Music, Noise-Exclusion, and Learning

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Children with language-based learning disorders show impaired processing of speech in challenging listening environments, suggesting a noise-exclusion deficit. Musical expertise induces neuroplastic changes throughout the nervous system, including sharpening of early sensory processing, improved linguistic ability, working memory, and source segregation—skills known to be crucial for speech in noise perception. Here we argue for the usefulness of music as an auditory training approach to improve speech perception in noise in individuals with broad noise-exclusion deficits.

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A rich body of work has focused on examining the role music plays to engender plastic changes in the brain. These studies have demonstrated dramatic neural changes in auditory, cognitive, and linguistic processing in musicians relative to nonmusicians. Together, these studies beg the question: is music training a viable intervention strategy in clinical populations showing deficits in auditory, cognitive, or linguistic function? Furthermore, is music training a more effective global intervention strategy, relative to other training regimens that target ameliorating specific deficits? These questions are clinically relevant, as well as theoretically important. In this review we focus on speech in noise processing in two populations—those with language-based learning disorders and musicians.

Hearing speech in noise is a difficult task for everyone, but young children and older adults are particularly vulnerable to the deleterious effects of background noise. Children with learning disorders can exhibit noise-exclusion as a primary symptom (Sperling, Lu, Manis, & Seidenberg, 2005). Musicians, in contrast, demonstrate enhanced noise-exclusion abilities (Parbery-Clark, Skoe, & Kraus, 2009; Parbery-Clark, Skoe, Lam, & Kraus, 2009). We will argue that perceiving sensory information in background noise is a complex task involving the abilities to extract key features in the signal while suppressing irrelevant details, temporarily store this information while ignoring noise, process a stream from a single source in the midst of numerous other sources (e.g., a speaker's voice), and use linguistic context to 'fill in' details lost in the noise. These components of speech in noise perception are enhanced in musicians and deficient in children with learning disabilities. We thus argue for the usefulness of music training as a global intervention strategy in individuals with noise-exclusion deficits.

Language-Based Learning Disabilities: Heterogeneous Disorder With a Common Symptom

It is estimated that as many as 5-10% of children exhibit language-based learning and reading disabilities. Although these reading and learning problems are regarded as having a neurological basis, the nature of the core neural deficit is unclear and is debated in extant literature (Ramus, 2001, 2003). Many researchers argue that phonological processing, i.e., the ability to store, manipulate, and use speech sounds, which is critical to reading and spelling development, is impaired in these children (Snowling, 1981, 2001). Others suggest that sensory processing, especially the ability to process fast temporal events, is impaired, leading to deficits in phonological processing and ultimately, readings skills (Merzenich et al., 1996; Tallal, 1980; Tallal, Stark, & Mellits, 1985). In the absence of an agreement on a 'core-deficit' even after decades of research, the current general consensus is that reading and learning disabilities are highly heterogeneous disorders, the diagnosis and treatment for which needs to be individual-specific (Katzir, 2009; Murphy & Pollatsek, 1994).

While the consensus has shifted towards acknowledging the heterogeneous nature of the disorder, recent studies have defined a common symptom in many children with learning disabilities. According to a recent proposal, children with learning problems show a distinct deficit in noise-exclusion, i.e., the ability to exclude noise during sensory or cognitive processing; (Sperling,

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Lu, Manis, & Seidenberg, 2005). Children with dyslexia, a neurological disorder affecting reading and spelling, show similar visual contrast thresholds relative to typically developing children when stimuli are presented in a no-noise background. However, when stimuli are presented in noise, poor readers show elevated thresholds. Thus, across modalities, sensory processing in children with dyslexia is context-specific, i.e., deficits are apparent only in noisy conditions (Sperling et al., 2005; Sperling, Lu, Manis, & Seidenberg, 2006). Based on these data, Sperling and colleagues coined the deficit as that of 'noise-exclusion.'

