5

Thinking Outside the Sound Booth: Assessing and Managing Auditory Processing Disorder in an Auditory-Cognitive Neuroscience Framework

Nina Kraus and Spencer B. Smith

Overview

Auditory processing disorder (APD) has traditionally been viewed within a *site-of-lesion* framework in which deficits are hypothesized to arise from impaired function of one or more specialized subunits of the auditory nervous system. This view is useful when examining patients with frank neurologic insults; however, in most cases of APD, no specific lesion can be found. In this chapter, we propose an *auditory-cognitive neuroscience framework* of auditory processing in which the "canonical" auditory pathway interfaces with cognitive, sensorimotor, and reward brain centers. Importantly, plasticity within this system can have *adaptive* or *maladaptive* consequences: auditory enrichment (e.g., musicianship or bilingualism) augments auditory-cognitive function while auditory deprivation (e.g., auditory-based learning disorders, poverty, or head injury) weakens it. Using a biomarker of auditory-cognitive function,

the frequency following response (FFR), we explore how both auditory expertise and disorder influence brain function. We conclude by offering suggestions for conducting auditory processing evaluations with the auditory-cognitive neuroscience framework in mind and review literature on remediation of auditory-based deficits using auditory training and FM systems.

Introduction

Professional and public awareness of auditory processing disorder (APD) has increased dramatically over the past two decades due to the collective efforts of expert task forces convened by the American Speech-Language-Hearing Association (ASHA) (2005 a, 2005b), American Academy of Audiology (AAA) (2010), and British Society of Audiology (BSA) (2011). Greater awareness, however, has not translated into greater clarity or clinician confidence regarding the etiology, diagnosis, and management of APD, and the disorder remains controversial. A survey of the APD literature suggests that this controversy arises in part from inadequate theoretical frameworks through which APD can be understood and empirically investigated (Cacace & McFarland, 2009, 2013; DeBonis & Moncrieff, 2008; Moore, 2006). For example, many clinical tools used to assess APD were developed by testing patients with frank neurological lesions, such as individuals with war-related head injuries, temporal lobe seizures/defects, and corpus callosectomies (Chermak & Musiek, 2013; Jerger, 2009). This *site-of-lesion* framework has been valuable in pinpointing areas of the brain involved in constituent aspects of auditory processing. However, in most cases of APD, a punctate site-of-lesion cannot be identified and the etiology may arise from a more diffuse combination of auditory and cognitive dysfunction (Bishop, Carlyon, Deeks, & Bishop, 1999; Hendler, Squires, & Emmerich, 1990; Jerger, Johnson & Loiselle, 1988; Moore, Ferguson, Edmondson-Jones, Ratib, & Riley, 2010; Moore, Rosen, Bamiou, Campbell, & Sirimanna 2013; Rappaport et al., 1994; Watson & Kidd, 2002).

Audition and cognition are tightly and reciprocally coupled; therefore, our view is that auditory-cognitive neuroscience can teach us a great deal about the nature of APD and how to remediate it (Banai & Kraus, 2007; Kraus & White-Schwoch, 2015; Moore et al., 2013; Musiek & Chermak, 2013; White-Schwoch & Kraus, 2017). We view the auditory-cognitive system as a distributed but integrated circuit in which the "canonical" auditory pathway provides a flexible scaffold that is shaped by cognitive interaction with sound over the lifespan. Importantly, the propensity of the auditory-cognitive system to *learn* can have *adaptive* or *maladaptive* consequences: auditory enrichment augments its function while auditory deprivation weakens it (Figure 5–1). Cases of both auditory expertise (e.g., musicianship) and disorder (e.g., auditory-based learning problems) provide insights into how different experiences mold auditory-cognitive system function and allow us to understand the nature of disorders as well as how training can positively impact the brain (White-Schwoch & Kraus, 2017). While an auditory-cognitive framework of APD may seem more abstract than a site-of-lesion framework to clinicians "in the trenches," it places diagnostic and remediation emphasis on deficits of *function* rather than *feature*. Therefore, the auditory-cognitive framework is very much in the spirit of recommendations from the abovementioned taskforces on APD in guiding "the development of more customized, *deficit-focused* intervention plans" (ASHA, 2005a).

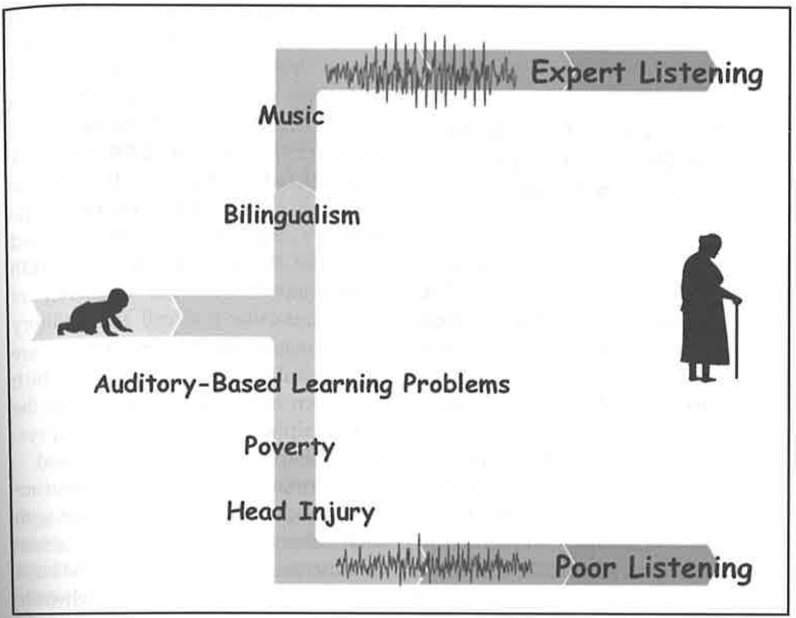

Figure 5–1. The auditory-cognitive system is shaped by adaptive or maladaptive learning over the lifespan. Adaptive learning supports expert listening, whereas maladaptive learning may underlie various disorders resulting in poor listening.

We begin this chapter by exploring the neural substrates of the auditory-cognitive system and discuss how neuroplasticity inherent to this system facilitates auditory learning. We then review how adaptive and maladaptive auditory learning across the lifespan have been evaluated in our lab using a combination of objective (i.e., electrophysiological) and subjective (i.e., behavioral) assessments. The chapter concludes with a proposed outline for APD evaluation that is guided by assessing the auditory-cognitive system holistically and some discussion of evidence-based interventions.

Learning and Plasticity in the Auditory-Cognitive System

Classic models of auditory processing posited that information proceeded sequentially through specialized stations of the auditory system with computational analysis becoming more complex at each ascending level (e.g., Webster, 1992). This view has been eroded to the point of near collapse by the preponderance of evidence demonstrating that the auditory system is bidirectional, highly interactive, and diffusely influenced by experience (Atiani, Elhilali, David, Fritz, & Shamma, 2009; Bajo, Nodal, Moore, & King, 2010; Bajo & King, 2012; Dragicevic et al., 2015; Fritz, Elhilali, David, & Shamma, 2007; Gao & Suga, 2000; Kraus & White-Schwoch, 2014; Leon Elgueda, Silva, Hamamé, & Delano, 2012; Mulders & Robertson, 2000; Ota, Oliver, & Dolan, 2004; Polley, Steinberg, & Merzenich, 2006; Rajan, 1990; Zhang & Dolan, 2006; Xiao & Suga, 2002).

Extensive afferent and efferent auditory pathways provide the neural scaffold for auditory learning to occur within a circuit from cochlea to cortex and back (see Celesia & Hickok, 2015 for an anatomical review). Perhaps some of the most compelling data on efferent modulatory effects on the afferent auditory system come from experiments in which auditory cortex or brainstem neurons were deactivated (either pharmacologically or temporarily via cryoloop cooling) or electrically stimulated in animal models. For example, cochlear outer hair cell and auditory nerve fiber function were modulated with activation or deactivation of the efferent system "upstream" in both the auditory brainstem and cortex (Dragicevic et al., 2015; Leon et al., 2012; Mulders & Robertson, 2000; Rajan, 1990; Ota et al., 2004; Zhang & Dolan, 2006). Further, the characteristic frequency of stimulated neurons in the auditory cortex (Xiao & Suga, 2002) and brainstem (Mulders & Robertson, 2000) corresponded with the frequency of maximum outer hair cell and auditory nerve fiber modulation. Such effects are demonstrative of the degree to which top-down influences can extend to the most peripheral sites in the auditory system to shape how sound is processed.

