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 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, we find brain structure in infancy that is prospectively associated with subsequent music aptitude skills at school age. Among inter-hemispheric white matter pathways traditionally linked with musical training, we find that structural organization of these pathways *in infancy* is associated with later music aptitude in early childhood. 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.

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[1–4]. Musical training is widely suggested to alter brain structure and function[5]; however, longitudinal evidence of brain changes associated with musical training is only emerging[6,7], whereas a disproportionate amount of supporting evidence stems from cross-sectional comparisons of musicians to 'non-musicians' in school-aged children and adults[5]. 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')[5]. Enhanced gray matter volume and cortical thickness have been identified among adult musicians compared to non-musicians in predominantly primary auditory[8–13], pre-supplementary/primary motor[4,14,15], and sensorimotor[4,16–20] cortices. Accordingly, structural and functional networks mediating auditory-motor interactions have been implicated via dorsal pathways that connect auditory and motor systems in the brain[21]. Diffusion-weighted imaging has further revealed distinct properties of white matter connections among musicians relative to non-musicians within auditory and motor-related pathways[22]. Specifically, prominent tracts implicated in musical training include two pathways known to be vital for oral and written language: the arcuate fasciculus[23], which connects inferior frontal and superior temporal regions, and the superior extension known as the superior longitudinal fasciculus[24,25] which further projects from fronto-temporal to parietal regions. In the motor domain, differences in white matter organization based on musical training have been suggested in the corticospinal tract[19,25–27] and internal capsule[19,20,28], though inconsistent findings have been reported[22]. Converging evidence suggests that musical training is associated with greater inter-hemispheric connectivity[6,7,19,28–32], with significant cross-sectional differences between musicians and non-musicians in the corpus callosum, the primary cortical pathway to connect the left and right hemispheres. Despite this growing body of evidence suggesting brain structure associated with musical training, 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[6,7]. Specifically, these changes have been observed following one year of instrumental music training among five-to-seven 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[7]. Following two years of musical training, six-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[6]. Moreover, significant increases in white matter structural organization as indicated by fractional anisotropy (FA), the degree of directionality in water diffusion within white matter pathways, were identified in the corpus callosum among musically trained children compared to children engaged in sports as well as passive controls[6]. 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*[33]. Regarding putative genetic predispositions, genome-wide association and twin studies suggest genetic contributions to one's musicality[34–36], implicating several genes expressed in brain tissue, including *VRK2*[37]. 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[38]). 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[25]. 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[39]. Therefore, striking evidence of neural predispositions for musical success has been observed among adults; however, scarcely any studies to date have examined possible neural predispositions from a developmental perspective in childhood.

Although neurobiological predispositions for success in music are evident in adulthood, it remains unclear whether and how early in development these putative predispositions emerge. Putative genetic predispositions implicating genes expressed in brain tissue[37] 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[40]. 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[41], such that the first two years of life signify the most robust period of white matter development in the brain[42,43]. Although white matter continues to mature and develop throughout early childhood and beyond[44,45], at this stage neuroplasticity is more so considered a process of refinement that builds upon the structural organization established during infancy[43]. 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 first two years of life signify the most rapid period of white matter development in the brain 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[46,47], we examine whether putative effects are specific to the music domain, or may be 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.

Methods

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 at 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: 5 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 selected measures of interest for the present study, which included Magnetic Resonance Imaging (MRI) and developmental milestones assessment 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 additional 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[55]); 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 (http://macses.ucsf.edu/default.php). 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.

Musicality Measures at Longitudinal Follow-up

At follow-up, musicality was characterized with administration of Edwin Gordon’s Primary Measures of Music Audiation (PMMA[56]). This measure provides indices of tonal and rhythmic discrimination abilities for administration with children from ages 5–8 years. Children are 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 consist of 40 items each, with a duration of approximately 12 minutes per subtest. Pre-recorded audio files with the associated paired electronic musical patterns were binaurally presented over child-friendly headphones at a consistent volume. In the Tonal subtest, each pattern consists of two-to-five note melodies with frequencies ranging from C4 to F5, and the rhythm is kept consistent. Conversely, in the Rhythm subtest, all notes have the same pitch, C5, but vary in duration and timing. After hearing the second pattern of the pair, participants are asked to determine if the two phrases are the same or different. To score PMMA, the raw score is first determined by the number of correct responses out of 40 total questions in each subtest. The raw scores and the participants' chronological age are used to determine the standardized percentile rankings.

Language Measures at Longitudinal Follow-up

In addition to musicality measures acquired at follow-up, a subset of language assessments from the same 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[57]) 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[58]) 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[59]). 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 administered and selected to measure 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.

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[60]. 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 x 220 mm; voxel resolution = 1.1 x 1.1 x 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/mm2; field of view = 256 x 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.

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[50,61–63]). 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.

Automated Fiber Quantification

White matter pathways were quantified utilizing the Automated Fiber Quantification (AFQ) software package (github.com/jyeatman/AFQ,[64]. Procedures employed follow those previously described in prior investigations with infants with the present research team[50,62]. In summary, whole-brain tractography was conducted via a deterministic streamline tracking algorithm[63,65], with an FA threshold of 0.1 and angle threshold of 40° (in accordance with previous investigations with this age range[50,62]). 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[63]. 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.