Recent studies have replicated these results in children with specific language impairment (SLI) using auditory stimuli. Specific language impairment, a disorder prevalent in 7.4% of the population, precludes normal language development despite normal hearing thresholds, intelligence, and exposure to language (Tomblin et al., 1997). Children with SLI are more likely to have difficulties in reading and spelling relative to those who have normal language development (Hall & Tomblin, 1978). Other work shows that, relative to children matched for age or language ability, children with SLI show a speech perception deficit under challenging listening conditions (Ziegler, Pech-Georgel, George, Alario, & Lorenzi, 2005). However, the speech perception deficits are nonexistent when speech is presented in optimal listening conditions. Based on their data, the authors suggest that a noise-exclusion deficit may exacerbate inefficient speech sound identification in these children. Consistent with findings in the visual domain, children with developmental dyslexia were shown to demonstrate difficulty in speech perception only in noisy backgrounds, akin to the visual noise-exclusion deficit reported by Sperling and colleagues (Ziegler, Pech-Georgel, George, & Lorenzi, 2009).

Children with auditory processing disorders, a controversial diagnostic category that describes those with a perceptual deficit in the auditory domain, can also exhibit impaired speech perception in noisy environments (Muchnik et al., 2004). Muchnik and colleagues argue that the noise-exclusion deficit in children with APD may result from an inability to use top-down feedback to fine-tune early sensory processing.

Taken together, a common symptom across these multiple disorders that are loosely categorized as 'learning disabilities' is noise-exclusion. It is arguable whether perceptual difficulties in noise are an underlying cause (Sperling et al., 2005) or a symptom that accentuates the difficulties faced by a nervous system that is unable to handle the demands of perceptual dynamics (Ziegler et al., 2009). Either way, because learning often takes place in noisy environments, children who are unable to exclude noise are at a serious disadvantage. In the next few paragraphs, we will explore experience-dependent neural plasticity in musicians and discoveries that indicate that musicians have enhanced perception of speech in noise relative to nonmusicians.

Experience Dependent Plasticity Due to Music Training: Enhanced Linguistic and Cognitive Processing in Musicians

Music is a complex auditory task and musicians spend years fine-tuning their skills. It is no wonder that previous research has documented neuroplasticity to musical sounds as a function of musical experience (Fujioka, Trainor, Ross, Kakigi, & Pantev, 2005; Koelsch, Schroger, & Tervaniemi, 1999; Musacchia, Sams, Skoe, & Kraus, 2007; Pantev et al., 1998; Pantev, Roberts, Schulz, Engelien, & Ross, 2001; Tervaniemi, Rytkonen, Schroger, Ilmoniemi, & Naatanen, 2001). More surprising, however, are findings that music training benefits auditory processing not only in the musical domain, but also in the processing of speech stimuli (Musacchia et al., 2007; Schon, Magne, & Besson, 2004; Wong, Skoe, Russo, Dees, & Kraus, 2007). Consistent findings across a range of studies that use methods spanning from neurophysiology to behavior indicate that music training improves a variety of verbal and nonverbal skills. These include verbal working memory (Chan, Ho, & Cheung, 1998; Forgeard, Winner, Norton, & Schlaug, 2008), processing of prosody and linguistic features in speech (Bidelman, Gandour, & Krishnan, in press; Chandrasekaran, Krishnan, & Gandour, 2009; Wong et al., 2007), phonological skills (Forgeard, Schlaug, et al., 2008), processing emotion in speech (Strait, Kraus, Skoe, & Ashley, 2009a), working memory (Parbery-Clark, Skoe, Lam, et al., 2009), auditory attention (Strait, Kraus, Parbery-Clark, & Ashley, 2010), and auditory stream segregation (Beauvois & Meddis, 1997). In the next few sections, we will highlight key findings from some of these studies.