Importantly, afferent and efferent auditory pathways not only interact with each other but with cognitive, sensorimotor, and reward centers in the brain (Figure 5–2; Kraus & White-Schwoch, 2015); this combination is a potent force both for online modulation of auditory function and neural remodeling (Atiani et al., 2009; Bakin & Weinberger, 1996; Bidelman, Schug, Jennings, & Bhagat, 2014; Bidelman & Howell, 2016; Bidelman, Schneider, Heitzmann, & Bhagat, 2017; Chandrasekaran, Hornickel, Skoe, Nicol, & Kraus, 2014; Kilgard & Merzenich, 1998; Kraus & White-Schwoch, 2015; Perrot & Collet, 2014; Smith & Cone, 2015; Zatorre, Chen, & Penhune, 2007; Wittekindt, Kaiser, & Abel, 2014). While classic studies of auditory learning demonstrated that cortical sound representation could be altered by behavioral conditioning (Galambos, Sheatz, & Vernier, 1955), research from the intermediate years has demonstrated that, as long as the efferent auditory system is intact, learning can occur even in the auditory subcortex (e.g., Bajo et al., 2010; Gao & Suga, 2000). Further, performance improvements associated with auditory learning persist long after the cortical shifts facilitating these changes have disappeared (Reed et al., 2011), suggesting that although the cortex is important for *initiating* auditory learning by linking sound to meaning, the subcortex may act as a primary repository in which those meaningful relationships are stored and automatically activated (Atiani et al., 2009; Fritz et al., 2005; Kilgard, 2012).

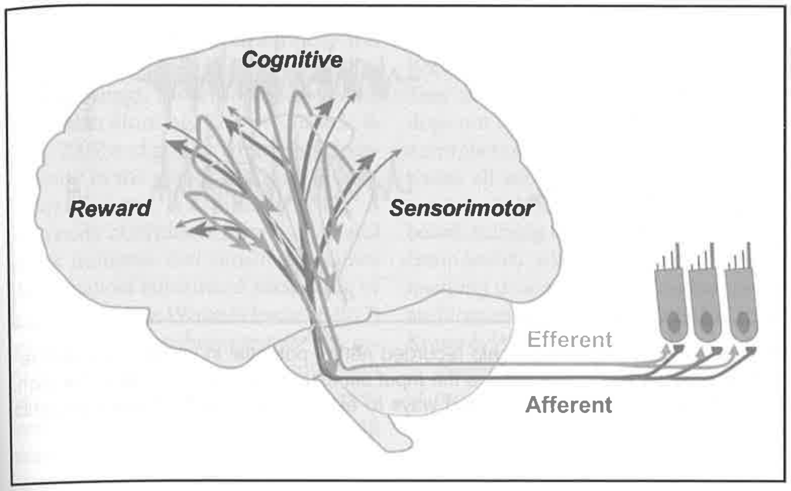

Figure 5–2. Afferent (gray) and efferent (blue) auditory systems provide the neural scaffolding for auditory-cognitive learning to occur. These pathways connect with cognitive, sensorimotor, and reward networks, which drive the process of learning. Adapted from Kraus & White-Schwoch, 2015.

Assessing Learning and Plasticity in the Human Auditory System

The primary approach that we have used to understand the human auditory-cognitive system and the effects of adaptive and maladaptive auditory learning is a neurobiological measure of brain function known as the frequency following response (FFR).[1] The FFR (Figure 5–3) is a sound-evoked electrical potential recorded from the scalp that is mainly generated by the inferior colliculus (Chandrasekeran & Kraus, 2012; Krishnan, 2002; Smith, Marsh, & Brown, 1975; Smith, Marsh, Greenberg, & Brown, 1978; Sohmer, Pratt, & Kinarti, 1977; but also see Coffey, Herholz, Chepesiuk, Baillet, & Zatorre, 2016). Unlike other auditory evoked potentials, the FFR physically resembles the evoking stimulus; it therefore captures the brain's representation of a multitude of speech (e.g.,

---

[1] The FFR has also been referred to by our lab and others as the "auditory brainstem response to complex sound" or cABR.

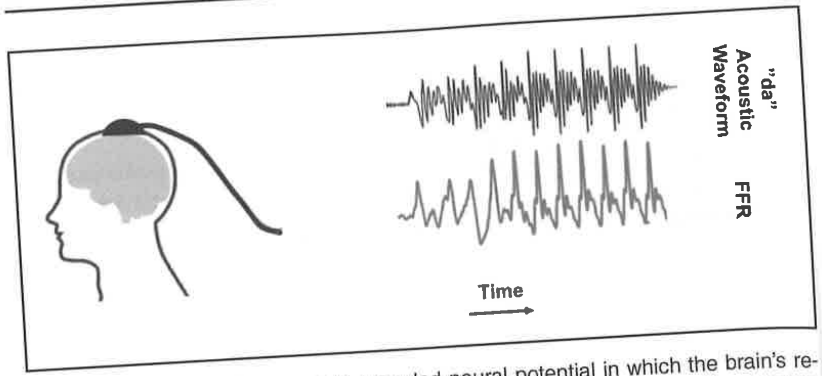

Figure 5–3. The FFR is a scalp recorded neural potential in which the brain's response (bottom waveform) mimics the input stimulus (top waveform) with precision. The FFR can be analyzed in myriad ways to extract how well the brain represents various aspects of sound.

voice pitch, harmonics, vowel formants, and consonant identities), music (e.g., pitch, timbre, attack, and consonance/dissonance), and other complex stimulus features. Further, FFRs can be assessed with regard to their stability and similarity to the input stimulus to discern the integrity, reproducibility, and quality of neural processing (see Skoe & Kraus, 2010 for an in-depth tutorial). Because the FFR is tightly coupled to a major convergence hub of multisensory afferent and efferent information in the inferior colliculus (Winer, 2006), it provides an extremely sensitive measure to study auditory learning due to both lifelong and short-term training experiences (Chandrasekaran, Skoe, & Kraus, 2014).

Adaptive Learning through Auditory Enrichment

Auditory enrichment contributes to greater neurobiological and cognitive function (Arnon et al., 2006; Engineer et al., 2004; Huttenlocher, 2009; Norena & Eggermont, 2005; Webb, Heller, Benson, & Lahav, 2015; White-Schwoch & Kraus, 2017). In our work, we have investigated the neural effects of auditory enrichment in musicians and bilinguals using the FFR (e.g., Krizman et al., Marian, Shook, Skoe, & Kraus, 2012; Skoe, Marian, & Kraus, 2014; Musacchia, Sams, Skoe, & Kraus, 2007; Strait, Parbery-Clark, Hittner, & Kraus, 2012; Wong, Skoe, Russo, Dees, & Kraus, 2007). In both instances, the auditory-cognitive system is more efficient at automatically processing specific aspects of sound through experience-related tuning of attention; the specific features that are accentuated through these types of enrichment, however, differ.

Musicianship

The effects of musical training on the brain are profound. In comparison to nonmusicians, lifelong musicians show structural brain differences including thicker gray matter in both auditory and motor cortices (Bangert & Schlaug, 2006; Elmer, Hänggi, Meyer, & Jäncke, 2013; Schneider, Sluming, Roberts, Bleeck, & Rupp 2005) and greater white matter connectivity in the corpus callosum (Steele, Bailey, Zatorre, & Penhune, 2013). A large body of evidence from our lab and others indicates that music experience also enhances subcortical processing of sound (Kraus & White-Schwoch, 2017) and that these enhancements are associated with myriad improvements in behavioral (e.g., speech-in-noise performance) and cognitive (e.g., working memory) domains (Kraus & Chandrasekaran, 2010).

