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RESEARCH ARTICLE

Neurobiological predispositions for musicality: White matter in infancy predicts school-age music aptitude

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Abstract

Musical training has long been viewed as a model for experience-dependent brain plasticity. Reports of musical training-induced brain plasticity are largely based on cross-sectional studies comparing musicians to non-musicians, which cannot address whether musical training itself is sufficient to induce these neurobiological changes or whether pre-existing neuroarchitecture before training predisposes children to succeed in music. Here, in a longitudinal investigation of children from infancy to school age ($n = 25$), we find brain structure in infancy that predicts subsequent music aptitude skills at school-age. Building on prior evidence implicating white matter organization of the corticospinal tract as a neural predisposition for musical training in adults, here we find that structural organization of the right corticospinal tract *in infancy* is associated with school-age tonal and rhythmic musical aptitude skills. Moreover, within the corpus callosum, an inter-hemispheric white matter pathway traditionally linked with musical training, we find that structural organization of this pathway in infancy is associated with subsequent tonal music aptitude. Our findings suggest predispositions prior to the onset of musical training from as early as infancy may serve as a scaffold upon which ongoing musical experience can build.

KEYWORDS
DTI, early childhood, experience-dependent plasticity, music, predisposition

Research Highlights

- Structural organization of the right corticospinal tract *in infancy* is associated with school-age musical aptitude skills.
- Longitudinal associations between the right corticospinal tract in infancy and school-age *rhythmic* music aptitude skills remain significant even when controlling for language ability.
- Findings support the notion of predispositions for success in music, and suggest that musical predispositions likely build upon a neural structural scaffold established in infancy.
- Findings support the working hypothesis that a dynamic interaction between predisposition and experience established in infancy shape the trajectory of long-term musical development.

1 | INTRODUCTION

The study of musical training as a model for experience-dependent brain plasticity has intrigued neuroscientists for decades, given a musician's intensive commitment to highly specialized training in auditory, somatosensory, and motor domains (Münte et al., 2002; Schlaug, 2001; Wan & Schlaug, 2010; Zatorre, 2005). Musical training is widely suggested to alter brain structure and function (Herholz & Zatorre, 2012); however, longitudinal evidence of brain changes associated with musical training is only emerging (Habibi et al., 2018; Hyde et al., 2009), whereas a disproportionate amount of supporting evidence stems from cross-sectional comparisons of musicians to "non-musicians" in school-aged children and adults (Herholz & Zatorre, 2012). Consequently, it remains unclear whether the characteristic "musician brain" is solely the result of musical training or may at least partly be attributed to certain pre-existing genetic, neural, perceptual, or cognitive factors that predispose individuals for success in music.

To date, the characteristic "musician's brain" has been well-established, yet largely draws from crude cross-sectional comparisons of school-age children and adults with musical training to those who have no history of formal musical training (i.e., "non-musicians"; for a review see Herholz & Zatorre, 2012). Enhanced gray matter volume and cortical thickness have been identified among adult musicians compared to non-musicians in predominantly primary auditory (Bermudez et al., 2009; Foster & Zatorre, 2010; Gaser & Schlaug, 2003a, 2003b; Jäncke et al., 1994; Schneider et al., 2002), pre-supplementary/primary motor (Amunts et al., 1997; Bangert & Schlaug, 2006; Schlaug, 2001), and sensorimotor cortices (Bengtsson et al., 2005; Chen et al., 2008a, 2008b; Elbert et al., 1995; Han et al., 2009; Schlaug, 2001). Accordingly, structural and functional networks mediating auditory-motor interactions have been implicated via dorsal pathways that connect auditory and motor systems in the brain (Zatorre et al., 2007).

Diffusion-weighted imaging has further revealed differences in white matter organization among musicians relative to non-musicians within auditory and motor-related pathways (Moore et al., 2014). Converging evidence suggests that musical training is associated with greater inter-hemispheric connectivity in the corpus callosum (Bengtsson et al., 2005; Elmer et al., 2016; Habibi et al., 2018; Hyde et al., 2009; Schlaug et al., 1995, 2009; Schmithorst & Wilke, 2002; Steele et al., 2013), the primary cortical pathway connecting left and right hemispheres, as indicated by greater fractional anisotropy (FA, the degree of directionality in water diffusion within white matter pathways) among musicians compared to non-musicians. These cross-sectional differences have been indicated predominantly (but not exclusively) in the posterior portion of the corpus callosum. Furthermore, FA in the posterior midbody of the corpus callosum has been shown to correlate with age of training onset (Steele et al., 2013). Musicians have also been characterized by larger volume and greater FA in the long direct segment of the arcuate fasciculus (Halwani et al., 2011), a pathway predominantly known to be vital for language which connects inferior frontal and superior temporal regions. Greater FA values have also been indicated in relation to musical expertise in the anterior indirect segment of the arcuate (Catani et al., 2005), also known as the superior longitudinal fasciculus (specifically the SLF II; Engel et al., 2014; Makris et al., 2005; Oechslin, 2010), which further projects from fronto-temporal to parietal regions. Greater FA in musicians compared to non-musicians has also been indicated in motor pathways including projections of the corticospinal tract (Rüber et al., 2015) and internal capsule (Bengtsson et al., 2005; Han et al., 2009); however, contradictory evidence has also indicated lower FA among musicians in both the corticospinal tract (Imfeld et al., 2009) and internal capsule (Schmithorst & Wilke, 2002). This conflicting evidence may be attributed to differences in methodological approaches or classification of musicians versus non-musicians (Moore et al., 2014). Another consideration that has yet to be fully addressed is that cross-sectional studies preclude determination of whether reported differences truly reflect training effects or may be at least partly influenced by possible neural predispositions that could facilitate training success.

Limited longitudinal evidence affirms working hypotheses that characteristic structural alterations among musicians reflect training-induced brain plasticity, illuminating the importance of and need for more longitudinal investigation. Structural brain changes have been indicated among school-age children following instrumental music training, relative to age-matched peers who participated in no more than general music education classes provided by standard curricula (Habibi et al., 2018; Hyde et al., 2009). Specifically, these changes have been observed following 1 year of instrumental music training among 5- to 7-year-old children in predominantly auditory and motor regions, with morphological changes indicated in right-hemispheric primary auditory and motor regions as well as in the corpus callosum among musicians compared to controls (Hyde et al., 2009). Following 2 years of musical training, 6-year-old children demonstrated a specialized lateralization effect in the superior temporal gyrus characterized by significantly more cortical thinning in the left versus right posterior superior temporal gyri relative to children in both active (sports training) and passive control groups (Habibi et al., 2018). Moreover, significant increases in white matter structural organization, as indicated by FA, were identified in the corpus callosum among musically trained children compared to children engaged in sports as well as passive controls (Habibi et al., 2018). These studies provide emerging longitudinal evidence of training-induced white matter plasticity through engagement in musical training.

Although longitudinal evidence of brain changes associated with musical training is emerging, a crucial question remains: are certain pre-existing factors evident even before the onset of musical training that predispose one to be musically inclined? While musical expertise is generally understood to be driven by environmental experience through intensive training, certain predispositions in genetic, neural, perceptual, and cognitive domains have been proposed to influence one's propensity for musical perception and production abilities regardless of formal training, known as *musicality* (Gingras et al., 2015). Environmental influences on the pursuit of musical training have long been attributed to parental factors, since the initial decision to take music lessons in early childhood is often made by parents, and children's duration of training has been predicted by parents' "openness-to-experience" (Corrigall & Schellenberg, 2015). Relatedly, families with higher levels of parental education and household income are more likely able to provide the resources and costs necessary to pursue musical training (Schellenberg, 2006). In addition, early musical experiences and culture-specific representations shape day-to-day musical exposure (i.e., enculturation), musical preferences (Soley & Hannon, 2010), and motivate the pursuit of formal training (Shahin et al., 2004). Meanwhile, children's personality traits have been shown to predict their duration of musical training, suggesting genetic predispositions in combination with environmental influences that impact the likelihood of a child pursuing musical training (Corrigall & Schellenberg, 2015; Corrigall et al., 2013).