Music Training Improves Language-Related Skills

The domains of music and language share many features, the most direct being that both exploit changes in pitch patterns to convey information. Music uses pitch contours and intervals to communicate melodies and tone centers. Pitch patterns in speech convey prosodic information; listeners use prosodic cues to identify indexical information, i.e., information about the speaker's intention as well as emotion and other social factors. Further, in tone languages, changes in pitch are used lexically; that is, in differentiating between words. A significant body of research has focused on the extent to which musical experience provides benefits in language abilities; the results unambiguously suggest that musicians show enhanced processing of prosodic and linguistic pitch. Musicians show an enhanced ability to detect subtle incongruity in prosodic pitch as well as consistent neural differences relative to nonmusicians (Besson, Schon, Moreno, Santos, & Magne, 2007; Magne, Schon, & Besson, 2006). Differences between musicians and nonmusicians show up even during preattentive stages of auditory processing (Chandrasekaran, Krishnan, et al., 2009b; Musacchia et al., 2007; Wong & Perrachione, 2007). Frequency-following responses (FFRs), which are ensemble neural responses originating at the auditory brainstem that reflect phase-locking to stimulus features, were recorded from musicians and nonmusicians who were listening to the speech syllable /da/ (Musacchia et al., 2007). Relative to nonmusicians, musicians showed more robust encoding of timing and pitch features in the speech signal at the level of the brainstem. Using FFR as an index, musicians showed a superior representation of dynamic pitch contours, as reflected by improved pitch tracking accuracy at the level of the brainstem (Wong et al., 2007). The ability to track non-native pitch contours correlated positively with number of years of music training, suggesting that it was musical experience that improved lower-level representation of non-native pitch. Musicians showed superior cortical representation of linguistic pitch in a non-native language relative to nonmusicians (Chandrasekaran, Krishnan, et al., 2009). In this study, native tone-language speakers showed the strongest representation of pitch, suggesting that the context of long-term training matters. From a functional perspective, the enhanced cortical and brainstem representations are indeed relevant. Musicians showed a superior propensity to use pitch in lexical contexts during a language learning task, relative to nonmusicians (Wong & Perrachione, 2007). Musician enhancement is not just restricted to pitch features. Studies also have demonstrated that musicians show superior brainstem representation of timing and harmonic structure in speech, features that are important for differentiating speech sounds (Musacchia et al., 2007; Parbery-Clark, Skoe, et al., 2009). Taken together, these studies demonstrate that musicians show a distinct advantage in the early auditory processing of speech features.

In a hallmark study, Chan and colleagues showed that participants with music training exhibited superior verbal memory relative to nonmusicians, as indicated by greater number of words recalled in a list learning task (Chan et al., 1998). Children who received instrumental music training not only showed enhanced processing of skills related to music, but also showed enhanced vocabulary relative to untrained controls (Forgeard, Winner, et al., 2008). In typically developing children with normal reading ability, musical discrimination skills significantly predicted phonological and reading skills (Forgeard, Schlaug, et al., 2008).

Music Training Improves Emotional and Cognitive Processing

Examining the subcortical encoding of a complex, emotionally-salient stimulus (a child's cry) as a function of musical experience, a recent study demonstrated increased neural efficiency in musicians (Strait et al., 2009a; Strait, Kraus, Skoe, & Ashley, 2009b). Relative to nonmusicians, musicians showed superior encoding of the most acoustically complex portion of the emotional stimuli, consistent with behavioral studies demonstrating enhanced emotional perception in musicians (Thompson, Schellenberg, & Husain, 2004), but see (Trimmer & Cuddy, 2008). Similarly, musicians also demonstrated selective neural enhancement of the upper note of musical chords (Lee, Skoe, Kraus, & Ashley, 2009). Music training also has been shown to improve working memory (Forgeard, Winner, et al., 2008; Jakobson, Lewycky, Kilgour, & Stoesz, 2008; Parbery-Clark, Skoe, Lam, et al., 2009), attention (Strait et al., 2010; Tervaniemi et al., 2009), and executive function (Bialystok & DePape, 2009) abilities. Musicians are also significantly better than nonmusicians in auditory stream segregation, presumably due to their music training (Beauvois & Meddis, 1997; Zendel & Alain, 2009).