Based on FFR studies, neural encoding of speech and music is more robust and temporally precise in musicians versus nonmusicians. Cross-sectional and longitudinal studies indicate that the length of musicianship is positively correlated with the size of these effects, suggesting that FFR differences are induced by *music experience* itself and are not solely innate (Habibi, Cahn, Damasio, & Damasio, 2016; Ilari, Keller, Damasio, & Habibi, 2016; Kraus, Hornickel, Strait, Slater, & Thompson, 2014; Musacchia et al., 2007; Tierney, Krizman, Skoe, Johnston, & Kraus, 2013; Krizman, & Kraus, 2015; Wong et al., 2007). FFR comparisons among different types of instrumentalists yields striking effects of experience. For example, piano players show stronger timbral encoding of a piano note (Figure 5–4) than non-piano players (Strait et al., 2012). The subcortical timbral and pitch sensitivities associated with musical specialization are preserved in cortical activity as well (Bidelman & Alain, 2015; Lee, Skoe, Kraus, & Ashley, 2009; Musacchia, Strait, & Kraus, 2008; Pantev, Roberts, Schulz, Engelien, & Ross, 2001; Shahin, Roberts, Chau, Trainor, & Miller, 2008). This demonstrates that musicianship does not shape auditory function with a simple volume knob effect that accentuates all aspects of sound; rather, the musician's brain is more like a mixing board, turning up behaviorally relevant components while minimizing others, resulting in specific neural signatures of auditory expertise (Kraus & Nicol, 2014; Kraus & White-Schwoch, 2017).

Importantly, the beneficial effects of music training on the brain are not specifically limited to musical skills but translate into listening and language skills. For example, musician FFRs to speech sounds are less degraded in the presence of reverberation and background noise, and this translates to better speech-in-noise perception across the life-span (Figure 5–5; Bidelman & Krishnan, 2010; Parbery-Clark, Skoe, Lam, & Kraus, 2009; Patel, 2011; Patel, 2014; Strait & Kraus, 2014; but also see Ruggles, Freyman, & Oxenham, 2014). Meaningful timing characteristics that allow for differentiation of consonants are more precisely represented in musicians versus nonmusicians of all ages (Kraus, Hornickel, Strait, Slater, & Thompson, 2014; Parbery-Clark, Anderson, Hittner, & Kraus, 2012a; Parbery-Clark, Tierney, Strait, & Kraus, 2012b; Strait, O'Connell, Parbery-Clark, & Kraus, 2013). Musicianship, or history of musicianship in childhood, offsets age-related decrements in neural processing and increases the consistency of the nervous system's response to sound (Pabery-Clark et al., 2012a; Pabery-Clark et al., 2012b; Skoe & Kraus, 2012; White-Schwoch, Carr, Anderson, Strait, & Kraus, 2013). Further, musicians' brains

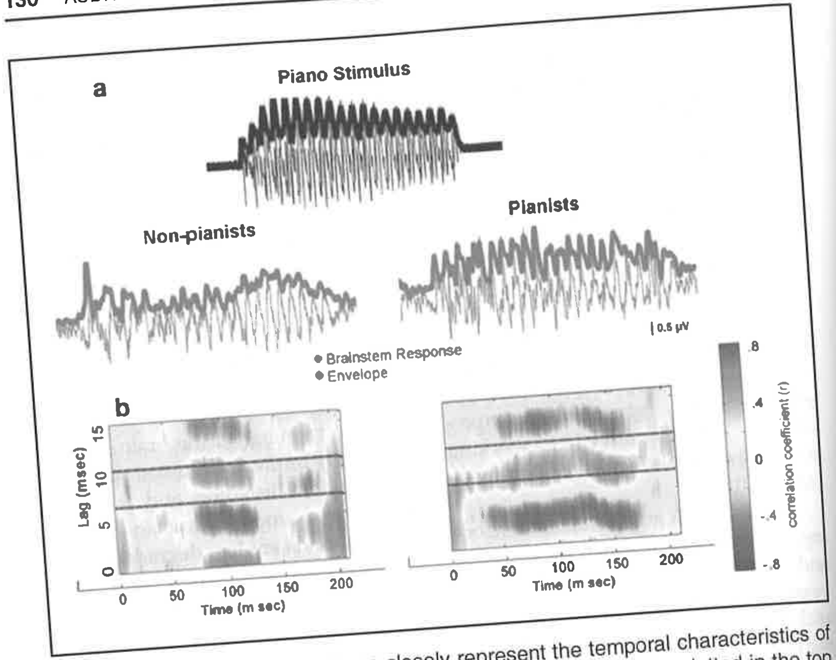

Figure 5–4. Pianists' FFRs more closely represent the temporal characteristics of a piano note than nonpianists. **A.** The waveform of a piano note is plotted in the top panel. FFRs (light red) from nonpianists (left) and pianists (right) are compared in the middle panel. Note that the major difference between groups is in the FFR temporal envelope (traced in dark red). **B.** The FFR temporal envelopes of nonpianists (left) are more poorly correlated with the piano note than pianists (right). Modified from Strait et al., 2012.

appear to benefit more from context and statistical predictability of sound than nonmusicians (Figure 5–6; Bidelman & Krishnan, 2010; Lee et al., 2009; Marmel Parbery-Clark, Skoe, Nicol, & Kraus, 2011; Parbery-Clark, Strait, Anderson, Hittner, & Kraus, 2011; Skoe et al., 2013a).

Taken together, these results indicate that musical experience shapes the brain to more effectively and automatically extract meaning from specific sound features. Many of the neural enhancements seen in musician brains are in domains that are impaired in disordered populations (e.g., temporal processing), suggesting that incorporating music into treatment for individuals with APD is an endeavor worth pursuing.

Bilingualism

Bilinguals must focus on connecting sounds to meaning in one language while suppressing the other. Through interaction with sound, the bilingual brain undergoes functional and structural changes in cortical language networks (Kim, Relkin, Kyoung-Min, & Hirsch, 1997; Crinion et al., 2006). Recent work from our lab indicates that bilinguals also show more robust and consistent subcortical encoding of speech fundamental frequency (Figure 5–7), which is known to be an important cue facilitating stream segregation and for indicating that a language switch has occurred (Altenberg & Ferrand, 2006; Krizman et al., 2012; Krizman, Slater, Skoe, Marian, & Kraus, 2015).

Much like musicianship, bilingualism also strengthens aspects of cognitive function, such as inhibitory control,

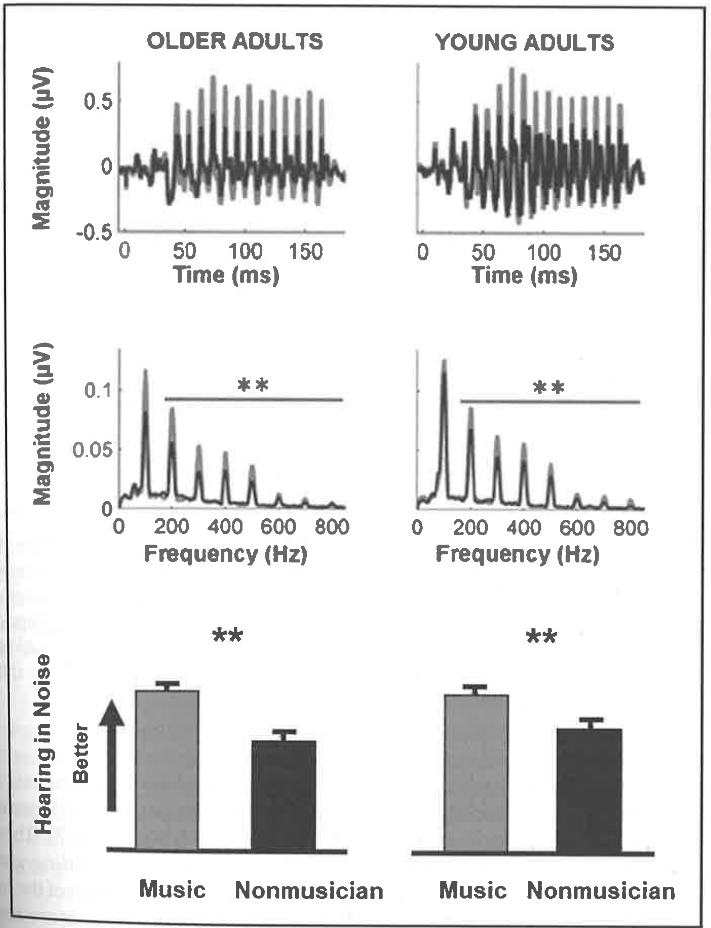

Figure 5–5. Musicians demonstrate more robust FFR waveforms (top) and spectral (middle) encoding of speech-in-noise than nonmusicians in both young and old age. These advantages are also seen in behavioral performance on a speech-in-noise task. (Musician = red; nonmusician = black).

