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Emergence of biological markers of musicianship with school-based music instruction

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Musician children and adults demonstrate biological distinctions in auditory processing relative to nonmusicians. For example, musician children and adults have more robust neural encoding of speech harmonics, more adaptive sound processing, and more precise neural encoding of acoustically similar sounds; these enhancements may contribute to musicians' linguistic advantages, such as for hearing speech in noise and reading. Such findings have inspired proposals that the auditory and cognitive stimulation induced by musical practice renders musicians enhanced according to biological metrics germane to communication. Cross-sectional methodologies comparing musicians with nonmusicians, however, are limited by the inability to disentangle training-related effects from demographic and innate qualities that may predistinguish musicians. Over the past several years, our laboratory has addressed this problem by examining the emergence of neural markers of musicianship in children and adolescents using longitudinal approaches to track the development of biological indices of speech processing. This work was conducted in partnership with successful community-based music programs, thus avoiding reliance on a synthetic program for the purposes of laboratory study. Outcomes indicate that many of musicians' auditory-related biological enhancements emerge with training and may promote the acquisition of language skills, including in at-risk populations.

Keywords: musicians; children; training; plasticity; brain; brainstem; speech; community interventions

Introduction

Cross-sectional comparisons of musicians to nonmusicians have established a variety of musician enhancements in auditory skills and their neural substrates, extending from enhanced perception and neural encoding of speech, most notably in suboptimal listening conditions,[1–6] to more proficient auditory working memory (for a review see Ref. 7) and auditory attention.[8,9] In response, there have been increasing efforts to deliver school-based music training programs to children in hopes of strengthening typical brain development as well as counteracting the challenges faced with atypical development, as with language-based learning impairment (e.g., dyslexia) and poverty. Music training leads to large-scale community-based interventions because of the ease of providing simultaneous instruction to large groups (e.g., El Sistema provides music instruction to hundreds of thousands of children in Venezuela annually[10]). Although intervention movements rely on the premise that musical practice shapes the developing brain, supporting data primarily stem from cross-sectional approaches, which confound effects of training with demographic and innate characteristics associated with individuals drawn to pursue—and stick with—musical practice. Only longitudinal studies can define the extent (and limits) of music training's effects on auditory system development and provide the strongest support for the administration of music-based strategies for engendering auditory learning. The few longitudinal studies that exist provide convincing support for influences of music training on child brain development.[11,12]

Our laboratory partnered with two ongoing and successful school-based music programs to conduct

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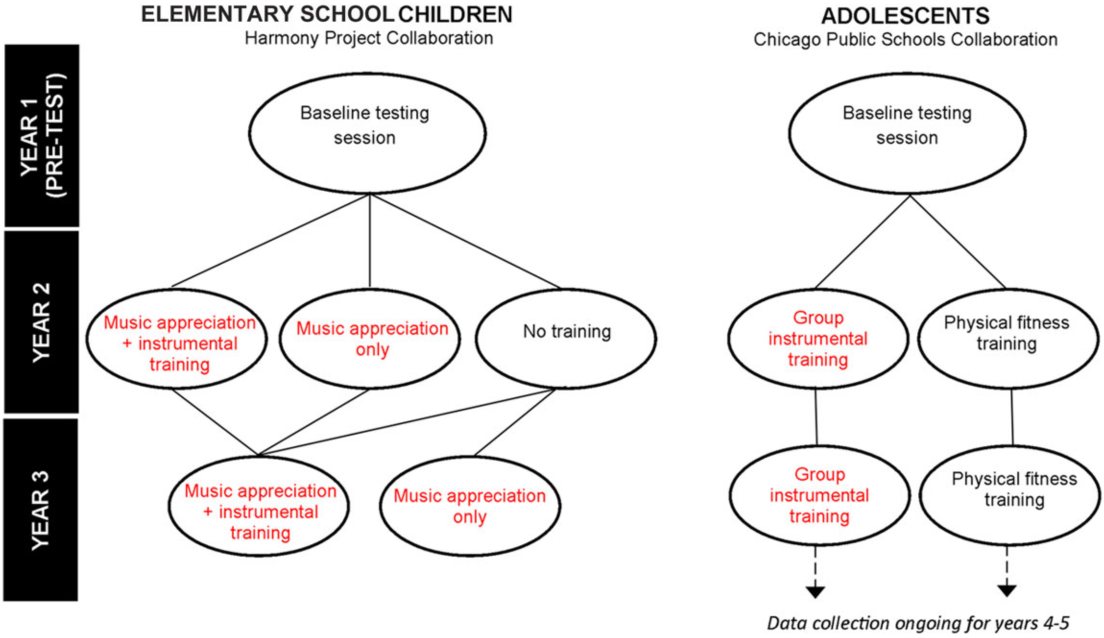