To summarize, relative to nonmusicians, musicians have shown enhanced verbal memory, improved sensory representation of speech features including pitch, timing, and timbre, enhanced stream segregation, working memory, attention, and executive skills. All these skills underlie successful perception of speech in noisy backgrounds. In the next section, we will review a study that directly compared speech in noise processing in musicians and nonmusicians.

Noise-Exclusion Ability is Enhanced in Musicians

Musicians, as a consequence of training that requires consistent practice, online manipulation, and monitoring of their instrument, are experts in extracting relevant signals from the complex soundscape (e.g., the sound of their own instrument in an orchestra). Researchers have asked whether or not this experience transfers to speech perception in noise. This would not be surprising considering the literature reviewed in the previous section that demonstrates the effect of musical experience on the skills that subserve successful perception of speech in noise. A recent Kraus lab study found a distinct speech in noise advantage for musicians, as measured by two standardized tests of hearing in noise (HINT, Hearing-in-noise test; QuickSIN) (Parbery-Clark, Skoe, Lam, et al., 2009). Along with the hearing in noise tests, cognitive and behavioral data also were collected from the participants. Musicians showed superior working memory and performed better on a frequency discrimination task. Across all participants, the number of years of consistent practice with a musical instrument correlated strongly with performance on QuickSIN, auditory working memory and frequency discrimination. These correlations strongly suggest that practice fine tunes cognitive and sensory ability, leading to an overall advantage in speech perception in noise in musicians.

Neural Bases of Speech Perception in Adverse Listening Conditions

The auditory system is composed of a number of neural structures that are interconnected via bottom-up (ascending) as well as top-down (descending) pathways. Perceiving speech in noisy environments is a complex task involving higher-level cognitive and lower-level sensory processing (Nahum, Nelken, & Ahissar, 2008). The signal has to be delivered to higher cortical structures with enough fidelity that it can be decoded as being meaningful (Hickok & Poeppel, 2007). For this to happen, the impact of background noise needs to be minimized. Recent studies have suggested an important role for the feedback (top-down) pathways in fine-tuning the auditory signal at early stages of auditory processing (Luo, Wang, Kashani, & Yan, 2008). These authors address three important principles underlying automatic sound selection by top-down feedback pathways. Specifically: a) feedback is initiated by higher level structures (i.e., cortex), b) efferent pathways carry this information to lower-level structures such as the auditory brainstem, and c) selectivity arises at the earliest stages of processing. This selectivity is important for higher-level structures to distinguish relevant information in the signal from irrelevant details. In the next few sections, we will examine cortical and brainstem processing of speech in noise (higher-level and lower-level structures, respectively). We will discuss the relevance of feedback-induced selective processing in individuals with substantial music training as well as those with learning disabilities.

Cortical Processing of Speech in Noise

A network of neural areas including sensory and cognitive areas are recruited while participants perform speech in noise tasks in the MRI scanner (Harris, Dubno, Keren, Ahlstrom, & Eckert, 2009; Wong et al., 2009; Wong, Uppunda, Parrish, & Dhar, 2008). In young adults, the bilateral auditory cortices are strongly activated when participants are listening to speech in noise, relative to quiet. These include the bilateral mid-STS (superior temporal sulcus) and the left posterior STG (superior temporal gyrus). The authors argue that the bilateral mid-STS activation reflects the increased attention to relevant auditory factors (fine-grained acoustic analyses including listening in regions where there is a lack of energy in the masker), whereas the left posterior STG activation reflects phonological memory as well as auditory-motor integration. There was also increased frontal lobe activation (left middle frontal gyrus; MFG), and insular activation, suggesting an increase in cognitive demand reflective of more effortful decision processes during auditory perception. A follow-up study examined the effect of aging on speech in noise perception (Wong et al., 2009). Older participants tended to recruit more attentional and cognitive areas relative to younger participants, coinciding with their poorer speech perception in noise. In contrast, younger participants recruited more sensory areas in the superior temporal gyrus. Taken together, these studies suggest that at the cortical stages of processing, both sensory and cognitive areas in the brain subserve speech in noise perception. More focal sensory activity was associated with superior speech perception in noise. In contrast, diffuse neural activity involving more extensive cognitive areas was associated with poor speech perception in noise.