Regarding putative genetic predispositions, genome-wide association and twin studies suggest genetic contributions to one's musicality (Drayna et al., 2001; Ullén et al., 2014; Wesseldijk et al., 2021), implicating several genes expressed in brain tissue (Niarchou et al., 2022). Thus, it is hypothesized that certain susceptibility genes and the pathways they regulate or interact with may shape neurobiological factors—and, in turn, alter perceptual and cognitive skills—that ultimately make an individual more receptive to environmental input (e.g., musical training; Keenan et al., 2001). In line with this hypothesis, neural predispositions in the adult brain observed prior to training onset—specifically, white matter organization in the bilateral corticospinal tract and right superior longitudinal fasciculus—have been shown to predict the rate of learning new musical skills in adults (Engel et al., 2014). Similarly, functional neural correlates of melody perception (within right auditory and subcortical regions including the hippocampus and caudate nuclei) have been shown to predict learning success rate following the onset of piano training in adults (Herholz et al., 2016). Therefore, striking evidence of neural predispositions for musical success has been observed among adults, though this is to be interpreted with consideration of likely environmental influences over time that contributed to shaping the neuroarchitecture observed. Although investigation in early childhood offers great potential to specify these possible predispositions early on, scarcely any studies to date have examined possible neural predispositions from a developmental perspective.

Although neurobiological predispositions for success in music are evident in adulthood (Engel et al., 2014; Herholz et al., 2016), it remains unclear whether and how early in development these putative predispositions emerge. Putative genetic predispositions implicating genes expressed in brain tissue (Niarchou et al., 2021) point towards the importance of a focus on early childhood development in this context, for whole-genome expression studies in the developing brain reveal that temporal dynamics of the transcriptome are more robust prenatally than at any postnatal stage (Naumova et al., 2013). In conjunction with dynamic changes in gene expression within brain tissue during prenatal and early postnatal development, the most rapid production of myelin (which forms around axons that comprise white matter to increase signal transmission efficiency) occurs during this time as well (Lenroot & Giedd, 2006), such that the first 2 years of life signify the most robust period of white matter development in the brain (Geng et al., 2012; Gilmore et al., 2018). Although white matter continues to mature and develop throughout early childhood and beyond (Barnea-Goraly et al., 2005; Lebel & Beaulieu, 2011), at this stage neuroplasticity is more so considered a process of refinement that builds upon the structural organization established during infancy (Gilmore et al., 2018). Therefore, longitudinal investigation from infancy is of crucial importance to uncover how early in development putative neural predispositions for success in music may emerge.

Here we examine the extent to which brain structure in infancy is associated with a child's future propensity for music. Although the most rapid period of white matter development in the brain is known to occur by toddlerhood and is increasingly recognized to set an important foundation for long-term development, this has yet to be examined in the context of putative predispositions for success in music. Therefore, using a longitudinal design in early childhood, we examine white matter organization *in infancy* in relation to children's musicality at school age. Moreover, in light of intricate links between musicality and general language abilities repeatedly demonstrated in prior research (Slevc, 2012; Swaminathan & Schellenberg, 2020), we examine whether putative effects are specific to the music domain, or may be at least partly attributed to general language abilities. To our knowledge, this is the first investigation to uncover neurobiological predispositions for musical training that can be detected in brain structure as early as infancy. This work points towards a dynamic developmental interaction between predisposition and training experience that shapes one's musicality and corresponding neural characteristics.

2 | METHODS

2.1 | Participants and design

Twenty-five children (14 female) were included in the present study, selected from a larger NICHD-funded investigation longitudinally tracking brain and language development from infancy to school age (NIH–NICHD R01 HD065762). Participants were recruited from the greater Boston area through the Research Participant Registry of the Division of Developmental Medicine at Boston Children's Hospital, advertisements at community events and schools, and social media. Children were initially recruited as infants (mean age in infancy: 9 months, standard deviation: 3.6 months; age range: 5–17 months), and follow-up assessment was employed when they reached school-age (mean age: 6 years, age range: 4–7 years). At the time of follow-up, the majority of children were within the first few months of kindergarten (i.e., onset of formal schooling), with five children in first grade and two in second grade. Selected children had completed select measures of interest for the present study, which included Magnetic Resonance Imaging (MRI) in infancy, then follow-up assessment with completion of music aptitude measures as part of a comprehensive battery of standardized cognitive-linguistic measures. The present focus on the music aptitude measure was acquired with a subset of children at follow-up. Accordingly, 25 children from the larger investigation met all inclusion criteria and yielded both diffusion tensor imaging (DTI) in infancy of sufficient quality for analysis as well as reliable performance on music aptitude measures at follow-up.

Children were longitudinally screened to ensure the following inclusion criteria were met: all children were from American English-speaking families with no history of premature birth or any psychiatric, neurological, or neurodevelopmental concerns. Of note, one child received a diagnosis of ADHD and Sensory Processing Disorder at follow-up but demonstrated nonverbal cognitive abilities and music discrimination skills within the average range. All children demonstrated typical nonverbal cognitive abilities, as indicated by standardized performance within or above one standard deviation of the mean on the Matrix Reasoning subtest of the Kaufman Brief Intelligence Test: 2nd Edition (KBIT-2; Kaufman & Kaufman, 2004; with missing data noted for three children). One child from the initial larger sample had to be excluded since the primary language spoken at home was not English. Of the 25 children included in the present study, 17 were right-handed, four were left-handed, one was ambidextrous, and three had unknown handedness preference at follow-up.

Parent report via questionnaire revealed that families included in the present analysis were characterized by middle to high socioeconomic backgrounds, with little variation. Of the 25 children in the sample, 23 had at least one parent with at least a Bachelor's degree, and of those 15 families reported an annual combined income of $100,000 or more, as indicated by responses on a questionnaire adapted from the MacArthur Research Network (https://www.macfound.org/networks/research-network-on-socioeconomic-status-health Predicting who takes music lessons: Parent and child characteristics). At the time of longitudinal follow-up (at school age), the majority of children in the present sample ($n = 22$) reportedly participated in extracurricular activities on average for approximately two hours per week. Informed written consent was provided by the parent/legal guardian of each child at each time point. At follow-up, children ages four and older also provided written assent. This study has been approved by the Institutional Review Board of Boston Children's Hospital.

2.2 | Musicality measures at longitudinal follow-up

At follow-up, musicality was characterized with administration of Edwin Gordon's Primary Measures of Music Audiation (PMMA; Gordon, 2002). This measure provides indices of tonal and rhythmic discrimination abilities. Children were asked to determine whether two aurally presented musical phrases sound the same or different across two conditions: one with variation in pitch (Tonal subtest) and one varying in rhythmic patterns (Rhythm subtest). These two subtests consisted of 40 items each, with a duration of approximately 12 minutes per subtest. Pre-recorded audio files with the associated paired synthesized musical patterns were binaurally presented over child-friendly headphones at a consistent volume. In the Tonal subtest, each pattern consisted of two-to-five note melodies with frequencies ranging from C4 to F5, and the rhythm was kept consistent. Conversely, in the Rhythm subtest, all notes had the same pitch, C5, but varied in duration and timing. After hearing the second pattern of the pair, participants were asked to determine whether the two phrases sounded the same or different. The raw score is determined by the number of correct responses out of 40 total questions in each subtest. The raw scores and the participants' school grade level are then used to determine norm-referenced percentile ranking scores.

2.3 | Language measures at longitudinal follow-up

In addition to musicality measures acquired at follow-up, a subset of language assessments from the same time point were selected from a larger battery of standardized measures. Core language constructs identified as of interest in the context of the present investigation included the following:

Phonological Awareness: The Segmentation subtest from the Woodcock Johnson Tests of Oral Language (WJ-IV OL; Schrank et al., 2014) was administered and utilized to indicate phonological awareness abilities. Children were asked to listen to words and then break them down into components by repeating back the word in a segmented manner (at the level of compound words, syllables, then individual speech sounds).

Phonological Short-term Working Memory: The Memory for Digits subtest of The Comprehensive Test of Phonological Processing (CTOPP-2; Wagner et al., 2013) assessed children's phonological working memory. Children were asked to repeat strings of numbers that varied in length from two-to-eight digits.

Vocabulary Knowledge (Receptive): Vocabulary knowledge in the receptive language domain was measured by The Peabody Picture Vocabulary Test (PPVT-4; Dunn & Dunn, 2007). For this measure, children were verbally presented with a single word and asked to select which picture out of four options best reflected the target.