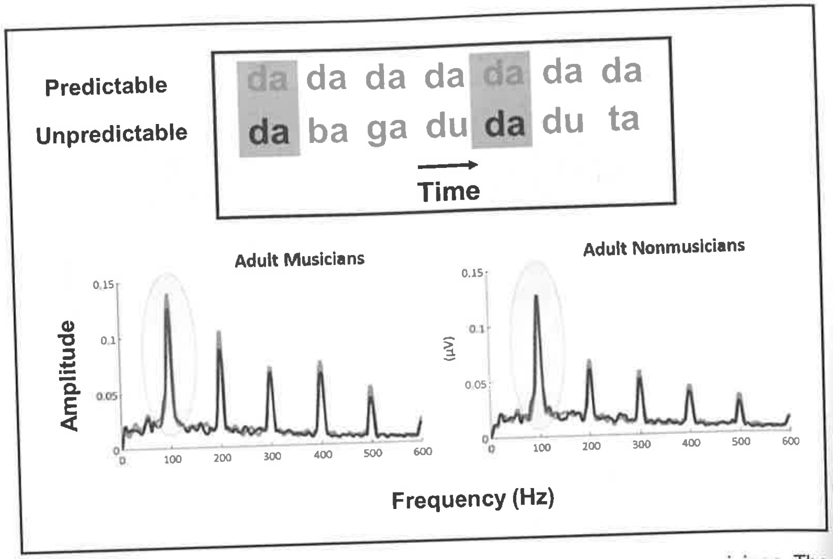

Figure 5–6. Musicians' brains benefit more from context than nonmusicians. The target stimulus /da/ was presented in predictable and nonpredictable sequences in two test conditions (top). FFRs to /da/ obtained in predictable versus nonpredictable conditions (gray boxes) were compared in musicians and nonmusicians. FFR spectra (bottom) demonstrated more robust fundamental frequency encoding in musicians when the stimulus was predictable (red) versus nonpredictable (black). This difference was not observed in nonmusicians.

auditory attention, and working memory (Bugos, Perlstein, McCrae, Brophy, & Bedenbaugh, 2007; Bialstyok, Craik, & Freedman, 2012; Kraus, Strait, & Parbery-Clark, 2012), and may offset age-related neural decline (Alladi et al., 2013; Bialystok et al., 2007). It has been suggested that these enhancements in cognitive function may drive changes in subcortical sound processing through efferent mechanisms (Ahissar, Nahum, Nelken, & Hochstein, 2009; Conway, Pisoni, & Kronenberger, 2009; Kraus & Chadrasekeran, 2010; Kraus et al., 2012; Nelkin & Ulanovsky, 2007). An interesting caveat to the auditory expertise of bilinguals is that, despite enhancements in neural and cognitive function, they perform *worse* than monolinguals on sentence in noise perception (Krizman, Bradlow, Lam, & Kraus, 2017). This is a seemingly paradoxical finding given that the neural representation of the fundamental frequency is also more resistant to noise than that of monolinguals (Figure 5–7B inset). When Krizman and colleagues (2017) investigated these differences further, they discovered that bilinguals outperformed monolinguals on a simple tone-in-noise task and both groups performed equally on a single word-in-noise task. Thus, the observed "disadvantage" of bilingualism only applied to sentences in noise. They hypothesized that this difference is likely due to the fact that in noise, words comprising sentences in one language may activate similar words in the other language's lexicon, thus interfering with performance on a task that requires rapid identification of word sequences. This complexity in bilingual expertise is an important consideration for remediation strategies, as the auditory and cognitive enhancements that come with learning a new language may be accompanied by functional trade-offs in certain situations, such as speech-in-noise perception.

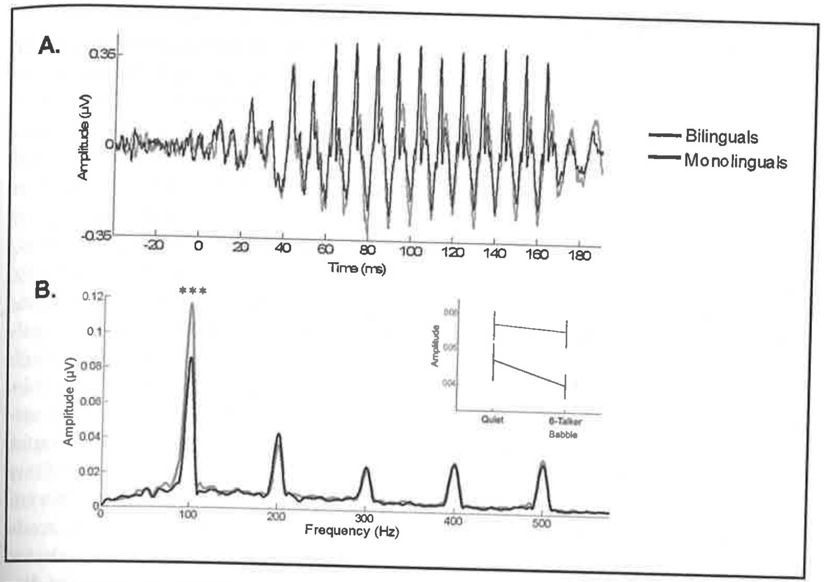

Figure 5–7. A. Bilinguals demonstrate more robust FFRs than monolinguals. **B.** This difference is mainly due to better fundamental frequency encoding in the bilingual brain. The FFR fundamental frequency is also more resilient to noise in bilinguals versus monolinguals (inset).

Maladaptive Learning through Auditory Deprivation

Continual practice with impaired representations of sound due to auditory-based learning disorders or head injury has a cascading negative effect on the entire auditory-cognitive system. Similarly, emerging evidence suggests that poverty, a form of sensory and cognitive deprivation, also has degradative effects on the auditory-cognitive system. In this section, we examine maladaptive auditory learning and review research from our lab and others suggesting that these three types of deprivation have systemic consequences on the auditory-cognitive system.

Auditory-Based Learning Disorders

The term *auditory-based learning disorder* (LD) broadly encompasses individuals with dyslexia/reading difficulty, specific language impairment (SLI), and APD. While this term is certainly far-reaching in scope, a common theme among the listed disorders is a core deficit in auditory processing (Kraus, McGee, Carrell, & Zecker, 1996; Tallal, 2004; Tazeau & Hamaguchi, 2013). Compared to their peers, LD children have demonstrated slower FFRs with less robust formant representation and poorer neural synchrony in response to the onset of speech sounds (Cunningham, Nicol, Zecker, Bradlow, & Kraus, 2001; King, Warrier, Hayes, & Kraus, 2002; Wible, Nicol, & Kraus, 2004). Further, the correlation between the FFRs of LD children and the evoking stimulus was poorer than their age-matched peers, especially in the presence of background noise. The disparity between LD children and their peers was also evident in cortical responses, demonstrating the systemic effects of LD on the auditory-cognitive system (Abrams, Nicol, Zecker, & Kraus, 2006; Cunningham et al., 2001; Wible, Nicol, & Kraus, 2005).