Sub-Cortical Processing of Speech in Noise

The human auditory brainstem response (ABR) has been used as an index of brainstem encoding of speech stimuli (for reviews, see Chandrasekaran & Kraus, 2010, and Skoe & Kraus, 2010). The ABR to a plosive speech syllable (for e.g., /da/) consists of an onset response that marks the consonant burst, and a frequency-following response that reflects phase-locked responses to the consonant-vowel transition as well as the vowel portion of the stimulus. The ABR to the consonant-vowel stop syllable has been extensively studied in typical and clinical populations (Tzounopoulos & Kraus, 2009). Stop consonants are particularly vulnerable to the deleterious effects of noise due to their transient nature (Brandt & Rosen, 1980). Because the FFR preserves spectral information up to about ~2000 Hz and reflects neural timing in the order of milliseconds, it can therefore be used to examine the fidelity of the brainstem representation of spectral and timing information. In general, the addition of background noise delays the timing of brainstem responses (Cunningham, Nicol, Zecker, & Kraus, 2000; Cunningham, Nicol, Zecker, Bradlow, & Kraus, 2001; Hall, 1992) and reduces spectral magnitude.

Recent studies have examined experience-dependent plasticity in the representation of speech in background noise. Music training modulates the effect of background noise on subcortical auditory representation (Parbery-Clark, Skoe, & Kraus, 2009). Musicians show less degraded brainstem representation of speech relative to nonmusicians, as evidenced by faster neural timing, enhanced spectral representation, and better stimulus-to-response correlations. The differences between musicians and nonmusicians are present, albeit to a lesser degree even in quiet backgrounds (Musacchia et al., 2007). In background noise however, the differences in spectral representation between musicians and nonmusicians are large, suggesting that musical experience protects against the debilitating effects of background noise (Parbery-Clark, Skoe, et al., 2009). Thus timing and spectral features are preserved to a greater extent due to musical experience.

Brainstem representation of speech in noise also has been examined in children with behavioral deficits in noise-exclusion. Relative to children who show good perception of speech in noise, those with noise-exclusion deficits show delayed brainstem response timing and poorer representation of pitch in background noise (Anderson, Skoe, Chandrasekaran, & Kraus, in press; Anderson, Skoe, Chandrasekaran, Zecker, & Kraus, 2010). Interestingly, these children do not differ in quiet conditions, revealing a biological basis for the behavioral deficits in noise-exclusion. Behavioral performance on hearing in noise tests is also associated with the brainstem differentiation of stop-consonants (ba/da/ga) (Hornickel, Skoe, Nicol, Zecker, & Kraus, 2009). Children who showed clear neural differentiation of the three contrastive stimuli at the level of the brainstem also demonstrated better speech in noise perceptual skills. Taken together, noise appears to blur the representation of timing and spectral elements important for speech perception in noise at the level of the brainstem.

Top-Down Shaping of Early Auditory Processing

Higher-level auditory structures influence processing in lower-level structures via the efferent auditory network called the corticofugal pathways. Such top-down influences back-project all the way to the cochlea through the medial olivocochlear bundle (MOCB). The functioning of MOCB can be noninvasively examined in humans by measuring the suppression of evoked otoacoustic emissions, which are sounds generated within the cochlea in response to acoustic stimulation. Electrical stimulation of the auditory cortex can modulate MOCB activity in human participants (Perrot et al., 2006). To study the role of top-down modulation on speech in noise perception, MOCB activity was examined in young participants who underwent a training program to discriminate speech presented in noisy environments (de Boer & Thorton, 2008). Interestingly, an increase in MOCB activity correlated with speech in noise performance in good perceivers. In fact, learning outcomes could be predicted by MOCB activity. The authors conclude that corticofugal feedback plays an important role during listening in noisy environments. In the context of previous animal and human studies that have examined the corticofugal pathway, it is possible that top-down modulation improves signal quality at the auditory periphery by selectively amplifying relevant features of the signal, and inhibiting irrelevant features in the presence of background noise. Recent studies have argued that children with learning problems show a deficit in the ability to modulate early sensory encoding of speech features. In contrast, studies also have suggested that musicians show a superior ability to modulate sensory representation based on top-down cues.