Oral Comprehension (Receptive): The Oral Comprehension subtest from the WJ-OL characterized listening, understanding, and reasoning by asking children to listen to a brief audio-recorded sentences and infer an omitted word at the end through use of semantic and syntactic information.

Sentence Repetition (Expressive): The Sentence Repetition subtest from the WJ-OL was employed to measure the children's ability to listen and accurately recall sentences of increasing length and syntactic complexity. Children were asked to repeat verbally presented sentences verbatim, which increased in length and complexity over the course of the subtest.

2.4 | Neuroimaging acquisition

Neuroimaging with infants was conducted while the infants were naturally sleeping by recreating the family's naptime or bedtime routine in the neuroimaging suite utilizing a previously established pediatric protocol for neuroimaging (Raschle et al., 2012). One researcher and parent were present in the neuroimaging suite throughout the duration of the session to closely monitor the infant's sleep state and potential arousal/motion. Diffusion-weighted and structural T1-weighted images were acquired on a 3.0 Tesla Siemens TrioTim MRI scanner with a standard Siemens 32-channel radio frequency head coil. Structural T1-weighted whole-brain multi-echo magnetization-prepared rapid gradient-echo sequences with prospective motion correction (mocoMEMPRAGE) were acquired with each infant (acquisition parameters: TR = 2270 ms; TE = 1450 ms; TA = 4.51 min; flip angle = 7°; field of view = 220 × 220 mm; voxel resolution = 1.1 × 1.1 × 1.0 mm (176 slices) with an inplane acceleration factor of 2). Acquisition of diffusion-weighted echo planar images included 64 slices from 30 gradient directions with 10 non-diffusion-weighted volumes (acquisition parameters: slice thickness = 2.0 mm; b = 1000 s/mm^2; field of view = 256 × 256 mm; TE = 88 ms; TR = 8320 ms; TA = 5:59 min; flip angle = 90°), one phase-encoding anterior-to-posterior (AP) volume, and one phase-encoding posterior-to-anterior (PA) volume.

2.5 | Diffusion-weighted image processing

Raw diffusion-weighted images were converted from DICOM to NRRD format utilizing the DWIConvert module from Slicer4 (www.slicer.org). Initial quality control of diffusion images was then conducted using DTIPrep in order to identify volumes with excessive motion artifacts (2 mm translation threshold and 0.5° rotation threshold). Volumes identified with artifacts exceeding these criteria were then removed prior to further processing. The majority of participants included (21/25) only had up to three poor gradients removed, and only one participant had more than 25% of gradients removed. Remaining diffusion-weighted images were corrected for susceptibility distortions via the FSL Topup module, then eddy current correction and motion correction were conducted utilizing the FSL Eddy module (https://fsl.fmrib.ox.ac.uk/fsl; Basser et al., 1994; Langer et al., 2017; Smith et al., 2004; Zuk et al., 2021). Diffusion-weighted images were subsequently processed with the VISTALab mrDiffusion toolbox and diffusion MRI software suite (www.vistalab.com), which included tensor-fitting estimations with a linear least-squares (LS) fit for diffusion tensor fitting.

2.6 | Automated fiber quantification

White matter pathways were quantified utilizing the Automated Fiber Quantification (AFQ) software package (https://github.com/jyeatman/AFQ; Yeatman et al., 2012). Procedures employed follow those previously described in prior investigations with infants with the present research team (Langer et al., 2017; Zuk et al., 2021). In summary, whole-brain tractography was conducted via a deterministic streamline tracking algorithm (Basser et al., 1994; Mori et al., 1999), with an FA threshold of 0.1 and angle threshold of 40° (in accordance with previous investigations with this age range (Langer et al., 2017; Zuk et al., 2021)). Region of interest (ROI)-based fiber tract segmentation and fiber-tract cleaning utilizing a statistical outlier rejection algorithm were employed, with subsequent FA quantification along the trajectory of each tract based on eigenvalues from the diffusion tensor estimation (Basser et al., 1994). FA estimates were sampled along 100 equidistant nodes for each tract of interest. In a final step, visual inspection of individual tracts was conducted to ensure that final white matter pathways of individual subjects reflected reliable reconstruction.

2.7 | White matter pathways of interest

The present investigation focused on the most prominent white matter pathways implicated in association with musical training as indicated by (a) tracts identified in longitudinal musical training studies among school-age children and adults: the corpus callosum (Habibi et al., 2018) and arcuate fasciculus (Moore et al., 2017), and (b) tracts previously shown to predict the subsequent rate of learning success prior to training onset: the corticospinal tract and superior longitudinal fasciculus (SLF; Engel et al., 2014). These tracts of interest were examined bilaterally to evaluate hemispheric specificity of associations with subsequent musicality. In addition, the present analysis characterized the corpus callosum major (i.e., splenium), as this posterior portion of the tract has been repeatedly implicated in music training studies to date (Bengtsson et al., 2005; Hyde et al., 2009).

Due to the automated tractography approach employed and ongoing methodological limitations of employing MRI in infancy (Turesky et al., 2021), not all individual tracts of interest were able to be reliably reconstructed for all infants. Visual inspection following automated fiber quantification confirmed that the majority of corpus callosum and corticospinal tracts were reliably reconstructed, however, a reduced overall number of infants resulted in reliable reconstruction of temporal tracts ($n = 17$ for left arcuate, $n = 14$ for bilateral SLF). This is suspected to be at least partly attributed to the spatiotemporal trajectory of infant brain development, as myelination in the temporal lobe is known to lag behind increased in myelination within occipital and parietal lobes (Deoni et al., 2011). Moreover, the right-hemispheric arcuate in particular was unable to be reconstructed for many infants (only $n = 8$ total), yet this is in line with previous work that has documented the inability to reliably reconstruct the right arcuate even among older children and adults (Catani & Mesulam, 2008). All tracts of interest were examined in group-level analyses, recognizing the limitations of the especially modest resultant sample size for temporal tracts.

2.8 | Statistical analyses

Multiple regression models were established with each white matter pathway of interest to investigate whether white matter organization in infancy (as indicated by FA) can predict subsequent musicality at school age. Age at time of scan in infancy was included in each model as a control predictor to account for potential age effects in white matter indices, and standardized performance on the music aptitude measures (tonal and rhythm) constituted the outcome variables of interest (with standardization indicated by percentile ranking in order to account for age at the time of follow-up). Thus, multiple regression analyses were conducted for FA of 100 individual nodes produced from AFQ for each white matter tract of interest, while accounting for infant age, with percentile ranking on music aptitude measures as the outcome variables. Multiple regression analyses were employed utilizing MATLAB (https://www.mathworks.com/products/matlab.html). In an attempt to account for potential effects of language, final multiple regression models were employed to determine the overall variance in school-age indices of musicality (tonal and rhythm) that could be explained by white matter organization in infancy while controlling for not only age but also school-age general language ability.

Correction for multiple comparisons was addressed via two steps in an effort to account for the limited sample size. First, parametric bootstrapping was conducted to simulate the sampling distribution in the general population in order to better evaluate the magnitude of present effects with a previously established approach involving simulation of 5000 replicated samples of the same size programmed in Matlab. Final significance values were taken following this parametric bootstrapping procedure for all analysis models, upon which node-level correction for multiple comparisons by tract was then implemented for resultant *p*-values via Family-Wise Error (FWE) correction. Scripts used for data processing and analyses may be found at https://github.com/TeddyTuresky/diffusionMusicality.

TABLE 1 Participant demographics and descriptive overview of measures of interest

		Mean	Standard deviation	Range
In Infancy				
Sample size	$n = 25$			
Sex	14 f /11 m			
Age (in months)		9	3.6	5–17
Longitudinal follow-up				
Age (in months)		72.3	8.63	57–95
Musicality measures				
Tonal		70.7	29.8	5–99
Rhythm		70.5	24.2	30–99
Language measures				
Phonological awareness		117.6	9.8	87–131
Phonological memory		102.8	14.2	75–131
Vocabulary knowledge		123.9	9.9	106–142
Oral comprehension		114.9	11.9	89–138
Sentence repetition		111.9	12.6	95–139

Note: Musicality measures indexed by percentile ranking, language measures by standard scores.