LD children with reading difficulty demonstrated slower FFR responses and poorer encoding of speech harmonics than their peers; however, fundamental frequency encoding was intact (Banai, K., Hornickel, J., Skoe, E., Nicol, T., & Kraus, 2009). Further, FFRs to the formant-transition components of different CV speech syllables were more poorly differentiated in reading impaired LD children versus their typical peers (Hornickel, Skoe, Nicol, Zecker, & Kraus, 2009). Tying electrophysiology to auditory-cognitive function, Anderson, Skoe, Chandrasekaran, and Kraus (2010) examined the relationship between noise-induced timing delays in the FFR, speech-in-noise perception, and reading skills. They found that children with greater noise-induced FFR timing shifts demonstrated both poorer speech-in-noise perception and reading fluency. Contrary to the abovementioned finding that musicians' brains benefit more from context and statistical predictability, the brains of LD children with reading disorders do not exploit these cues (Chandrasekeran, Hornickel, Skoe, Nicol, & Kraus, 2009). Collectively, these data suggest that auditory processing deficits underlying poor acquisition of reading skills are tied to variability, instability, and inconsistency in neural processing and inability to encode information unfolding over a rapid time course, such as formant transitions (Hornickel & Kraus, 2013). These data are in agreement with work in animal models of dyslexia demonstrating greater trial-to-trial variability and poorer discrimination ability in neural responses to speech sounds (Centanni et al., 2013; Centanni et al., 2014).

Children with SLI also show deficiencies in neural encoding and perception of rapidly changing sounds (Benasich & Tallal, 2002; Marler & Champlin, 2005). Basu, Krishnan, and Weber-Fox (2010) reported that the brains of children with SLI demonstrated poorer phase-locking to rapidly changing tonal stimuli than age-matched peers. Further, phase-locking deteriorated greatly in SLI children with increased stimulus presentation rates. In a small study by Rocha-Muniz, Befi-Lopes, and Schochat (2012), FFRs to the speech sound /da/ were recorded in typically developing, SLI, and APD children. Although the differences between groups were small, the authors reported that the FFRs of children with APD were characterized by timing deficiencies only, whereas FFRs of SLI children demonstrated both timing and spectral harmonic deficiencies. The degree to which neural signatures of various subtypes of LD can be differentiated for clinical diagnostic purposes is a question that is still being investigated; however, the broad and overlapping symptomologies of each disorder make this issue a difficult one to address. Importantly, the auditory-cognitive neuroscience framework places emphasis on identifying and remediating *functional* deficits. In this regard, the exactness of diagnosis in children with LD does not seem to be as important as addressing their primary complaints and symptoms in the absence of an occult lesion with thoughtful selection of remediation strategies. We view the FFR as an enormous step forward in determining whether sound is normally represented in the auditory system and, as discussed below, encourage its clinical use in this capacity.

Lastly, it is interesting to note that even disease processes thought to be transient in nature can leave a long-lasting legacy on auditory-cognitive function through maladaptive learning. For example, animal models of temporary conductive hearing loss have demonstrated that subcortical and cortical connectivity and function in the auditory system is disrupted by blocking the ear during critical periods of development (Takesian, Kotak, & Sanes, 2010; Webster, 1977; Webster & Webster, 1979; Xu, Kotak, & Sanes, 2007). In humans, a history of conductive hearing loss or aural atresia results in deficits in binaural processing and speech-in-noise performance long after the hearing loss has been remediated (Whitton & Polley, 2011). Presumably, individuals with this specific type of APD would be ideal candidates for auditory training or music therapy to restructure the auditory-cognitive system. To our knowledge, no work has been done using the FFR to evaluate individuals with history of conductive hearing loss who continue to demonstrate auditory processing deficits.

Poverty

The topic of poverty is perhaps an unintuitive addition to this text. Consider, however, that a child raised in a low socioeconomic status (SES) household hears 30 million fewer words and 60% less linguistic variety by age three than his or her peers (Hart & Risley, 1995). Further, residents in low SES neighborhoods have higher exposure to air, water, and noise pollution than residents in middle-class neighborhoods (Adler & Newman, 2002; Evans & Kantrowitz, 2002; Steptoe & Feldman, 2001). The former issue is important because air pollution is likely related to the higher incidence of middle ear disease in low SES children (Nittrouer & Burton, 2005), which, as mentioned above, continues to affect the auditory system long after the disease has been resolved. The latter issue is known not only to interfere with academic achievement (Goines & Hagler, 2007) and trigger physiologic stress responses (Evans, Bullinger, & Hygge, 1998), but it also reorganizes the brain through maladaptive auditory learning. In experimental animals, for example, background noise alters cochlear topographic maps during critical developmental periods (Eggermont & Komiya, 2000; Chang & Merzenich, 2003) and may also result in degeneration of auditory nerve fibers (Bharadwaj, Masud, Mehraei, Verhulst, &

Shinn-Cunningham, 2015; Kujawa & Liberman, 2009; Sergeyenko, Lall, Liberman, & Kujawa, 2013).

FFR studies demonstrate that low SES children of mothers with lower levels of education have less stable neural responses and poorer encoding of speech harmonics in comparison to their counterparts with higher maternal education (Skoe, Krizman, Anderson, & Kraus, 2013). Additionally, these children demonstrated robust stochastic (i.e., "noisier") neural activity at rest and poorer scores on reading and auditory working memory tests. The auditory-cognitive effects of SES appear to be offset by music training. For example, low SES children who engaged in music lessons showed improvement in neurophysiologic CV syllable distinction after engaging in two years of practice (Kraus et al., 2014; Kraus & White-Schwoch, 2017). This is commensurate with animal data indicating that auditory enrichment offsets the effects of maladaptive auditory learning due to nontraumatic noise exposure (Norena & Eggermont, 2005, 2006). Additional benefits of music practice extended to improvement in speech-in-noise perception and tests associated with reading fluency (Slater, Tierney, & Kraus, 2013; Strait, Skoe, O'Connell, 2014; Slater, Skoe, Strait, O'Connell, et al., 2015).

Head Injury

A variety of neurological insults, such as blast exposure or concussion, compromise auditory processing in complex soundscapes (e.g., Fausti, Wilmington, Gallun, Myers, & Henry, 2009). As described above, listening and interacting with sound involves coordination between components of diverse brain networks; an insult to any one component in these networks may degrade their total function. Using the FFR to explore how head injury impacts auditory processing and brain health is in its infancy. Preliminary studies from our lab demonstrate that children and collegiate football players who have sustained sports-related concussions show a reduction in the fundamental frequency component of the FFR (Kraus et al., 2017). This reduction is evident even after one concussion and partially recovers over time. In the case of children, the fundamental frequency component was used to correctly identify 90% of concussion cases and clear 95% of controls with no history of concussion. Our reports are consistent with those of Vander Werff and colleagues (2012, 2017) who found that FFR peak latencies were prolonged in individuals with long-term symptoms following mild traumatic brain injury. This nascent work holds promise for using the FFR to understand the biological consequences of head injury that lead to auditory processing and other deficits.

Key Questions to Guide APD Evaluations

Viewing APD through the lens of auditory-cognitive neuroscience places emphasis on holistic *function* of the auditory-cognitive system and therefore necessitates a multifaceted test battery approach. We believe that as doctoral-level professionals, audiologists are well equipped to employ such a battery incorporating basic hearing, electrophysiologic, and cognitive tests. In the following sections, we present questions that are aimed at guiding clinical assessment of individuals with APD within this framework and provide some suggestions for answering each question.

What Is the Patient's Primary Complaint?

Commonly reported complaints from individuals suspected of APD include distractibility and inattention to sounds, trouble following verbal instructions, and inordinate difficulty understanding speech in noise (AAA, 2010; ASHA, 2005a, 2005b; BSA, 2011). An imperative first step in assessing and managing APD is determining whether a patient complains of any or all of these problems. This information can be gleaned through case history and questionnaires that address functional aspects of auditory-cognitive processing. For adults, the latter may be in the form of the Speech, Spatial, and Qualities of Hearing Scale (SSQ; Gatehouse & Noble, 2004). For children, this may be a parental or teacher questionnaire assessing auditory behavior, such as The Listening Inventory (TLI; Geffner & Ross-Swain, 2006), the Auditory Behavior in Everyday Life (ABEL; Purdy, Farrington, Moran, Chard, & Hodgson, 2002), or Screening Instrument for Targeting Educational Risk (SIFTER; Anderson, 1989). An additional questionnaire to consider is the ADHD Rating Scale (DuPaul et al., 1998), which asks questions regarding the frequency of behaviors associated with ADHD. Given the comorbidity of APD and ADHD, results of the ADHD Rating Scale may be used to pinpoint the nature of the patient's listening deficits. Questionnaires provide structure to the information gathering process and demonstrate to patients and/or their families that the clinician has an organized approach for conducting an APD evaluation (Musiek & Chermak, 2013). Further, they zero in on specific aspects of auditory processing that are challenging for a particular patient.