Top-Down Feedback Failure in Children with Learning Disabilities

Why do children with learning problems show deficits in noise-exclusion? According to the anchor-deficit hypothesis (Ahissar, 2007; Ahissar, Lubin, Putter-Katz, & Banai, 2006), children with reading problems are unable to use prior experience to improve auditory representation. The use of prior experience is important for noise-exclusion. Take the example of a conversation with a friend in a noisy bar. The ability to 'tag' the predictable element in this kind of environment, e.g., your friend's voice, plays an important role in determining successful communication (Brokx & Nooteboom, 1982). Children with learning problems, according to the anchor-deficit hypothesis, are unable to improve representation based on contextual demands. At a subcortical level, we found that typically developing children showed an enhanced representation of pitch features in a predictable context, relative to when speech sounds were presented in a unpredictable context (Chandrasekaran, Hornickel, Skoe, Nicol, & Kraus, 2009). The extent of this context-dependent modulation in the representation of pitch features positively correlated with speech in noise perception. In contrast, children with developmental dyslexia showed no improvement in the representation of pitch features in the predictable context. These children also showed reduced performance on a speech in noise perceptual task. Based on these findings, we argued that top-down contextual cues continuously improve processing of relevant speech features in typically-developing children (Chandrasekaran, Hornickel, et al., 2009). This ability is likely an important determiner of successful auditory perception in challenging listening environments.

Top-Down Selective Enhancement of Speech Features in Musicians

One of the mechanisms used to explain the findings of music-induced experience dependent plasticity at the level of the brainstem is increased efficiency of top-down predictive coding (Strait et al., 2010). Enhanced responses to native as well as non-native speech stimuli have been argued to be a result of an increased efficiency of the corticofugal network (Musacchia et al., 2007; Parbery-Clark, Skoe, et al., 2009; Patel & Iversen, 2007; Wong et al., 2007). Musicians showed enhanced induced gamma-band activity (GBA), which is oscillatory brain activity in the 25 Hz-100 Hz range. Induced GBA is argued to reflect integration of top-down and bottom-up sensory processing (Trainor, Shahin, & Roberts, 2009). One year of music training in children has been shown to increase induced GBA relative to untrained participants (Shahin, Roberts, Chau, Trainor, & Miller, 2008).