3 | RESULTS

3.1 | Longitudinal associations between white matter in infancy and school-age musicality

To examine longitudinal associations between white matter in infancy and subsequent school-age musicality, longitudinal multiple regression models were constructed for each white matter pathway of interest with age at time of scan as a control predictor, and each musicality index (tonal and rhythm discrimination tests from Gordon's *Primary Measures of Music Audiation*, indexed by percentile ranking) as outcome variables of interest. Significant effects indicated for each model met thresholds for parametric bootstrapping and subsequent Family-Wise Error (FWE) rate adjustment to correct for multiple comparisons. All children were from families of middle to high socioeconomic backgrounds, with minimal variation. For an overview of participant demographics, see Table 1.

In line with prior evidence implicating the corticospinal tract as a neural predisposition for musicality in adults (Engel et al., 2014), this pathway is also indicated in our results in infancy. Specifically, white matter organization of the right corticospinal tract (as indicated by FA) in infancy is associated with subsequent school-age tonal music aptitude (nodes 83–86, $p < 0.0026$, *FWE-Corrected*) and rhythmic music aptitude abilities (nodes 79–86, $p < 0.003$, *FWE-Corrected*), while controlling for age (see Figure 1 for an overview).

Here we also find that structural organization of the corpus callosum major (as indicated by FA) is associated with subsequent tonal music aptitude, controlling for age (nodes 23–25, $p < 0.0026$, *FWE-Corrected*, Figure 2). The corpus callosum has been implicated in longitudinal training studies as a specific pathway associated with changes as a direct result of musical training (Habibi et al., 2018; Hyde et al., 2009); yet here we also report that structural organization of this pathway from as early as infancy is associated with subsequent musicality. No significant effects were observed for the AF or SLF in relation to subsequent musicality indexes, though this is likely due to the reduced overall number of reliable reconstructions in these temporal neural pathways in infancy, resulting in an insufficient sample size ($n \leq 17$).

3.2 | To what extent may brain-behavior links between white matter in infancy and subsequent indices of musicality be explained by general language skills?

Emerging evidence suggests that musicality is intricately linked with language comprehension and expression (e.g., Slevc, 2012; Swaminathan & Schellenberg, 2020), which raises a question as to whether brain-behavior links between white matter and musicality may be at least partly attributed to general language skills. Our results indicate positive relationships between tonal music aptitude and sentence repetition (as indicated by standardized performance in sentence repetition from the *Woodcock Johnson Tests of Oral Language*, $r = 0.555$, $p_{corrected} = 0.005$), a standardized, structured measure of expressive language abilities, as well as phonological working memory (as indicated by the digit span subtest of *The Comprehensive Test of Phonological Processing*, $r = 0.524$, $p_{corrected} = 0.009$; for an overview see Table 2). These correlations met the False Discovery Rate (FDR) adjustment for correction for multiple comparisons. Rhythmic music aptitude was also marginally associated with sentence repetition ($r = 0.446$,

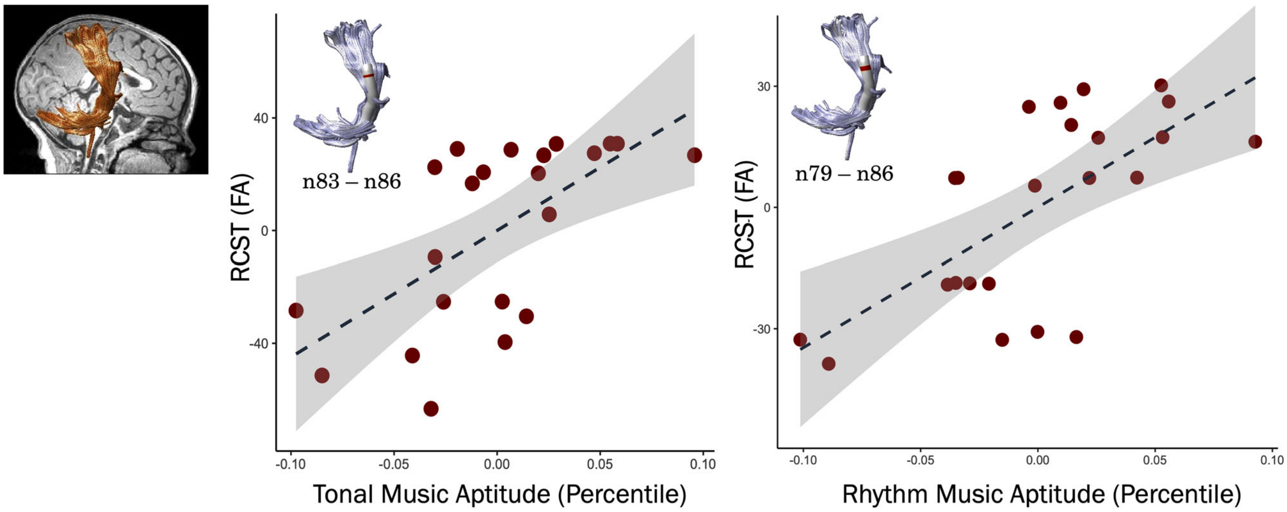

FIGURE 1 Structural organization of the right corticospinal tract in infancy significantly contributes to the prediction of school-age tonal and rhythmic music aptitude abilities (displayed in terms of the centered residuals produced from partial correlations). Nodes in the superior segment of the right corticospinal tract that show significant effects are marked in red on the 3-dimensional rendered tract ($p < 0.05$, FWE-corrected).

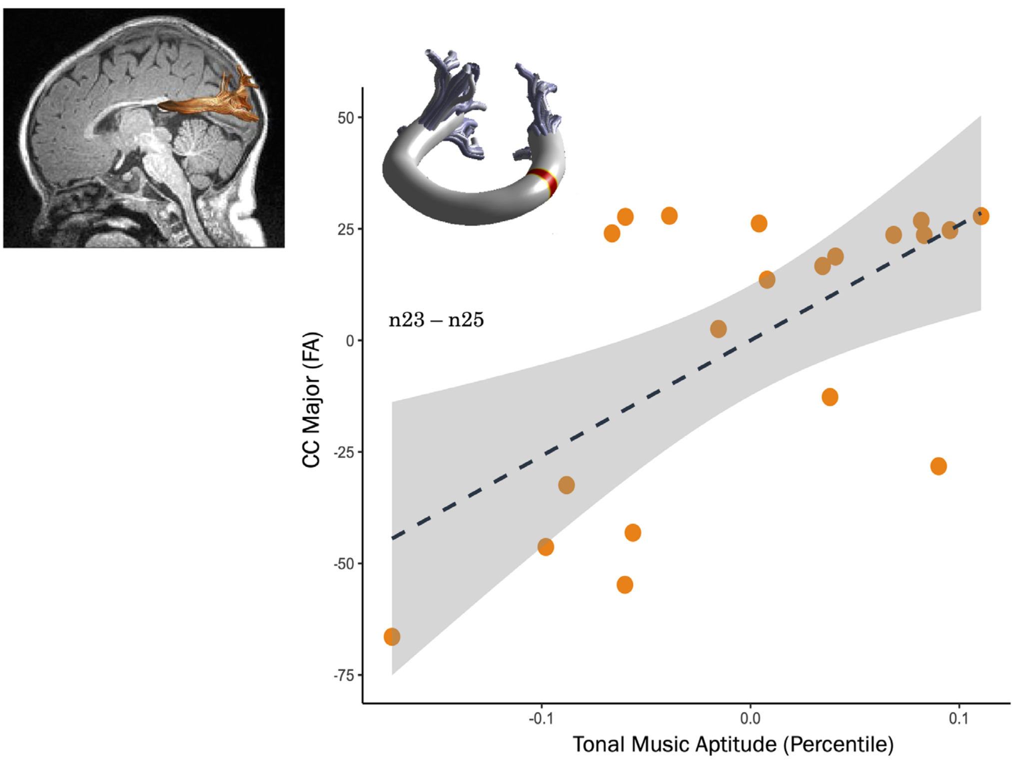

FIGURE 2 Structural organization of the corpus callosum major in infancy significantly contributes to the prediction of school-age tonal music aptitude abilities (displayed in terms of the centered residuals produced from partial correlations). Nodes in the corpus callosum that show significant effects are marked in orange on the 3-dimensional rendered tract ($p < 0.05$, FWE-corrected).

