,69) = 11.706$, $MSE = 1146.824$, $p = .001$	$F(1,69) = 1.141$, $MSE = 111.804$, $p = .289$
Gordon's PMMA	*$F(1,69) = 11.375$, $MSE = 767.467$, $p = .001$	$F(1,69) = 2.075$, $MSE = 140.013$, $p = .155$

* Significant at $p < .05$.

Table 3
Summary of participants in age-matched samples

	Instrumental group		Control group	
	Males	Females	Males	Females
Right-handers	22	13	16	12
Non-right-handers	2	2	2	1

Table 2
ANCOVA results for each outcome by group (controlling for Age and SES) using full sample

	Means (*SD*)		Group effect
	Instrumental	Control	
Object Assembly		9.68 (3.15)	$F(1,69) = 2.269$, $MSE = 25.052$, $p = .14$
Block Design	12.38 (4.96)	10.84 (4.2)	$F(1,69) = 0.251$, $MSE = 5.222$, $p = .62$
Vocabulary	13.41 (3.42)	13.19 (2.51)	$F(1,69) = 1.005$, $MSE = 8.175$, $p = .32$
Raven's	39.15 (13.61)	32.73 (10.07)	$F(1,64) = 0.573$, $MSE = 62.954$, $p = .45$
Gordon's PMMA	63.37 (8.18)	60.47 (9.75)	$F(1,67) = 0.006$, $MSE = 0.394$, $p = .94$
RH tapping	81.89 (12.4)	78.03 (13.68)	$F(1,66) = 0.122$, $MSE = 15.062$, $p = .73$
LH tapping	71.90 (11.22)	66.16 (9.0)	$F(1,67) = 0.127$, $MSE = 234.622$, $p = .13$
Auditory Analysis	17.87 (11.36)	16.14 (10.54)	$F(1,66) = 0.883$, $MSE = 77.097$, $p = .35$

Table 4
Means, ANOVA, and ANCOVA results by group, using age-matched sample

	Means (*SD*)		ANOVA results/ANCOVA results
	Instrumental	Control	
Object Assembly	10.96 (2.77)	9.69 (3.38)	$F(1,53) = 2.303$, $MSE = 21.812$, $p = .14$/$F(1,53) = 1.147$, $MSE = 11.074$, $p = .33$
Block Design	12.61 (4.79)	11.04 (4.27)	$F(1,53) = 1.607$, $MSE = 33.175$, $p = .21$/$F(1,53) = 0.573$, $MSE = 11.581$, $p = .45$
Vocabulary	13.14 (3.49)	13.12 (2.67)	$F(1,53) = 0.001$, $MSE = 1.018\text{E}{-}02$, $p = .97$/$F(1,53) = 0.608$, $MSE = 5.368$, $p = .44$
Raven's CPM-SPM	36.68 (13.33)	35.00 (9.23)	$F(1,48) = .245$, $MSE = 33.811$, $p = .62$/$F(1,48) = 0.023$, $MSE = 3.051$, $p = .88$
Gordon's PMMA	61.85 (8.9)	60.88 (10.2)	$F(1,52) = 0.136$, $MSE = 12.392$, $p = .71$/$F(1,48) = 0.012$, $MSE = 1.078$, $p = 0.91$
RH tapping	77.69 (11.27)	80.04 (13.11)	$F(1,51) = 0.484$, $MSE = 71.98$, $p = .49$/$F(1,51) = 0.181$, $MSE = 27.114$, $p = .67$
LH tapping	69.27 (9.68)	67.58 (8.47)	$F(1,52) = 0.451$, $MSE = 37.626$, $p = .51$/$F(1,52) = .447$, $MSE = 37.99$, $p = 0.50$
Auditory Analysis	14.19 (10.69)	17.40 (10.09)	$F(1,51) = 1.239$, $MSE = 134.157$, $p = .27$/$F(1,51) = 2.365$, $MSE = 252.485$, $p = .13$

To determine whether Gordon's PMMA correlated with any of the cognitive tests, two-tailed bivariate Pearson correlations were performed on the age-matched samples, collapsed across group. Before correcting for multiple tests, performance on Gordon's PMMA correlated with performance on the Block Design ($r = .306$, $p = .026$), Vocabulary ($r = .334$, $p = .02$), Ravens ($r = .54$, $p < .001$), and Auditory Analysis ($r = .573$, $p < .001$), but not with the Object Assembly test. However, after Bonferroni correction for multiple tests, the only two significant correlations were between the Gordon's PMMA and the Ravens, and the Gordon's PMMA and the Auditory Analysis test (Table 5).