Is Sound Getting In?

Fortunately, audiologists are highly proficient with techniques designed to answer this question, and pure tone audiometry, tympanometry, acoustic reflex threshold testing, otoacoustic emissions, and auditory brainstem response measurements are staples of the standard audiologic toolkit (Gelfand, 2009). When a patient enters the clinic with the primary complaint of auditory processing difficulty, a prerequisite question before moving forward with APD testing is whether he or she has medically treatable and/or audiologically manageable hearing loss (ASHA, 2005; AAA, 2010). In addition to a traditional audiogram, we also recommend testing extended high frequency hearing thresholds (8–20 kHz) for the following reasons. Extended high frequency energy is important for listening in noisy, reverberant rooms and impairments in this range provide an early indication of progressive or potentially preventable hearing loss (Badri, Siegel, & Wright, 2011; Besser, Festen, Goverts, Kramer, & Pichora-Fuller, 2015; Collins, Cullen, & Berlin, 1981; Hunter et al., 1996; Moore et al., 2017; Vitela, Monson, & Lotto, 2015). Further, extended high frequency hearing loss may be a telltale sign of "hidden hearing loss"—that is, listening difficulty in the presence of normal hearing on a standard audiogram (Liberman, Epstein, Cleveland, Wang, & Maison, 2016).

How Precisely Is Sound Being Processed in the Brain, and Is there Evidence of Biological Dysfunction?

Earlier in this chapter, we presented evidence that the FFR is a biological index of auditory processing. Further, it has been successfully used to explore different types of auditory learning and to assess the auditory-cognitive system. In the context of clinical APD testing, the FFR can be used to assess whether a biological dysfunction in how sound is processed underlies behavioral complaints. Further, the FFR can be used to track training-related changes in biological function.

We believe that the FFR is ready for clinical use *now* and that it would augment the APD test battery. Using a 40 ms /da/ stimulus and a recording protocol similar to the auditory brainstem response, FFRs can be collected from patients in under 10 minutes (Skoe & Kraus, 2010). Responses to this stimulus have high test-retest reliability, and normative data for FFRs from birth to 72 years have been published (Skoe et al., 2015). We suggest that assessing three domains of the FFR (Table 5–1) is sufficient and appropriately expedient for clinical use: (1) *FFR peak timing* is a metric that allows the tester to assess how quickly speech is processed in the brain. The six characteristic peaks of the FFR to a short /da/ stimulus that represent the onset, transition, and steady state portions of the token can also be compared to published norms. (2) *Fundamental frequency amplitude* can be evaluated in the FFR spectrum. This feature tracks with speech-in-noise performance across the lifespan (Anderson, Skoe, Chandrasekaran, & Kraus, 2010; White-Schwoch, Parbery-Clark, & Kraus, 2013) and has been shown to improve with speech-in-noise training (Song, Skoe, Banai, & Kraus, 2012). (3) *Response consistency* is a measurement of how correlated the first half of FFR response sweeps are to the second half. This is thought to be an indication of overall auditory processing health and correlates with language and attention skills (Hornickel & Kraus, 2013). Deficiencies in one or more of these metrics is indicative of dysfunction in how sound is encoded. A normal FFR in a patient complaining of APD symptoms may indicate that the disorder may lie outside the resolution of the test (e.g., distractibility). Importantly, many other stimuli can be used to evoke FFRs (Skoe & Kraus, 2010); research will likely continue to reveal more effective stimuli for clinically resolving differences between normal and impaired listeners (i.e., FFRs to speech in noise).

Table 5–1. FFR Domains Suggested for Clinical Use

FFR Analysis Parameter	Purpose
Peak timing	FFR absolute peak latencies can be compared to published norms to assess abnormalities in neural timing.
Fundamental Frequency	Transforming the FFR waveform into the frequency domain produces a spectrum. The spectral amplitude corresponding to the fundamental frequency can be compared to published norms to assess the strength of neural encoding.
Response Consistency	Correlating FFR waveforms calculated from the first half of sweeps to the last half of sweeps provides a value between 0–1. A value of 0 means that the waveforms are not at all correlated, whereas a value of 1 means responses are perfectly correlated. Poorly correlated waveforms indicate poor response consistency.

How Well Does a Listener Extract Meaning from Sound?

This question can be answered using a battery of assessments (Table 5–2). First, a simple nonlinguistic test assessing temporal resolution is appropriate to assess whether listeners can identify an auditory target in simultaneous or backward masking. One such example is the IMAP temporal resolution (or "tone-in-noise") test (Barry, Ferguson, & Moore, 2010). Second, speech-in-noise tests, such as the QuickSIN (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004), Hearing in Noise Test (HINT;

Table 5–2. Suggested Cognitive Tests for APD Evaluations

Domain	Test	Purpose
Audition	• IMAP Temporal Resolution Test (5 min.) • QuickSIN, HINT, or SCAN Auditory Figure-Ground Subtest (5 min.)	To assess listener's ability to extract meaning from simple and complex sound in degraded situations
Attention	• NIH Toolbox Flanker Inhibitory Control and Attention Test (3 min.) OR • IMAP Cued Attention Test (10 min.)	To assess patient's sustained attention and ability to inhibit superfluous information
Working memory	• NIH Toolbox List Sorting Working Memory Test (7 min.) OR • Woodcock-Johnson Auditory Working Memory Test (7 min.)	To assess patient's ability to remember visual and auditory sequences

Nilson, Soli, & Sullivan, 1994), or Auditory Figure-Ground Subtest of the SCAN-C (Keith, 2000), provide useful information regarding the degree of difficulty that patients experience when listening in noisy environments. The latter two tests are more appropriate for younger children, as they are normed to 6 and 5 years of age, respectively. Interestingly, Anderson, Parbery-Clark, White-Schwoch, and Kraus (2012) reported that FFR measures are more predictive of patient *self-perceived* speech-in-noise difficulty on the SSQ than the QuickSIN. This finding emphasizes the importance of using a test battery approach in the evaluation of individuals with suspected APD.

Given the tight coupling of audition and cognition, we also recommend tests assessing cognitive function. Table 5–2 lists normed tests from the NIH Toolbox (www.nihtoolbox.com) (Woodcock & Johnson, 1989) and IMAP suite (Barry et al., 2010) that assess specific domains of cognitive function pertinent to an APD battery. Cognitive testing may shed light on specific aspects of auditory-cognition (e.g., auditory attention) that require remediation. Further, they may guide audiologists in making appropriate referrals to other professionals, such as psychologists or speech-language pathologists.

An Auditory-Cognitive Neuroscience Approach to APD Remediation

The discussion regarding APD evaluation above was centered on assessing the *functional* aspects of auditory-cognitive processing. Ideally, using a protocol similar to the one mentioned above will yield specific aspects of dysfunction that can be targeted for remediation. In this section, we review some evidence indicating that auditory training has both neural and behavioral benefits that are generalizable to other skills. Further, we discuss evidence supporting the use of FM systems for individuals with auditory-cognitive deficits, as these devices are instrumental in helping users forge links between sound and meaning by directing attention to important signals in the environment.

Auditory Training Effects on Neural and Behavioral Function

Changes in neural function have been observed after repeated practice with computer-based and lab-based training programs in both children and adults (Chandrasekaran, Kraus, & Wong, 2012; de Boer & Thornton, 2008; Merzenich et al., 1996; Moore, Rosenberg, & Coleman, 2005; Song, Skoe, Banai, & Kraus, 2011; Song, Skoe, Wong, & Kraus, 2008; Tallal et al., 1996; Tremblay et al., 1997). For example, training on speech discrimination increased cortical sensitivity to previously indistinguishable contrasts in young adults (Tremblay, Kraus, Carrell, & McGee, 1997). This training also generalized to untrained contrasts. Following Fast ForWord training, children with learning impairments who initially demonstrated abnormal cortical activity during rhyming tasks or in response to rapidly presented stimuli had larger and more typical activity during these tasks (Gaab, Gabrieli, Deutsch, Tallal, & Temple, 2007; Temple et al., 2003).