$p_{uncorrected}$ = 0.029; for an overview see Table 3), but this relationship did not survive correction for multiple comparisons. To account for potential effects of language, final multiple regression models estimate the overall variance in school-age indices of musicality (tonal and rhythm) that can be explained by white matter organization in infancy while controlling for age and school-age general language ability (as indicated by standardized performance in sentence repetition).

With *tonal* music aptitude as the outcome variable, predictors of interest included the mean FA of white matter pathways indicated in provisional models: right corticospinal tract (nodes 83–86) and corpus

TABLE 2 Intercorrelations between tonal music aptitude, language, and white matter variables

	1	2	3	4	5	6	7	8
1. Tonal music aptitude	1							
2. Phonological awareness	0.39	1						
3. Phonological memory	0.52**	0.3	1					
4. Vocabulary knowledge	0.39	0.35	0.21	1				
5. Oral comprehension	0.19	0.22	0.32	0.44*	1			
6. Sentence repetition	0.56**	0.42*	0.79***	0.39	0.52**	1		
7. Right CST[a]	0.62**	0.56**	0.35	0.3	−0.07	0.42*	1	
8. Corpus callosum[a]	0.52*	0.31	0.58**	0.17	0.1	0.57**	0.27	1

[a]Average of significant nodes indicated for the Right CST (average nodes 83-86) and corpus callosum (average nodes 23-25) in relation to tonal music aptitude skills.
*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

TABLE 3 Intercorrelations between rhythmic music aptitude, language, and white matter variables

	1	2	3	4	5	6	7
1. Rhythmic music aptitude	1						
2. Phonological awareness	0.36	1					
3. Phonological memory	0.37	0.3	1				
4. Vocabulary knowledge	0.47*	0.35	0.21	1			
5. Oral comprehension	−0.002	0.22	0.32	0.44*	1		
6. Sentence repetition	0.45*	0.42*	0.79***	0.39	0.52**	1	
7. Right CST[a]	0.69***	0.56**	0.22	0.3	−0.03	0.35	1

[a]Average of significant nodes indicated for the Right CST (average nodes 79-86) in relation to rhythmic music aptitude skills.
*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

callosum major (nodes 23–25). With age and language ability as control predictors, the final model explains 60.2% of the variance in tonal music aptitude abilities. In accounting for language, white matter pathways as predictors of interest no longer significantly contribute to the prediction of subsequent tonal music aptitude (right corticospinal: $\beta = 0.442$, $p = 0.057$, corpus callosum: $\beta = 0.441$, $p = 0.068$).

With *rhythmic* music aptitude abilities as the outcome variable, the predictor of interest included significant nodes (mean FA) of the right corticospinal tract (nodes 79–86) indicated in the provisional model, with age and language ability as control predictors. This model explains 54.3% of the variance in rhythmic music aptitude abilities. Structural organization of the right corticospinal tract (as indicated by FA) was the only predictor found to significantly contribute to the variance in rhythmic music aptitude ($\beta = 0.612$, $p = 0.002$).

4 | DISCUSSION

Our findings not only provide further support for neural predispositions for musical training but suggest that these predispositions may be detected in early childhood, from as early as *infancy*. Specifically, here we find that structural organization of the right-hemispheric corticospinal tract in infancy significantly contributes to the prediction of children's school-age tonal and rhythmic music aptitude skills. Moreover, structural organization of the corpus callosum in infancy is associated with subsequent tonal music aptitude skills. Considering intricate links between musicality and language indicated in previous work (e.g., Slevc, 2012; Swaminathan & Schellenberg, 2020), we then accounted for language to examine to what extent observed effects may be attributed to language abilities. When controlling for language, effects involving tonal music aptitude become insignificant, whereas longitudinal associations between the right-hemispheric corticospinal tract in infancy and school-age *rhythmic* music aptitude remain. Our findings in the right-hemispheric corticospinal tract align with previous work implicating this pathway in neural predispositions for success in music (Engel et al., 2014), and extend our knowledge by illuminating the significant role of this pathway in contributing to the subsequent trajectory of musical aptitude (i.e., musicality) from as early as infancy.

Findings implicating the corticospinal tract as a neural predisposition for musical success is directly in line with previous work in musically untrained adults and further extends beyond in illuminating contributions of this pathway from a developmental perspective in early childhood. Specifically, white matter organization in the bilateral corticospinal tract has been shown to predict the rate of learning new musical skills in adults (Engel et al., 2014). Although this work provided initial support for the notion that neural predispositions for success in music may be observed prior to the onset of formal musical training, this had only been investigated among musically untrained adults. This has been a major limitation of the field, since observations are primarily made based on the mature adult system, without addressing the likely contributions of factors in early childhood that may give rise to some underlying components of the brain characteristics identified in adulthood. Here we demonstrate that the role of the corticospinal tract in predicting subsequent musical capacities is not only evident in the mature adult system but may be observed within the first 2 years of life in early childhood.

The present analysis approach accounted for language abilities in an effort to examine whether observed predispositions are specifically linked with music or may also be attributed to language outcomes. This approach illuminated the distinct role of the right-hemispheric corticospinal tract in infancy in predicting subsequent rhythm discrimination abilities. Building on well-established links between music and language abilities (Slevc, 2012; Swaminathan & Schellenberg, 2020), all longitudinal relationships between white matter in infancy and subsequent school-age tonal discrimination abilities became insignificant when accounting for language abilities. These findings support the notion that behavioral and neural underpinnings of tonal discrimination abilities may be intricately linked with those of language abilities, as heightened perception of pitch manipulations in both melodies and linguistic spoken phrases (i.e., vocal intonation) has been previously established, particularly among musicians compared to nonmusicians (Deguchi et al., 2012; Schön et al., 2004). Moreover, white matter pathways indicated in relation to tonal discrimination abilities, the corticospinal tract and corpus callosum, have not only been implicated in musical but also linguistic abilities in previous work (Bartha-Doering et al., 2021; Walton et al., 2018; Zuk et al., 2021). Therefore, our findings associated with tonal discrimination abilities may reflect neural foundations established in infancy that are not only linked with subsequent *tonal* music aptitude but also language abilities in general. While these findings represent a first attempt to establish neural predispositions for music from infancy while accounting for language ability, it is also important to consider that the present analysis approach may introduce potential collider bias, for it is possible that the brain structure presently identified may be jointly attributed to music and language abilities due to resource sharing, that is, shared neural resources involved in music and language (Patel, 2011). Since this study signifies a first step towards uncovering possible neural predispositions in infancy, it remains unclear whether any potential collider bias for music and language capacities may be evident this early in development. Therefore, future research is warranted to further address possible resource sharing in this context, to determine the extent to which music and language may share deep connections in terms of cognitive and neural processing (Patel, 2011).

In the present findings, the relationship between the right-hemispheric corticospinal tract and subsequent *rhythmic* music aptitude remained even when accounting for language abilities. These findings point towards the specificity of a neural predisposition for musicality that is rooted in rhythmic abilities and does *not* seem to be attributed to variance explained by general language abilities. This builds on the rapidly growing body of evidence implicating rhythmic abilities as a central phenotype underlying the genetic basis of musicality (Niarchou et al., 2021), by providing direct evidence of a specific neural pathway (i.e., right-hemispheric corticospinal tract) that is evident within the first 2 years of life in relation to subsequent rhythmic abilities. Our findings, focused on neural foundations established in infancy, align with genetic musicality studies implicating genes expressed in brain tissue (Niarchou et al., 2021) that are known to be more robust in gene expression prenatally than at any postnatal stage (Johnson et al., 2009). Therefore, the present findings provide further support for the working hypothesis that certain susceptibility genes and the pathways they regulate or interact with may shape neurobiological factors—and, in turn, alter perceptual and cognitive skills—that ultimately make an individual more receptive to environmental input, such as musical training/experience.