To analyze our structural MR images, we applied an optimized method of VBM (Ashburner & Friston, 2000; Gaser & Schlaug, 2003; Good et al., 2001) using the SPM2 package (Institute of Neurology, London, UK). The resulting gray and white matter images were smoothed with a Gaussian kernel of 12 mm FWHM. Voxel-by-voxel *t* tests using the general linear model were used to search for gray and white matter differences between groups. All voxels with a gray or white matter volume value below 0.25 (out of a maximum value of 1.0) were excluded from the analysis due to insufficient gray or white matter. All statistical images were corrected for multiple comparisons, and a threshold of $p < .05$ was used. No significant voxel-by-voxel differences ($p > .05$, FDR corrected) in either gray or white matter concentrations were found between Instrumental and Control groups (Fig. 1 for group-averaged gray matter images).

We then tested for differences in total brain volume, total gray matter, total white matter, and corpus callosum size. No differences between groups were found, as shown in Table 6. We also performed multiple correlations between cognitive test scores and interindividual differences in gray matter concentrations. We found no correlations between performances on any cognitive, musical, or motor test and any of the brain markers.

Table 6
Total brain volume, gray matter, white matter, and corpus callosum size by group (mean [in cc] ± *SD*)

	Brain volume	Gray matter	White matter	Corpus callosum
Instrumental	1033 (94)	683 (67)	348 (31)	528 (79)
Control	1032 (116)	681 (88)	344 (32)	512 (75)

4. Discussion

The first aim of this study was to determine whether structural brain differences approximating those between adult musicians and non-musicians can be seen in a group of children starting instrumental music training compared to those not planning to play an instrument. No pre-existing differences of any kind could be found in our group of young children. Since most of the children in our music group will probably not go on to become musicians, this finding does not allow the conclusion that musicians were not atypical as children. However, the fact that the children beginning music lessons show no pre-existing differences from the control group lays the groundwork for a longitudinal study (now in progress) of the effects of music training on

Table 5
Intercorrelations among outcome variables for age-matched groups (two-tailed bivariate correlations)

	Block	Object	Vocabulary	Raven's	Auditory Analysis
Gordon's PMMA	*.306	−.073	*.334	**.540	**.573
Block		**.489	**.436	**.610	**.513
Object			.023	.267	.119
Vocabulary				*.355	**.490
Raven's					**.587

* Significant at $p < .05$.

** After a Bonferroni correction only correlations at $p < 0.003$ are deemed to be significant.

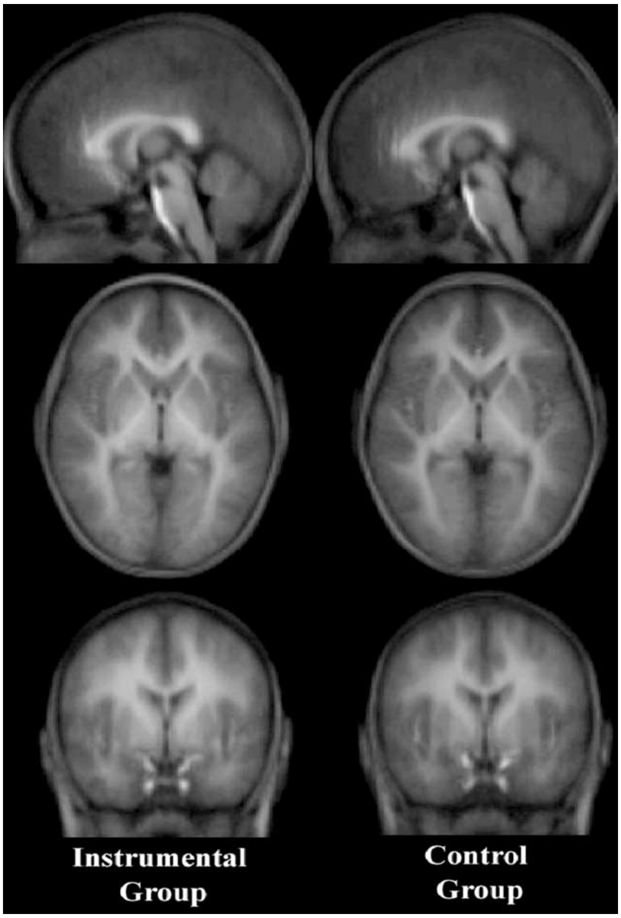

Fig. 1. Three orthogonal slices of the mean spatially standardized T1-weighted images of the instrumental and the control group. No differences in gray matter or white matter volume were detected by voxel-based morphometric analysis.