Training-related plasticity has also been demonstrated in the auditory subcortex. Young adults who participated in Listening and Communication Enhancement (LACE) training demonstrated more resilient FFRs in noise as well as improved speech-in-noise perception (Song et al., 2011). After participating in Earobics, LD children also showed more robust FFRs to speech presented in background noise (Russo, Nicol, Zecker, Hayes, & Kraus, 2005). LD children who initially had abnormal FFR timing showed improved cortical responses to speech after playing Earobics and improved speech sound discrimination that resembled that of typically developing children (Hayes, Warrier, Nicol, Zecker, & Kraus, 2003; King et al., 2002). Children with LD who did not initially have abnormal FFRs did not show this change in cortical activity with training (Hayes et al., 2003), suggesting that the FFR may be useful for predicting who will benefit from auditory training regimens.

Auditory training also yields *behavioral* benefits in both trained and untrained auditory processes. For example, typically developing and LD children who participated in speech-sound discrimination training (Phonomena and Fast ForWord programs, respectively) showed gains on measures of cognitive language ability, such as phonological awareness, that were not explicitly trained (Merzenich et al., 1996; Moore et al., 2005; Tallal et al., 1996). These gains were maintained for six months after training ceased (Moore et al., 2005) and, in the case of LD children, performance improved to age-appropriate levels (Merzenich et al., 1996; Tallal et al., 1996).

Neural and Behavioral Benefits of FM Systems

Frequency-modulation (FM) systems are commonly prescribed treatment devices for children with APD (Chermak, 2002; Keith, 1999). FM systems reduce the impact of background noise on the auditory signal by directly transmitting microphone input to a headset or monitor speaker, effectively enhancing the signal-to-noise ratio for the listener (Crandell, Smaldino, & Flexer, 2005). Friederichs and Friederichs (2005) reported enhancements in neural markers of attention after one year of FM system use by children with APD. Electrophysiological responses to infrequently presented attended tones were enhanced, suggesting more robust neural activity reflecting attention after FM system use. These neural enhancements coincided with improved frequency discrimination and teacher-rated attentiveness, supporting the idea that FM systems reinforce sound-to-meaning relationships. No changes were seen for children with APD who did not wear the FM system.

FFR enhancement has also been observed in children with reading impairments following FM system use for one academic year. Children who wore an FM system showed more consistent FFRs throughout the recording session, whereas control children in the same academic environment did not (Hornickel et al., 2012). These training-related effects were restricted to the FFR formant transition. Further, children with the poorest FFR consistency at pretest showed the greatest benefit from the FM system and the largest gains in phonological awareness. Thus, FM systems appear to address neural variability and timing deficits by directing and enhancing auditory attention to meaningful sounds through enhanced signal-to-noise ratios.

FM systems can also benefit behavior and academic performance (Blake, Field, Foster, Platt, & Wertz, 1991; DiSarno, Schowalter, & Grassa, 2002; Purdy et al., 2009; Rosenberg et al., 1999). After 6 weeks of use, teachers rated students with reading delays who used an FM system as having better classroom attention skills and the students rated their own hearing in difficult situations as better (Purdy, Smart, Baily, & Sharma, 2009). Children with APD who wore classroom FM systems improved on parent and teacher ratings of academic performance and psychosocial function (Johnston, John, Kreisman, Hall, & Crandell, 2009). Additionally, they improved on perception of speech in background noise when using the FM system and perceiving speech in quiet without the FM system, reaching the same levels as their typically developing peers.

Summary

In this chapter, we proposed that the auditory-cognitive system is a distributed but integrated circuit that can be adaptively or maladaptively shaped by experience over the lifespan. Within this framework, auditory expertise and disorder can be viewed along the same continuum of auditory learning. Using a biomarker of auditory-cognitive function, we provided evidence that auditory enrichment augments this system, while deprivation weakens it. We put forth a test battery approach that allows clinicians to examine basic hearing, neurophysiologic, and cognitive function to holistically assay the auditory-cognitive system. Lastly, we demonstrated that remediation strategies for auditory-based learning disorders, such as auditory training and FM systems, show positive impacts on the brain and behavior. Future work will further address the effectiveness of music training or therapy for remediating issues like APD.

Key Points Learned

- Plasticity in the auditory-cognitive system can have adaptive or maladaptive consequences resulting in auditory expertise or disorder. The FFR, an objective test of auditory function, is sensitive to measuring such changes due to plasticity.
- Musicians and bilinguals provide models of auditory expertise, and aspects of their FFR (e.g., fundamental frequency) and cognitive function (e.g., auditory attention) are enhanced through engagement with sound.
- Auditory-based learning disorders, poverty, and head trauma provide models of auditory dysfunction, which is captured by the FFR and is reflected in poor performance on auditory tests.
- Viewing assessment and management of APD patients through an auditory-cognitive framework emphasizes the interplay between audition and cognition and thus necessitates a holistic test battery. The power of neuroplasticity may be harnessed to remediate APD, but this requires more investigation.

Acknowledgments. This work was supported by the National Institute of Child Health and Human Development (#HD069414), National Association of Music Merchants (http://www.namm.org/), the Knowles Hearing Center (http://comm.soc.northwestern.edu/knowles-hearing-center/), and Med-El.

References

Abrams, D. A., Nicol, T., Zecker, S. G., & Kraus, N. (2006). Auditory brainstem timing predicts cerebral asymmetry for speech. *The Journal of Neuroscience, 26*(43), 11131–11137.

Adler, N. E., & Newman, K. (2002). Socioeconomic disparities in health: pathways and policies. *Health Affairs, 21*(2), 60–76.

Ahissar, M., Nahum, M., Nelken, I., & Hochstein, S. (2009). Reverse hierarchies and sensory learning. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 364*(1515), 285–299.

Alladi, S., Bak, T. H., Duggirala, V., Surampudi, B., Shailaja, M., Shukla, A. K., . . . & Kaul, S. (2013). Bilingualism delays age at onset of dementia, independent of education and immigration status. *Neurology, 81*(22), 1938-1944.

Altenberg, E. P., & Ferrand, C. T. (2006). Fundamental frequency in monolingual English, bilingual English/Russian, and bilingual English/Cantonese young adult women. *Journal of Voice, 20*(1), 89–96.

American Academy of Audiology (2010). Diagnosis, treatment and management of children and adults with central auditory processing disorder [Clinical Practice Guidelines]. Retrieved from www.audiology.org/resources/documentlibrary/Documents/CAPD Guidelines 82010.pdf.

American Speech-Language-Hearing Association (2005a). (Central) auditory processing disorders [Technical Report]. Retrieved from http://www.asha.org/docs/html/TR2005-00043.html

American Speech-Language-Hearing Association (2005b). (Central) auditory processing disorders—The role of the audiologist [Position Statement]. Retrieved from http://www.asha.org/docs/html/PS2005-00114.html

Anderson, S., Skoe, E., Chandrasekaran, B., & Kraus, N. (2010). Neural timing is linked to speech perception in noise. *The Journal of Neuroscience*, *30*(14), 4922–4926.

Anderson, S., Parbery-Clark, A., White-Schwoch, T., & Kraus, N. (2012). Aging affects neural precision of speech encoding. *The Journal of Neuroscience*, *32*(41), 14156–14164.

Anderson, S., White-Schwoch, T., Parbery-Clark, A., & Kraus, N. (2013). A dynamic auditory-cognitive system supports speech-in-noise perception in older adults. *Hearing Research*, *300*, 18–32.

Anderson, K. L. (1989). *SIFTER: Screening Instrument for Targeting Educational Risk in Children Identified by Hearing Screening Or who Have Known Hearing Loss: User's Manual*. Interstate Printers & Publishers, Danville, IL.

Arnon, S., Shapsa, A., Forman, L., Regev, R., Bauer, S., Litmanovitz, I., & Dolfin, T. (2006). Live music is beneficial to preterm infants in the neonatal intensive care unit environment. *Birth*, *33*(2), 131–136.