Figure 1. Schematics of two ongoing longitudinal studies of music training.

experimental studies of music training's effects on auditory development in children and adolescents following 1–3 years of music training. Instead of relying on a program developed by scientists for the purposes of laboratory study, our partnerships allowed us to evaluate the effects of established music programs with unprecedented ecological validity. One partnership was with Harmony Project (Los Angeles, CA; www.harmony-project.org), a nonprofit organization that has used a public health model to provide free music instruction to at-risk children from gang-reduction zones for over a decade. Our second partnership was with Chicago Public Schools, including a network of charter schools that in some cases require students to choose between music and physical fitness training (see Fig. 1 for an overview of both projects). Notably, both partners predominantly serve underprivileged youth who would otherwise not have access to music training. This overview introduces emerging outcomes of this work to advance what we know about how musicianship makes its mark on the developing brain.

Accessing the biology underlying automatic sound processing in humans

Although a panoply of metrics has been applied to the study of the musician's brain, the present work focuses on automatic sound processing, accessed through the auditory brainstem response to complex sounds (cABR). The cABR's primary generator is the inferior colliculus (IC) of the auditory midbrain, which provides a site of convergence for lower-level parallel processing pathways but is also the recipient of top-down innervations from primary auditory cortex and other cortical sites, including the centers of memory and attention. Because of this, the cABR does not solely reflect early or subcortical sensory processing. Rather, it reflects the automatic sound processing accomplished by the integrated auditory network. The repeated coactivation of these pathways as we cognitively engage with sound strengthens the automatic sound processing we measure from the IC. The attention musicians have paid to sound in the past thus can strengthen automatic sound processing in the present, effectively changing how we hear.

Sound waves contain information across multiple timescales, from microseconds to seconds, that must be processed simultaneously. The cABR provides access to neural sound processing at a very precise level of detail (i.e., at the microsecond level). Because brainstem neurons phase-lock up to, and in some cases beyond, 1000 Hz, the cABR preserves acoustic characteristics of evoking sounds. In fact, the cABR is unique in its preservation of sound

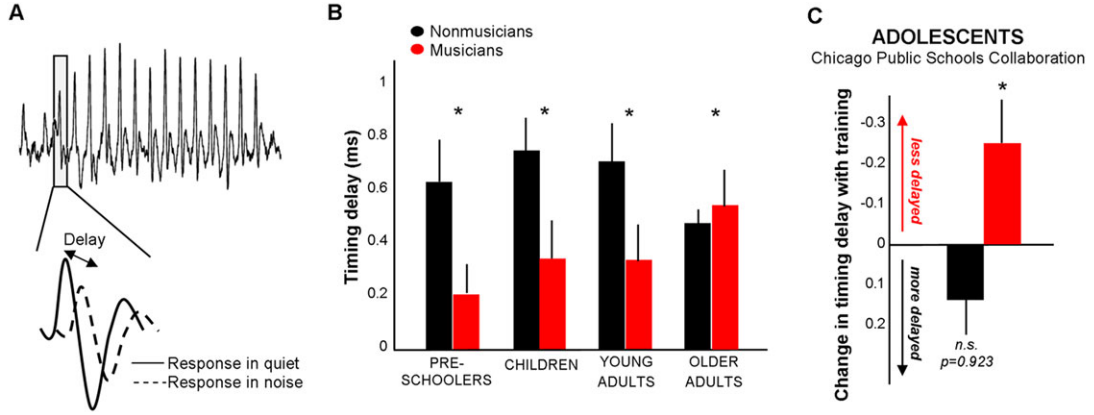

Figure 2. Effects of noise on the neural encoding of speech. (A) Noise delays the brain's response to speech; the more the delay, the worse the speech perception. (B) Musicians across the life span have less noise-delayed neural responses to speech than nonmusicians. (C) Adolescents who engaged in 2 years of music training developed less delayed responses to speech in noise, whereas adolescents engaged in the physical fitness classes did not ($^*P < 0.05$).