brain development. In this longitudinal study, we are retesting and rescanning these children at yearly intervals. In addition, by looking retrospectively at the brains of those children who stick with their music training over time and emerge showing exceptional talent and achievement, we will be able to test (to our knowledge for the first time) whether the brains of musicians look different prior to training, and/or respond differently to training compared to those of children taking music lessons but showing only average talent or interest in music.

The possibility that the atypicalities in musicians' brains are environmentally induced through intensive training is consistent with results of several other studies mentioned earlier. First, areas in adult musicians' brains shown to be enlarged are greatest in those musicians who began training at a relatively young age (Elbert et al., 1995; Pantev et al., 1998; Schlaug, 2001). Second, degree of structural brain differences between musicians and non-musicians correlates with intensity of musical training (Gaser & Schlaug, 2003; Hutchinson et al., 2003; Schneider et al., 2002). Third, functional brain differences between two different types of instrumentalists suggest that differences evolved as a function of playing and training on a specific instrument (Pantev et al., 2001).

Further evidence that music training accounts for the brain differences in adult musicians comes from a study showing electrophysiological effects (enhanced P2) of instrumental music training in 4- to 5-year-olds after 1 year of piano or violin training in response to tones from their instrument (Shahin, Roberts, & Trainor, 2004), with some specific effects depending on the instrument studied. Skilled violinists and pianists also show an enhanced P2 component while listening to music compared to non-musicians (Shahin et al., 2003).

Evidence from brain plasticity in animals and evidence for the effects of early experience lend further credence to the view that structural brain differences between musicians and non-musicians evolve as a function of long-term skill acquisition and training of specialized skills (Anderson et al., 2002; Dawson, Ashman, & Carver, 2000; Greenough & Black, 1992; Kaufman & Charney, 2001; Rosenzwig & Bennett, 1996; Wiesel & Hubel, 1963). Animal studies have shown that microstructural changes such as increases in number of synapses, glial cells, and capillary density within the cerebellum and primary motor cortex, as well as new brain cells in the hippocampus, occur after long-term motor exercises and motor learning in rats (Anderson et al., 1994; Black, Isaacs, Anderson, Alcantra, & Greenough, 1990; Isaacs, Anderson, Alcantara, Black, & Greenough, 1992; Kempermann, Kuhn, & Gage, 1997; Kleim et al., 1996). Similarly, animal studies have demonstrated plasticity in the auditory cortex in response to learning (Kilgard et al., 2001; Metherlate & Weinberger, 1990). The sum of these changes could amount to structural differences detectable on a macrostructural level (see Anderson et al., 2002).

There is also evidence for structural plasticity in the adult human brain. London taxi drivers have a larger than normal posterior hippocampal volume, argued to be due to the intense visual–spatial demands of their job (Maguire et al., 2000). And adults trained for 3 months in juggling showed an increase in gray matter in particular brain areas, followed by a decrease after a 3-month cessation of juggling (Draganski et al., 2004). Taken together, these animal and human studies are consistent with structural differences in adult musicians being due to training rather than being inborn markers of musical interest and/or ability.

The second aim was to determine whether children who choose to participate music training perform at a higher level than those who do not seek such training on any cognitive outcome previously found to be enhanced by, or associated with, music training. We found no pretraining differences in visual–spatial or verbal skills; in addition, we found no differences in finger-tapping (motoric) skills, and no differences in tasks assessing music perception skills.

The third aim was to determine whether there are pre-existing correlations between perceptual skills in music (as measured by Gordon's PMMA) and any of the cognitive, motoric, or neural outcomes that have been shown to be associated with music training. No pre-existing correlations were found between Gordon's PMMA and any of the visual–spatial tests (e.g., Object Assembly) that have been previously shown to be enhanced by music training (Rauscher & Zupan, 2000; Rauscher et al., 1997). The lack of pre-existing correlation makes it more likely that the kinds of skills that have been reported in children who have studied music are an outcome of music training.