Although the present study attempts to account for variance that may be explained by general language abilities in the relation between white matter and musicality, findings are to be interpreted in the context of some considerations. Tonal music aptitude skills were observed to be significantly related to language measures in the present battery (sentence repetition and phonological working memory); hence, it is unsurprising that all longitudinal relationships between white matter in infancy and subsequent tonal discrimination abilities became insignificant when accounting for language. By contrast, rhythmic music aptitude was only marginally associated with these language measures, and this relationship did not survive correction for multiple comparisons. Rhythm discrimination skills have been closely linked with other language constructs that were not directly measured in the present study, such as grammar and syntax (Gordon et al., 2015; Swaminathan & Schellenberg, 2020). Therefore, it is possible that more comprehensive characterization of language abilities is necessary to build a better understanding of the complex nature of the inter-relationships between music, language, and the brain. Future research is needed with study designs in this context that can directly address the possible role of brain structure as a mediator or moderator underlying well-established links between music and language abilities. It is also important to note the limitations of the musicality measures presently employed, for although the Gordon's PMMA was the only norm-referenced music aptitude measure available at the time of data collection, this measure was established decades ago and only offers grade-based norms. Overall, this illuminates the need for future research to utilize more refined speech, language, and musicality measures to further specify the nature of inter-relationships between music, language, and the brain throughout development.

Although our findings suggest specific neural predispositions for musicality that are evident in infancy, the present study design precludes determination of whether these neural predispositions may be attributed to genetic and/or environmental influences. Genetic contributions to musicality have been proposed (Drayna et al., 2001; Ullén et al., 2014), implicating genes expressed in brain tissue (Niarchou et al., 2021). Yet, we captured brain structure among these infants several months since birth (with an average age of 9 months), which coincides with an especially rich time for environmental input (Dehaene-Lambertz & Spelke, 2015). Therefore, it remains unclear to what extent these findings reflect experience-driven effects, for the white matter organization presently observed in infancy is likely shaped by both prenatal and postnatal environmental experiences in these infants' everyday lives, such as parents singing to their infants and providing general exposure to music. In addition, interpretation of the present findings is provisional due to the limited sample size. Follow-up investigation with a larger sample size is warranted to verify observed effects with greater power and further investigate the possible role(s) of the AF and SLF in this context. Both the AF and SLF have been implicated in music and language specialization (Halwani et al., 2011; Oechslin, 2010), but were unfortunately most likely underpowered in the present analysis due to an insufficient number of reliable tract reconstructions. On another note, minimal socioeconomic variation controlled the present sample; therefore, future work will be necessary to evaluate putative neural predispositions among a sample with varied socioeconomic representation. Overall, further longitudinal work starting earlier in infancy with a larger sample size is needed to disentangle genetic versus environmental contributions to putative predispositions and further specify the role of early childhood experiences in shaping the subsequent trajectory of musical development.

In conclusion, our findings suggest certain neural predispositions may be detected in infancy, during a period of heightened brain plasticity, and these predispositions may serve as a scaffold upon which ongoing musical experience and training can build neural specificity over time. Our results support the previously established working hypothesis that certain genes, critical for brain development, contribute to the development of white matter that is highly receptive to environmental input, and these factors together establish a neural foundation for musicality that is then built upon and refined by ongoing experience and formal training over time (Zuk & Gaab, 2018). This work supports the importance of early childhood musical experiences, especially during the most robust period of brain development within the first 2 years of life.

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CONFLICT OF INTEREST

The author(s) declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The datasets generated during and/or analyzed during the current study are available from the senior author, Dr. Nadine Gaab, on reasonable request.

ETHICS APPROVAL STATEMENT

This study has been approved by the Institutional Review Board of Boston Children's Hospital, confirming that the study conforms to recognized ethical standards.

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REFERENCES

Amunts, K., Schlaug, G., Jäncke, L., Steinmetz, H., Schleicher, A., Dabringhaus, A., & Zilles, K. (1997). Motor cortex and hand motor skills: Structural compliance in the human brain. *Human Brain Mapping*, *5*, 206–215. https://doi.org/10.1002/(SICI)1097-0193(1997)5:3%3c206::AID-HBM5%3e3.0.CO;2-7

Bangert, M., & Schlaug, G. (2006). Specialization of the specialized in features of external human brain morphology. *European Journal of Neuroscience*, *24*, 1832–1834. https://doi.org/10.1111/j.1460-9568.2006.05031.x

Barnea-Goraly, N., Menon, V., Eckert, M., Tamm, L., Bammer, R., Karchemskiy, A., Dant, C. C., & Reiss, A. L. (2005). White matter development during childhood and adolescence: A cross-sectional diffusion tensor imaging study. *Cerebral Cortex*, *15*, 1848–1854. https://doi.org/10.1093/cercor/bhi062

Bartha-Doering, L., Kollndorfer, K., Schwartz, E., Fischmeister, F. P. S., Alexopoulos, J., Langs, G., Prayer, D., Kasprian, G., & Seidl, R. (2021). The role of the corpus callosum in language network connectivity in children. *Developmental Science*, *24*, e13031. https://doi.org/10.1111/desc.13031

Basser, P. J., Mattiello, J., & LeBihan, D. (1994). MR diffusion tensor spectroscopy and imaging. *Biophysical journal*, *66*, 259–267. https://doi.org/10.1016/S0006-3495(94)80775-1

Bengtsson, S. L., Nagy, Z., Skare, S., Forsman, L., Forssberg, H., & Ullén, F. (2005). Extensive piano practicing has regionally specific effects on white matter development. *Nature Neuroscience*, *8*, 1148–1150. https://doi.org/10.1038/nn1516

Bermudez, P., Lerch, J. P., Evans, A. C., & Zatorre, R. J. (2009). Neuroanatomical correlates of musicianship as revealed by cortical thickness and voxel-based morphometry. *Cerebral Cortex*, *19*, 1583–1596. https://doi.org/10.1093/cercor/bhn196

Catani, M., Jones, D. K., & ffytche, D. H. (2005). Perisylvian language networks of the human brain. *Annals of Neurology*, *57*, 8–16.

Catani, M., & Mesulam, M. (2008). The arcuate fasciculus and the disconnection theme in language and aphasia: History and current state. *Cortex; A Journal Devoted to the Study of the Nervous System and Behavior*, *44*, 953–961.

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008a). Moving on time: Brain network for auditory-motor synchronization is modulated by rhythm complexity and musical training. *Journal of Cognitive Neuroscience*, *20*, 226–239. https://doi.org/10.1162/jocn.2008.20018

Chen, J. L., Penhune, V. B., & Zatorre, R. J. (2008b). Listening to musical rhythms recruits motor regions of the brain. *Cerebral Cortex*, *18*, 2844–2854. https://doi.org/10.1093/cercor/bhn042

Corrigall, K., Schellenberg, E. G., & Misura, N. (2013). Music training, cognition, and personality. *Frontiers in Psychology*, *4*, 1–10. https://doi.org/10.3389/fpsyg.2013.00222

Corrigall, K. A., & Schellenberg, E. G. (2015). Predicting who takes music lessons: Parent and child characteristics. *Frontiers in Psychology*, *6*, 1–8. https://doi.org/10.3389/fpsyg.2015.00282

Deguchi, C., Boureux, M., Sarlo, M., Besson, M., Grassi, M., Schön, D., & Colombo, L. (2012). Sentence pitch change detection in the native and unfamiliar language in musicians and non-musicians: Behavioral, electrophysiological and psychoacoustic study. *Brain Research*, *1455*, 75–89. https://doi.org/10.1016/j.brainres.2012.03.034

Dehaene-Lambertz, G., & Spelke, E. S. (2015). The infancy of the human brain. *Neuron*, *88*, 93–109. https://doi.org/10.1016/j.neuron.2015.09.026

Deoni, S. C., Mercure, E., Blasi, A., Gasston, D., Thomson, A., Johnson, M., Williams, S. C. R., & Murphy, D. G. M. (2011). Mapping infant brain myelination with magnetic resonance imaging. *Journal of Neuroscience*, *31*, 784–791. https://doi.org/10.1523/JNEUROSCI.2106-10.2011

Drayna, D., Manichaikul, A., Lange, M. d., Snieder, H., & Spector, T. (2001). Genetic correlates of musical pitch recognition in humans. *Science*, *291*, 1969–1972. https://doi.org/10.1126/science.291.5510.1969

Dunn, L. M., & Dunn, D. M. (2007).*PPVT-4: peabody picture vocabulary test*. (Pearson Assessments).