details, especially when contrasted with slower and more abstract cortical evoked potentials that consist of general-onset peaks that do not provide one-to-one reflections of acoustic stimulus parameters. This is why we use cABRs to get a glimpse into the auditory system's transcription of the acoustics of sound, such as a sound's fundamental frequency and other spectral components (e.g., harmonics, speech formants). Because cABRs are temporally precise, we can also use them to assess neural timing by measuring the timing of discrete peaks (e.g., Fig. 2A)—which are reliable on the order of fractions of a millisecond (in contrast to the slower and more variable timing afforded by cortical evoked potentials). Other techniques assess frequency-specific timing by using phase-locking techniques (e.g., see Refs. 13 and 14) and cross-phase analyses that compare timing between two responses (e.g., see Ref. 15). Analytical techniques such as these allow us to capture the precision with which the auditory system encodes the acoustics of incoming sounds and ask which sound features are enhanced with training.[39]

Emergence of biological markers of musicianship

We have confirmed that adult musicians do not demonstrate overall enhanced automatic sound processing. Rather, adult musicians demonstrate selective enhancements and more adaptive auditory processing compared to nonmusicians, which may account in part for their enhanced auditory abilities relative to nonmusicians (for review, see Ref. 16). For example, although adult musicians do not have more robust neural encoding of the base pitch, or fundamental frequency (F0), of speech, they do have more robust representations of higher frequency speech components such as the harmonics. Similarly, adult musicians' cABRs are not always faster than nonmusicians', but they are faster in challenging listening conditions, as in the presence of background noise (Fig. 2B). Musicians also demonstrate more temporally distinct responses to acoustically similar speech sounds, leading to more differentiated neural responses to syllables such as [ba] and [ga] (Fig. 3B), as well as increased trial-to-trial response consistency.[17] Many of these musician enhancements have been observed early in life, even in children with just a few years of training,[4,8] leading us to question whether these enhancements result from training or innate predispositions in children drawn to music.

Our partnerships with school-based music programs enabled us to directly test whether these musician-associated enhancements could be brought about by music training using longitudinal designs in children and adolescents. These studies were carried out in youth who would not otherwise have had access to music instruction. Although still ongoing, both studies have yielded evidence for the training-induced plasticity of automatic sound processing, specifically observed in neural responses to speech. For example, a comparison of 21 adolescents engaged in group music training with 22 adolescents engaged in physical fitness training

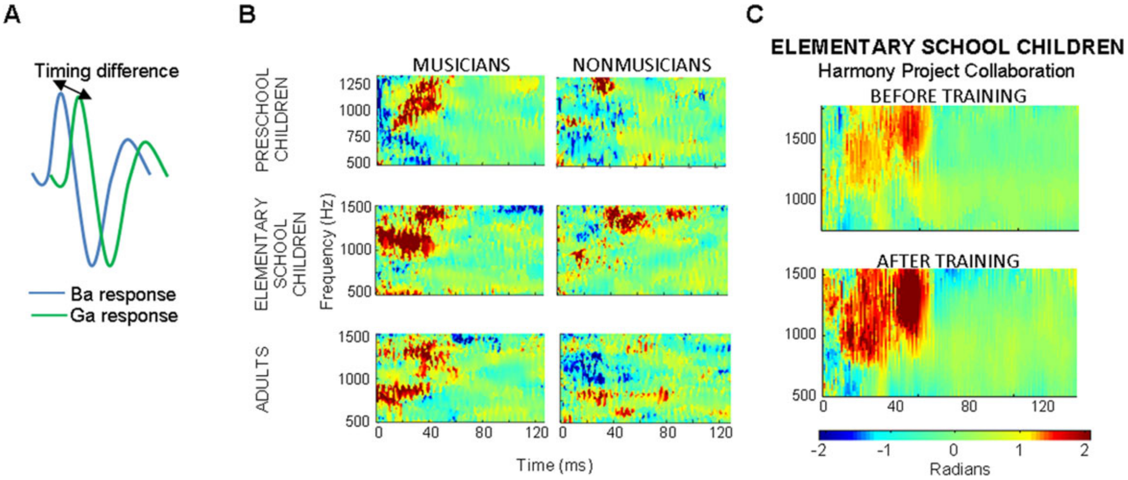

Figure 3. Comparison of neural responses to acoustically similar speech syllables, [ba] and [ga]. (A) The consonants of these syllables are distinguished neurally based on slight differences in response timing, with [ga] eliciting an earlier response than [ba]. (B) We compared neural responses to these sounds by comparing differences in the phases of the two responses: the expected timing pattern would be indicated in red over the first 50 ms of the response, resulting from an earlier response to [ga]. Musicians across the life span have more temporally distinct responses to similar syllables than nonmusicians. (C) Children who underwent 2 years of music training developed more distinct responses to these two syllables. Our control group showed no measurable changes.

revealed that 2 years of group music training can result in less delayed neural responses to speech in noisy backgrounds[18] (Fig. 1C). Furthermore, the 26 children who were randomly assigned to music training during 1 year of our collaboration with Harmony Project developed more distinct neural encoding of the difficult-to-distinguish stop consonants [ba] and [ga] over 2 years of training, whereas their control group counterparts, who only received 9 months of training, did not[19] (Fig. 3C). Notably, no between-group distinctions were observed for any neural or cognitive metric before the onsets of the studies. Comparisons of training results between child and adolescent studies were unfortunately precluded because we did not collect responses to speech in noise in younger children or stop-consonant differentiation in adolescents. These comparisons will be left to future work.