We did, however, find positive correlations between Gordon's PMMA, on the one hand, and the Raven's Progressive Matrices and the Auditory Analysis test, on the other. The correlation with the Raven's Progressive Matrices may be the result of pattern recognition skills across domains (auditory and visual) since those skills are required by both the tests. The correlation with the Auditory Analysis test is consistent with previous functional imaging studies reporting that musical tasks activate language areas and vice versa, suggesting that music and language share neural substrates (Gaab, Gaser, Zaehle, Jancke, & Schlaug, 2003; Gaab & Schlaug, 2003; Koelsch, Maess, Grossmann, & Friederici, 2002, 2004; Patel, 2003). Similar associations between musical aptitude and literacy have been found by others (Anvari, Trainor, Woodside, & Levy, 2002). In addition, there are studies that have associated pitch pattern recognition with reading skills (Foxton et al., 2003).

It is unclear at present whether music training might enhance cognition as a result of the attention, motivation, concentration, and discipline fostered by music training. If so, music should enhance all areas of cognition equally (as was claimed by Schellenberg, 2004; who found that music training raises IQ scores) and other forms of intensive training should have the same effect. Alternatively, it is possible that music training has specific effects that other forms of training do not have; cognitive enhancement effects of music training might be due to the particular kind of skills required by music study, skills such as decoding visual information into motor activity, memorizing extended passages of music, learning music structures and rules, learning to make fine auditory spectral and temporal discriminations, and learning to perform skilled bimanual finger movements.

Children in this study were not randomly assigned to an instrumental or control group. Such a design would not have been practical because it would have required us to offer free music lessons and supply musical instruments (something our budget would not allow). However, there are theoretical reasons to study a non-randomly assigned group. Our primary question was whether those children who go on to become musicians look different prior to or in response to training. For this question, it makes most sense to study children who voluntarily seek to study music, as some of these children may go on to show unusual musical ability and may even become musicians. Random assignment would be most appropriate for answering another question: can the atypicalities found in musicians' brains be accounted for entirely by environmentally induced simulation.

Our current longitudinal study will be able to answer the first question. We are now following these children over the course of several years and will be comparing our control group to those in our music group who drop out, those who persist, and those who show exceptional talent and/or achievement, and an exceptional emotional response to music. We will then be able to look back at the scans (anatomical and functional) of these subsets of children to determine whether their scans show atypicalities prior to training and/or in response to training.

Our current longitudinal study will also allow us to examine the role of several predictor variables on brain and cognitive outcomes. Since we have added new children to our music group, variance in the amount of training is built into the study, as well as variance in intensity of practice. We will thus be able to test whether intensity of training (product of years of study × hours of weekly practice) predicts outcomes. Since some of our music children are learning to play via the Suzuki method (and not learning to read notation), we will be able to test whether skill in reading notation predicts transfer to visual spatial outcomes. And we will be able to test whether type of instrument learned (string vs. keyboard) predicts specific brain changes, and whether those who learn a string instrument develop greater music perceptual skill (as measured by Gordon's PMMA) than those learning piano, since producing the correct tone on a string instrument requires careful attention to the sound, whereas producing the correct tone on a piano requires simply pressing the right key. In short, the study reported here lays the groundwork for the first prospective study of the effect of instrumental music training on children's brain and cognitive development, and also allows a retrospective analysis of the brain and cognitive development of those few children who emerge showing exceptional talent, achievement, and interest in music.

Acknowledgments

This study was supported by a grant from the National Science Foundation (BCS-0132508), and supplemental funds from the International Foundation for Music Research (IFMR), the Grammy Foundation Recording Academy, and a Boston College Research Expense grant. We also wish to thank the following

Boston area and music schools for their help in recruitment of children: Brookline Music School, the Cambridge Public Schools (in particular, the Peabody and Mariah L. Baldwin Schools), the Conservatory Lab Charter School, Longy School of Music, Creative Arts for Kids, Indian Hill Music Center, New England Conservatory of Music Preparatory Division, Powers Music School, Project STEP of the Boston Symphony Orchestra, and Winchester Community Music School. We also thank the New England Piano Teachers' Association for their help, and all of the children and their parents who have agreed to participate in this study.

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