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., & Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science*, *270*, 305–307. https://doi.org/10.1126/science.270.5234.305

Elmer, S., Hänggi, J., & Jäncke, L. (2016). Interhemispheric transcallosal connectivity between the left and right planum temporale predicts musicianship, performance in temporal speech processing, and functional specialization. *Brain Structure and Function*, *221*, 331–344.

Engel, A., Hijmans, B. S., Cerliani, L., Bangert, M., Nanetti, L., Keller, P. E., & Keysers, C. (2014). Inter-individual differences in audio-motor learning of piano melodies and white matter fiber tract architecture. *Human brain mapping*, *35*, 2483–2497. https://doi.org/10.1002/hbm.22343

Foster, N. E. V., & Zatorre, R. J. (2010). Cortical structure predicts success in performing musical transformation judgments. *Neuroimage*, *53*, 26–36. https://doi.org/10.1016/j.neuroimage.2010.06.042

Gaser, C., & Schlaug, G. (2003a). Brain structures differ between musicians and non-musicians. *Journal of Neuroscience*, *23*, 9240–9245.

Gaser, C., & Schlaug, G. (2003b). Gray matter differences between musicians and nonmusicians. *Annals of the New York Academy of Sciences*, *999*, 514–517. https://doi.org/10.1196/annals.1284.062

Geng, X., Gouttard, S., Sharma, A., Gu, H., Styner, M., Lin, W., Gerig, G., & Gilmore, J. H. (2012). Quantitative tract-based white matter development from birth to age 2 years. *Neuroimage*, *61*, 542–557. https://doi.org/10.1016/j.neuroimage.2012.03.057

Gilmore, J. H., Knickmeyer, R. C., & Gao, W. (2018). Imaging structural and functional brain development in early childhood. *Nature Reviews Neuroscience*, *19*, 123–137.

Gingras, B., Honing, H., Peretz, I., Trainor, L. J., & Fisher, S. E. (2015). Defining the biological bases of individual differences in musicality. *Philosophical Transactions of the Royal Society B*, *370*, 20140092.

Gordon, E. (2002).*Primary measures of music audiation kit*. (GIA Publications).

Gordon, R. L., Shivers, C. M., Wieland, E. A., Kotz, S. A., Yoder, P. J., & McAuley, J. D. (2015). Musical rhythm discrimination explains individual differences in grammar skills in children. *Developmental Science*, *18*, 635–644. https://doi.org/10.1111/desc.12230

Habibi, A., Damasio, A., Ilari, B., Veiga, R., Joshi, A. A., Leahy, R. M., Haldar, J. P., Varadarajan, D., Bhushan, C., & Damasio, H. (2018). Childhood music training induces change in micro and macroscopic brain structure: Results from a longitudinal study. *Cerebral Cortex*, *28*, 4336–4347. https://doi.org/10.1093/cercor/bhx286

Halwani, G. F., Loui, P., Rüber, T., & Schlaug, G. (2011). Effects of practice and experience on the arcuate fasciculus: Comparing singers, instrumentalists, and non-musicians. *Frontiers in Psychology*, *2*, 156.

Han, Y., Yang, H., Lv, Y. - T., Zhu, C. - Z., He, Y., Tang, H. - H., Gong, Q. - Y., Luo, Y. - J., Zang, Y. - F., & Dong, Q. (2009). Gray matter density and white matter integrity in pianists' brain: A combined structural and diffusion tensor MRI study. *Neuroscience Letters*, *459*, 3–6. https://doi.org/10.1016/j.neulet.2008.07.056

Herholz, S. C., Coffey, E. B. J., Pantev, C., & Zatorre, R. J. (2016). Dissociation of neural networks for predisposition and for training-related plasticity in auditory-motor learning. *Cerebral Cortex*, *26*, 3125–3134.

Herholz, S. C., & Zatorre, R. J. (2012). Musical training as a framework for brain plasticity: Behavior, function, and structure. *Neuron*, *76*, 486–502. https://doi.org/10.1016/j.neuron.2012.10.011

Hyde, K. L., Lerch, J., Norton, A., Forgeard, M., Winner, E., Evans, A. C., & Schlaug, G. (2009). Musical training shapes structural brain development. *Journal of Neuroscience*, *29*, 3019–3025. https://doi.org/10.1523/JNEUROSCI.5118-08.2009

Imfeld, A., Oechslin, M. S., Meyer, M., Loenneker, T., & Jancke, L. (2009). White matter plasticity in the corticospinal tract of musicians: A diffusion tensor imaging study. *Neuroimage*, *46*, 600–607. https://doi.org/10.1016/j.neuroimage.2009.02.025

Jäncke, L., Schlaug, G., Huang, Y., & Steinmetz, H. (1994). Asymmetry of the planum parietale. *Neuroreport: An International Journal for the Rapid Communication of Research in Neuroscience*, *5*, 1161–1163. https://doi.org/10.1097/00001756-199405000-00035

Johnson, M. B., Kawasawa, Y. I., Mason, C. E., Krsnik, Z., Coppola, G., Bogdanović, D., Geschwind, D. H., Mane, S. M., State, M. W., & Sestan, N. (2009). Functional and evolutionary insights into human brain development through global transcriptome analysis. *Neuron*, *62*, 494–509. https://doi.org/10.1016/j.neuron.2009.03.027

Kaufman, A. S., & Kaufman, N. L. (2004). *KBIT2: kaufman brief intelligence test*.

Keenan, J. P., Thangaraj, V., Halpern, A. R., & Schlaug, G. (2001). Absolute pitch and planum temporale. *Neuroimage*, *14*, 1402–1408. https://doi.org/10.1006/nimg.2001.0925

Langer, N., Peysakhovich, B., Zuk, J., Drottar, M., Sliva, D. D., Smith, S., Becker, B. L. C., Ellen Grant, P., & Gaab, N. (2017). White matter alterations in infants at risk for developmental dyslexia. *Cerebral Cortex*, *27*, 1027–1036.

Lebel, C., & Beaulieu, C. (2011). Longitudinal development of human brain wiring continues from childhood into adulthood. *Journal of Neuroscience*, *31*, 10937–10947. https://doi.org/10.1523/JNEUROSCI.5302-10.2011

Lenroot, R. K., & Giedd, J. N. (2006). Brain development in children and adolescents: Insights from anatomical magnetic resonance imaging. *Neuroscience & Biobehavioral Reviews*, *30*, 718–729.

Moore, E., Schaefer, R., Bastin, M., Roberts, N., & Overy, K. (2014). Can musical training influence brain connectivity? Evidence from diffusion tensor MRI. *Brain Sciences*, *4*, 405–427. https://doi.org/10.3390/brainsci4020405

Makris, N., Kennedy, D. N., McInerney, S., Gregory Sorensen, A., Wang, R., Caviness, Jr, V. S., & Pandya, D. N. (2005). Segmentation of subcomponents within the superior longitudinal fascicle in humans: A quantitative, in vivo, DT-MRI study. *Cerebral Cortex*, *15*, 854–869. https://doi.org/10.1093/cercor/bhh186

Moore, E., Schaefer, R. S., Bastin, M. E., Roberts, N., & Overy, K. (2017). Diffusion tensor MRI tractography reveals increased fractional anisotropy (FA) in arcuate fasciculus following music-cued motor training. *Brain and cognition*, *116*, 40–46. https://doi.org/10.1016/j.bandc.2017.05.001

Mori, S., Crain, B. J., Chacko, V. P., & Van Zijl, P. C. (1999). Three-dimensional tracking of axonal projections in the brain by magnetic resonance imaging. *Annals of Neurology: Official Journal of the American Neurological Association and the Child Neurology Society*, *45*, 265–269. https://doi.org/10.1002/1531-8249(199902)45:2%3c265::AID-ANA21%3e3.0.CO;2-3

Münte, T. F., Altenmüller, E., & Jäncke, L. (2002). The musician's brain as a model of neuroplasticity. *Nature Reviews Neuroscience*, *3*, 473–478.