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[6] and arcuate fasciculus[66], 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[25]). The present analysis characterized the corpus callosum major (i.e., splenium), as the posterior portion of the tract has been repeatedly implicated in music training studies to date[7,19]. Other tracts of interest were examined bilaterally to evaluate hemispheric specificity of prospective associations with subsequent musicality.

Due to the automated tractography approach employed and ongoing methodological limitations of employing MRI in infancy[67], 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[68]. Moreover, the right-hemispheric arcuate in particular was unable to be reconstructed for many infants ($n = 8$), 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[69]. All tracts of interest were examined in group-level analyses, recognizing the limitations of the especially modest resultant sample size for temporal tracts.

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) is prospectively associated with 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 (rhythm and melody subtests) 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 each white matter tract of interest along 100 individual nodes produced from AFQ 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 a final step, an average of significant nodes identified within each tract was estimated to determine prediction estimates by tract for each outcome, while accounting for control predictors (age and 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 5,000 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.

Results

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.

In line with prior evidence implicating the corticospinal tract as a neural predisposition for musicality in adults[25], this pathway is also indicated in our results in infancy. Specifically, white matter organization of the right corticospinal tract (as indicated by fractional anisotropy, FA) in infancy is prospectively 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.

Here we also find that structural organization of the corpus callosum major (as indicated by FA) is prospectively associated with subsequent tonal music aptitude, controlling for age (nodes 23–25, *FWE-Corrected*). The corpus callosum has been implicated in longitudinal training studies as a specific pathway associated with changes as a direct result of musical training [6,7]; yet here we also report that structural organization of this pathway from as early as infancy is associated with subsequent musicality.

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[46,47], which raises a question as to whether brain-behavior links between white matter and musicality may be explained by 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*, $r = 0.555$, $p = 0.005$), a standard 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*, $r = 0.524$, $p = 0.009$). These correlations met the False Discovery Rate (FDR) adjustment for correction for multiple comparisons. Rhythmic music aptitude was also marginally associated with sentence repetition ($r = 0.446$, $p_{uncorrected} = 0.029$), 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 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: $\beta = .442$, $p = 0.057$, corpus callosum: $\beta = .441$, $p = 0.068$).

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 ($\beta = .612$, $p = 0.002$).

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 is prospectively associated with 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[46,47], we then accounted for language to determine whether 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[25], 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[25]. 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 two years of life in early childhood.

Establishing the specificity of putative neural predispositions for music by accounting for general language abilities illuminates 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[46,47], all longitudinal relationships between white matter in infancy and subsequent 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[48,49]. 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[50–52]. Therefore, our findings associated with tonal discrimination abilities likely reflect neural foundations established in infancy that are not only linked with subsequent *tonal* music aptitude but also language abilities in general.

By contrast, 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[37], by providing direct evidence of a specific neural pathway (i.e., right-hemispheric corticospinal tract) that is evident within the first two 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, including *VRK2*[37], 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 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[34,35], implicating genes expressed in brain tissue[37]. Yet, we captured brain structure among these infants several months since birth (with an average age of nine months), which coincides with an especially rich time for environmental input[53]. 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. Moreover, 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. Further longitudinal work starting earlier in infancy 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 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. 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[54]. This work supports the importance of early childhood musical experiences, especially during the most robust period of brain development within the first two years of life.

Declarations

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Figures

Figure 1

Structural organization of the right corticospinal tract in infancy is prospectively associated with 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).

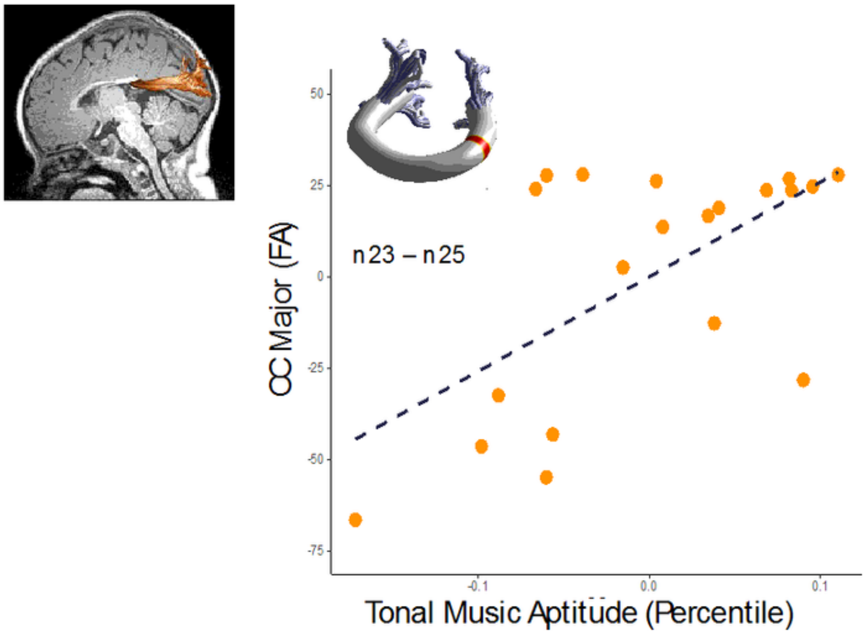

Figure 2

Structural organization of the corpus callosum major in infancy is prospectively associated with school-age tonal and rhythmic 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 red on the 3-dimensional rendered tract ($p < 0.05$, FWE-corrected).