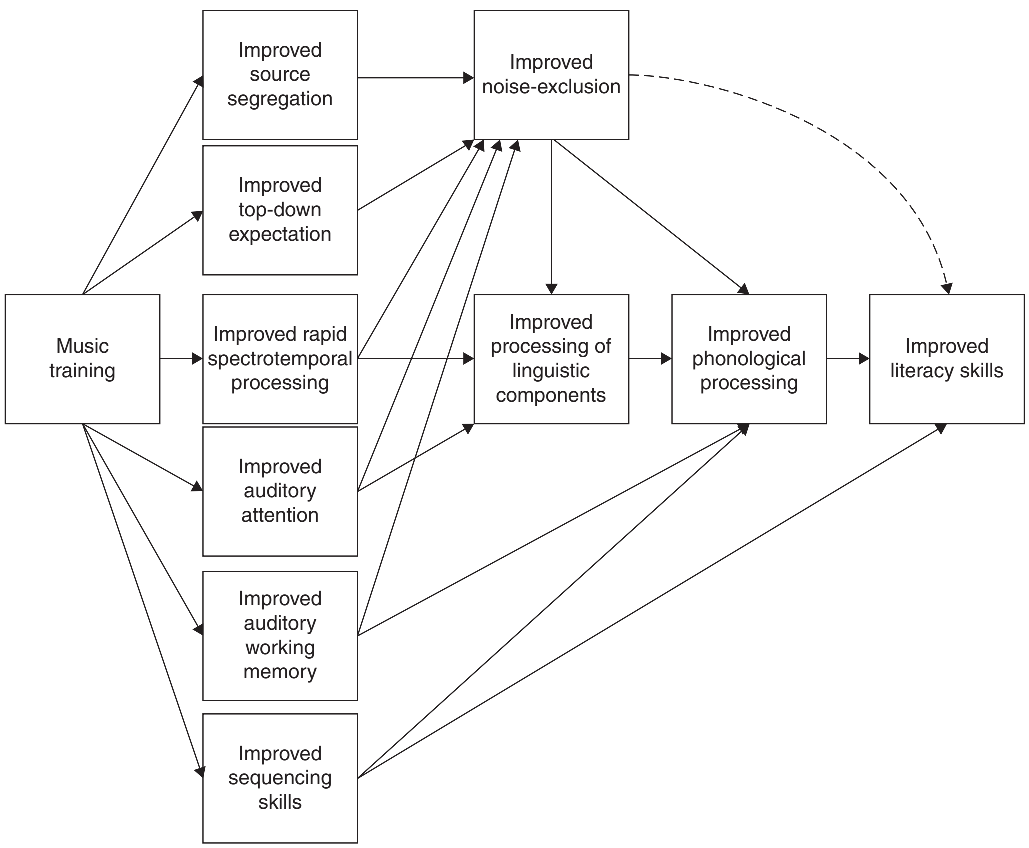

FIGURE 1. Modified from Tallal and Gaab (2006). Tallal and Gaab argue for an effect of music training on literacy skills routed through an improvement in auditory spectrotemporal processing, or via improved cognitive ability. Here we modify their model to include the possibility that improved noise-exclusion as a result of sensory and cognitive tuning in musicians can result in improved phonological processing and literacy skills. Music training improves sensory representation, sequencing skills, working memory, auditory attention, stream segregation, and top-down expectations. These cognitive and sensory skills are essential for noise-exclusion, which is found to be deficient in children with learning and literacy problems. We argue that improving these core skills via music training improves noise exclusion and may benefit literacy and learning ability.

These authors argue that GBA changes reflect increased efficiency of top-down processes, and that music has dramatic effects on cognitive-sensory interaction.

A Case for Music Training in Ameliorating Noise-Exclusion Deficits

A persuasive argument for the use of music as a rehabilitative aid for children with learning impairments has been made elsewhere (Habib & Besson, 2009; Overy, 2003; Tallal & Gaab, 2006). It has been argued that music training may improve rapid spectrotemporal processing that underlies the ability to process speech sounds, leading to improved literacy skills (Tallal & Gaab, 2006). This line of argument suggests a benefit only for individuals who show deficits in rapid spectrotemporal processing, but not all individuals with learning disabilities show sensory issues in quiet conditions (Ramus, 2001, 2004; Ramus et al., 2003). An underlying problem that exacerbates sensory processing is inadequate noise-exclusion (Ziegler et al., 2005; Ziegler et al., 2009). Here we propose that music may improve literacy skills through an enhancement of noise-exclusion ability mediated by improved auditory working memory, attention, sensory representation of key sound features, top-down expectation based processing, and stream segregation (Figure 1).

Indeed, more research is needed to design the most efficient treatment approach and to help make decisions on the type and length of music training required to bring about improvements in noise-exclusion ability. However, an improvement in noise-exclusion via music training seems logical given that musical experience benefits all the underlying skills necessary for successful communication in background noise; skills that pose threats to successful learning (Figure 2).