A frequent concern among music educators is the efficacy of general music (sometimes called music appreciation) compared to instrumental training classes. We were able to subdivide the children taking part in Harmony Project into groups that exclusively received general music appreciation classes or children who additionally engaged in supervised instrumental training and practice.[40] Although there was no difference between these groups before they enrolled in the program, after 1 year in Harmony Project, the instrumentally trained children had developed more robust responses to speech. Specifically, instrumentally trained children had developed faster neural responses to speech syllables as well as more robust neural encoding of speech harmonics. These results are a testament to the importance of active engagement during auditory learning in order to drive neuroplasticity. In a follow-up study, the children who were rated as the most engaged in their classes (on the basis of attendance and class participation) developed stronger neural responses to speech than their less engaged peers.[41]

In addition to the neurophysiological effects of music training reviewed above, the longitudinal study of music training in school-aged children yielded further data substantiating effects of music training on reading and speech perception abilities. Namely, children who underwent music training demonstrated better reading and speech-in-noise perception than their untrained peers following 2 years of training.[20,42] These effects were observed alongside better rhythmic synchronization abilities in children who underwent music training, after only 1 year of training.[21] Given consistent relationships that have been reported between language perception and reading-related skills and rhythmic synchronization ability,[22–26] observed in children even before the onset of formal reading instruction,[27] it is possible that music training's emphasis on rhythmic abilities provides a transfer mechanism to augment language functions (for review, see Refs. 28 and 29).

Discussion

We partnered with existing community-based organizations that provide music training to disadvantaged youth to test the influence of music training on the development of neural mechanisms underlying automatic sound processing. Although musicians may have a variety of innate characteristics that predistinguish them from nonmusicians, the nervous system is clearly modifiable with training and enrichment. Musicians' signature speech-processing enhancements, for example, can indeed be engendered by music training. Because the same neural mechanisms reported here that strengthen with music training have been associated with child speech perception and reading development,[30–32] even in children before the onset of reading instruction,[33] these outcomes may provide implications for the impact of music training on child language abilities.[29] This work may also bear implications for offsetting the disadvantaged rearing environment associated with poverty: children raised in low-income settings develop degraded neural encoding of speech when compared to mid- to high-income peers.[34] The findings reviewed here are in low-income children and adolescents and may indicate the habilitative power of music training to offset the degrading effects of a low-income rearing environment. In fact, the neural enhancements observed in the most engaged Harmony Project students served to offset the signature effects of poverty on neural encoding.[41]

How these enhancements are engendered is another question. One possibility is that they reflect music training's targeted exercising of the cognitive auditory system. Music and speech activate many shared auditory processing sites, but music places higher demands on these shared networks than does speech in terms of the precision of processing (for extended discussion of this point, see Ref. 35). The cABR's primary generator, the IC, is highly innervated by top-down projections from the cortex. Direct measurements in animal models indicate that corticocollicular projections are integral to the cellular changes that take place in the IC with learning.[36] Musicians' strengthened auditory cognitive system may engender sensory learning by strengthening automatic sound processing throughout the nervous system (for further discussion, see Refs. 16 and 37).

This mechanistic framework is supported by patterns in child brain development and the potential for plasticity at different developmental stages. The descending connectivity that supports top-down control over sensory processing emerges during early childhood and develops into young adulthood. This contrasts with the myelination of the auditory brainstem, which is thought to be complete within the first 2 years of life.[38] Within the cortex, deeper layers mature prior to superficial layers, which is significant because these outer layers facilitate top-down connectivity. This developmental sequence accounts for why the descending auditory system is more drastically shaped by interactions with the auditory environment, especially during the sensitive developmental period that comprises early childhood. A musician's strengthened automatic interaction with sound may reflect a stronger auditory cognitive system, strengthened through consistent cognitive interactions with sound.

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Conflicts of interest

The authors declare no conflicts of interest.

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