Naumova, O. Y. u., Lee, M., Rychkov, S. Y. u., Vlasova, N. V., & Grigorenko, E. L. (2013). Gene expression in the human brain: The current state of the study of specificity and spatiotemporal dynamics. *Child Development*, *84*, 76–88. https://doi.org/10.1111/cdev.12014

Niarchou, M., Gustavson, D. E., Sathirapongsasuti, J. F., Anglada-Tort, M., Eising, E., Bell, E., McArthur, E., Straub, P., The 23andMe Research Team, Devin McAuley, J., Capra, J. A., Ullén, F., Creanza, N., Mosing, M. A., Hinds, D., Davis, L. K., Jacoby, N., & Gordon, R. L. (2021). *Genome-wide association study of musical beat synchronization demonstrates high polygenicity*. https://doi.org/10.1101/836197. bioRxiv.

Niarchou, M., Gustavson, D. E., Sathirapongsasuti, J. F., Anglada-Tort, M., Eising, E., Bell, E., McArthur, E., Straub, P., The 23andMe Research Team, Devin McAuley, J., Capra, J. A., Ullén, F., Creanza, N., Mosing, M. A., Hinds, D., Davis, L. K., Jacoby, N., & Gordon, R. L. (2022). Genome-wide association study of musical beat synchronization demonstrates high polygenicity. *Nature Human Behaviour*, *6*, 1292–1309.

Oechslin, M. S. (2010). The plasticity of the superior longitudinal fasciculus as a function of musical expertise: A diffusion tensor imaging study. *Frontiers in Human Neuroscience*, *3*, 76.

Patel, A. D. (2011).). Language, music, and the brain: A resource-sharing framework. in *Language and music as cognitive systems*. (eds. P. Rebuschat, M. Rohmeier, J. A. Hawkins, & I. Cross,), (Oxford University Press, https://doi.org/10.1093/acprof:oso/9780199553426.003.0022

Raschle, N., Zuk, J., Ortiz-Mantilla, S., Sliva, D. D., Franceschi, A., Ellen Grant, P., Benasich, A. A., & Gaab, N. (2012). Pediatric neuroimaging in early childhood and infancy: Challenges and practical guidelines. *Annals of the New York Academy of sciences*, *1252*, 43–50. https://doi.org/10.1111/j.1749-6632.2012.06457.x

Rüber, T., Lindenberg, R., & Schlaug, G. (2015). Differential adaptation of descending motor tracts in musicians. *Cerebral Cortex*, *25*, 1490–1498. https://doi.org/10.1093/cercor/bht331

Schellenberg, E. G. (2006). Long-term positive associations between music lessons and iQ. *Journal of Educational Psychology*, *98*, 457–468. https://doi.org/10.1037/0022-0663.98.2.457

Schlaug, G. (2001). The brain of musicians: A model for functional and structural adaptation. *Annals of the New York Academy of Sciences*, *930*, 281–299. https://doi.org/10.1111/j.1749-6632.2001.tb05739.x

Schlaug, G., Forgeard, M., Zhu, L., Norton, A., Norton, A., & Winner, E. (2009). Training-induced neuroplasticity in young children. *Annals of the New York Academy of Sciences*, *1169*, 205–208. https://doi.org/10.1111/j.1749-6632.2009.04842.x

Schlaug, G., Jäncke, L., Huang, Y., Staiger, J. F., & Steinmetz, H. (1995). Increased corpus callosum size in musicians. *Neuropsychologia*, *33*, 1047–1055. https://doi.org/10.1016/0028-3932(95)00045-5

Schmithorst, V. J., & Wilke, M. (2002). Differences in white matter architecture between musicians and non-musicians: A diffusion tensor imaging study. *Neuroscience Letters*, *321*, 57–60. https://doi.org/10.1016/S0304-3940(02)00054-X

Schneider, P., Scherg, M., Dosch, H. G., Specht, H. J., Gutschalk, A., & Rupp, A. (2002). Morphology of heschl's gyrus reflects enhanced activation in the auditory cortex of musicians. *Nature Neuroscience*, *5*, 688–694.

Schön, D., Magne, C., & Besson, M. (2004). The music of speech: Music training facilitates pitch processing in both music and language: Music and prosody: An ERP study. *Psychophysiology*, *41*, 341–349. https://doi.org/10.1111/1469-8986.00172.x

Schrank, F. A., Mather, N., & McGrew, K. S. (2014).*Woodcock-Johnson IV tests of oral language*. (Riverside).

Shahin, A., Roberts, L. E., & Trainor, L. J. (2004). Enhancement of auditory cortical development by musical experience in children. *Neuroreport*, *15*, 1917–1921. https://doi.org/10.1097/00001756-200408260-00017

Slevc, L. R. (2012). Language and music: Sound, structure, and meaning. *WIREs Cognitive Science*, *3*, 483–492. https://doi.org/10.1002/wcs.1186

Smith, S. M., Jenkinson, M., Woolrich, M. W., Beckmann, C. F., Behrens, T. E. J., Johansen-Berg, H., Bannister, P. R., De Luca, M., Drobnjak, I., Flitney, D. E., Niazy, R. K., Saunders, J., Vickers, J., Zhang, Y., De Stefano, N., Brady, J. M., & Matthews, P. M. (2004). Advances in functional and structural MR image analysis and implementation as FSL. *Neuroimage*, *23*, S208–S219. https://doi.org/10.1016/j.neuroimage.2004.07.051

Soley, G., & Hannon, E. E. (2010). Infants prefer the musical meter of their own culture: A cross-cultural comparison. *Developmental Psychology*, *46*, 286–292.

Steele, C. J., Bailey, J. A., Zatorre, R. J., & Penhune, V. B. (2013). Early musical training and white-matter plasticity in the corpus callosum: Evidence for a sensitive period. *Journal of Neuroscience*, *33*, 1282–1290. https://doi.org/10.1523/JNEUROSCI.3578-12.2013

Swaminathan, S., & Schellenberg, E. G. (2020). Musical ability, music training, and language ability in childhood. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *46*, 2340–2348.

Turesky, T. K., Vanderauwera, J., & Gaab, N. (2021). Imaging the rapidly developing brain: Current challenges for MRI studies in the first five years of life. *Developmental Cognitive Neuroscience*, *47*, 100893 https://doi.org/10.1016/j.dcn.2020.100893

Ullén, F., Mosing, M. A., Holm, L., Eriksson, H., & Madison, G. (2014). Psychometric properties and heritability of a new online test for musicality, the swedish musical discrimination test. *Personality and Individual Differences*, *63*, 87–93. https://doi.org/10.1016/j.paid.2014.01.057

Wagner, R. K., Torgesen, J. K., Rashotte, C. A., & Pearson, N. A. (2013). *Comprehensive test of phonological processing– 2nd ed (CTOPP-2)*. Pro-Ed.

Walton, M., Dewey, D., & Lebel, C. (2018). Brain white matter structure and language ability in preschool-aged children. *Brain and Language*, *176*, 19–25. https://doi.org/10.1016/j.bandl.2017.10.008

Wan, C. Y., & Schlaug, G. (2010). Music making as a tool for promoting brain plasticity across the life span. *The Neuroscientist*, *16*, 566–577. https://doi.org/10.1177/1073858410377805

Wesseldijk, L. W., Mosing, M. A., & Ullén, F. (2021). Why is an early start of training related to musical skills in adulthood? A genetically informative study. *Psychological Science*, *32*, 3–13.

Yeatman, J. D., Dougherty, R. F., Myall, N. J., Wandell, B. A., & Feldman, H. M. (2012). Tract profiles of white matter properties: Automating fiber-tract quantification. *PLoS ONE*, *7*, e49790 https://doi.org/10.1371/journal.pone.0049790

Zatorre, R. (2005). Music, the food of neuroscience? *Nature*, *434*, 312–315. https://doi.org/10.1038/434312a

Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music: Auditory–motor interactions in music perception and production. *Nature Reviews Neuroscience*, *8*, 547–558.

Zuk, J., & Gaab, N. (2018). Evaluating predisposition and training in shaping the musician's brain: The need for a developmental perspective. *Annals of the New York Academy of Sciences*, *1423*, 40–50. https://doi.org/10.1111/nyas.13737

Zuk, J., Yu, X., Sanfilippo, J., Figuccio, M. J., Dunstan, J., Carruthers, C., Sideridis, G., Turesky, T. K., Gagoski, B., Grant, P. E., & Gaab, N. (2021). White matter in infancy is prospectively associated with language outcomes in kindergarten. *Developmental Cognitive Neuroscience*, *50*, 100973 https://doi.org/10.1016/j.dcn.2021.100973

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