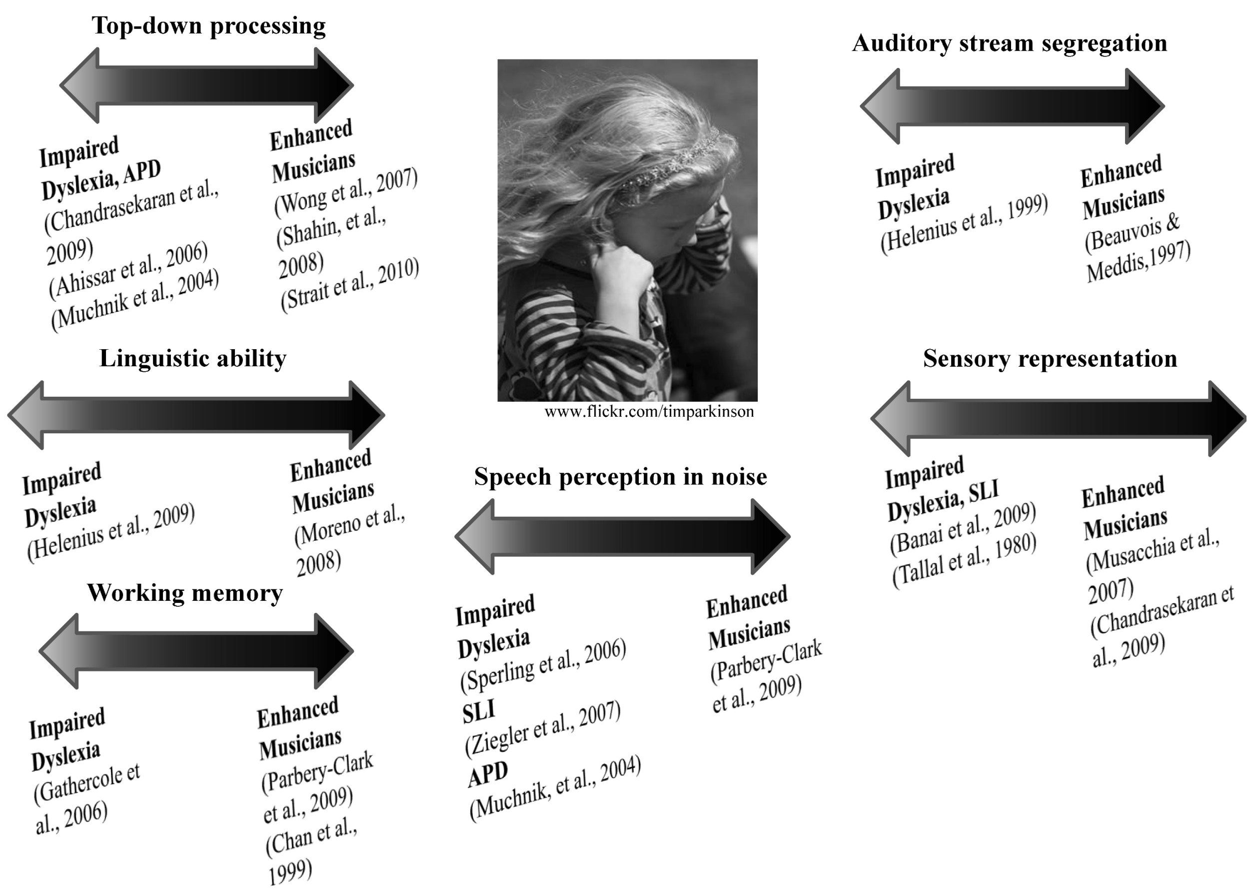

FIGURE 2. Components of speech perception in noise in individuals with learning impairment and those with musical experience. Multiple sensory and cognitive components are involved in speech perception in noise. Each of these components has been found to be deficient in children with learning/literacy disorders. These may contribute to impaired speech perception in noise in these children. The same cognitive and sensory skills are enhanced by musical experience leading to superior speech perception in noise ability in musicians.

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