Atiani, S., Elhilali, M., David, S. V., Fritz, J. B., & Shamma, S. A. (2009). Task difficulty and performance induce diverse adaptive patterns in gain and shape of primary auditory cortical receptive fields. *Neuron*, *61*(3), 467–480.

Badri, R., Siegel, J. H., & Wright, B. A. (2011). Auditory filter shapes and high-frequency hearing in adults who have impaired speech in noise performance despite clinically normal audiograms a. *The Journal of the Acoustical Society of America*, *129*(2), 852–863.

Bajo, V. M., Nodal, F. R., Moore, D. R., & King, A. J. (2010). The descending corticocollicular pathway mediates learning-induced auditory plasticity. *Nature Neuroscience*, *13*(2), 253–260.

Bajo V. M., King, A. J. (2012) Cortical modulation of auditory processing in the midbrain. *Front Neural Circuits*, *6*, 114.

Bakin, J. S., & Weinberger, N. M. (1996). Induction of a physiological memory in the cerebral cortex by stimulation of the nucleus basalis. *Proceedings of the National Academy of Sciences*, *93*(20), 11219–11224.

Bangert, M., Schlaug, G. (2006). Specialization of the specialized in features of external human brain morphology. *Eur. J. Neurosci*. 24(6), 1832–1834.

Banai, K., & Kraus, N. (2007). Neurobiology of (central) auditory processing disorder and language-based learning disability. *Handbook of (Central) Auditory Processing Disorder*, *1*, 89–116.

Banai, K., Hornickel, J., Skoe, E., Nicol, T., Zecker, S., & Kraus, N. (2009). Reading and subcortical auditory function. *Cerebral Cortex*, *19*(11), 2699–2707.

Barry, J. G., Ferguson, M. A., & Moore, D. R. (2010). Making sense of listening: The IMAP test battery. *Journal of Visualized Experiments: JoVE* (44).

Basu, M., Krishnan, A., & Weber-Fox, C. (2010). Brainstem correlates of temporal auditory processing in children with specific language impairment. *Developmental Science*, *13*(1), 77–91.

Baum, A., Garofalo, J. P., & Yali, A. N. N. (1999). Socioeconomic status and chronic stress: does stress account for SES effects on health? *Annals of the New York Academy of Sciences*, *896*(1), 131–144.

Benasich, A. A., & Tallal, P. (2002). Infant discrimination of rapid auditory cues predicts later language impairment. *Behavioural Brain Research*, *136*(1), 31–49.

Besser, J., Festen, J. M., Goverts, S. T., Kramer, S. E., & Pichora-Fuller, M. K. (2015). Speech-in-speech listening on the LiSN-S test by older adults with good audiograms depends on cognition and hearing acuity at high frequencies. *Ear and Hearing*, *36*(1), 24–41.

Bharadwaj, H. M., Masud, S., Mehraei, G., Verhulst, S., & Shinn-Cunningham, B. G. (2015). Individual differences reveal correlates of hidden hearing deficits. *Journal of Neuroscience*, *35*(5), 2161–2172.

Bialystok, E., Craik, F. I., & Freedman, M. (2007). Bilingualism as a protection

against the onset of symptoms of dementia. *Neuropsychologia*, *45*(2), 459–464.

Bidelman, G. M., & Krishnan, A. (2010). Effects of reverberation on brainstem representation of speech in musicians and non-musicians. *Brain Research*, *1355*, 112–125.

Bidelman, G. M., Schug, J. M., Jennings, S. G., & Bhagat, S. P. (2014). Psychophysical auditory filter estimates reveal sharper cochlear tuning in musicians. *The Journal of the Acoustical Society of America*, *136*(1), EL33–EL39.

Bidelman, G. M., & Alain, C. (2015). Musical training orchestrates coordinated neuroplasticity in auditory brainstem and cortex to counteract age-related declines in categorical vowel perception. *Journal of Neuroscience*, *35*(3), 1240–1249.

Bidelman, G. M., & Howell, M. (2016). Functional changes in inter- and intra-hemispheric cortical processing underlying degraded speech perception. *NeuroImage*, *124*, 581–590.

Bidelman, G. M., Schneider, A. D., Heitzmann, V. R., & Bhagat, S. P. (2017). Musicianship enhances ipsilateral and contralateral efferent gain control to the cochlea. *Hearing Research*, *344*, 275–283.

Bishop, D. V., Carlyon, R. P., Deeks, J. M., & Bishop, S. J. (1999). Auditory temporal processing impairment: Neither necessary nor sufficient for causing language impairment in children. *Journal of Speech, Language, and Hearing Research*, *42*, 1295–1310.

Blake, R., Field, B., Foster, C., Platt, F., & Wertz, P. (1991). Effect of FM auditory trainers on attending behaviors of learning-disabled children. *Language, Speech, and Hearing Services in Schools*, *22*, 111–114.

British Society of Audiology. (2011). Auditory Processing Disorder Steering Committee Interim Position Statement on APD [Position Statement]. Retrieved from http://www.thebsa.org.uk/wpcontent/uploads/2014/04/BSA_APD_PositionPaper_31March11_FINAL.pdf

Bugos, J. A., Perlstein, W. M., McCrae, C. S., Brophy, T. S., & Bedenbaugh, P. H. (2007). Individualized piano instruction enhances executive functioning and working memory in older adults. *Aging and Mental Health*, *11*(4), 464–471.

Cacace, A., & McFarland, D. (2009). *Controversies in central auditory processing disorder*. San Diego, CA: Plural.

Cacace, A. T., & McFarland, D. J. (2013). Factors influencing tests of auditory processing: A perspective on current issues and relevant concerns. *J Am Acad Audiol*, *24*, 572–589.

Celesia, G., & Hickok, G. (2015). Auditory pathways: anatomy and physiology. *The Human Auditory System: Fundamental Organization and Clinical Disorders*, *129*, 3.

Centanni, T. M., Booker, A. B., Sloan, A. M., Chen, F., Maher, B. J., Carraway, R. S., . . . Kilgard, M. P. (2013). Knockdown of the dyslexia-associated gene Kiaa0319 impairs temporal responses to speech stimuli in rat primary auditory cortex. *Cerebral Cortex*, *24*(7), 1753–1766.

Centanni, T. M., Chen, F., Booker, A. M., Engineer, C. T., Sloan, A. M., Rennaker, R. L., . . . Kilgard, M. P. (2014). Speech sound processing deficits and training-induced neural plasticity in rats with dyslexia gene knockdown. *PLoS One*, *9*(5), e98439.

Chandrasekaran, B., & Kraus, N. (2010). The scalp recorded brainstem response to speech: Neural origins and plasticity. *Psychophysiology*, *47*(2), 236–246.

Chandrasekaran, B., Hornickel, J., Skoe, E., Nicol, T., & Kraus, N. (2009). Context-dependent encoding in the human auditory brainstem relates to hearing speech in noise: Implications for developmental dyslexia. *Neuron*, *64*, 311–319.

Chandrasekaran, B., & Kraus, N. 2012. Biological factors contributing to reading ability: Subcortical auditory function. In A. A. Benasich & R. H. Fitch (Eds.), *Developmental dyslexia: Early precursors, neurobehavioral markers and biological substrates*.

Chandrasekaran, B., Kraus, N., & Wong, P. C. (2012). Human inferior colliculus activity relates to individual differences in spoken language learning. *Journal of Neurophysiology, 107*(5), 1325–1336.

Chandrasekaran, B., Skoe, E., & Kraus, N. (2014). An integrative model of subcortical auditory plasticity. *Brain Topography, 27*(4), 539–552.

Chang, E. F., & Merzenich, M. M. (2003). Environmental noise retards auditory cortical development. *Science, 300*(5618), 498–502.

Chermak, G. D. (2002). Deciphering auditory processing disorders in children. *Otolaryngologic Clinics of North America, 35*, 733–749.

Chermak, G. D., & Musiek, F. E. (Eds.). (2013). *Handbook of Central Auditory Processing Disorder, Volume II: Comprehensive Intervention* (Vol. 2). Plural Publishing.

Coffey, E. B., Herholz, S. C., Chepesiuk, A. M., Baillet, S., & Zatorre, R. J. (2016). Cortical contributions to the auditory frequency-following response revealed by MEG. *Nature Communications, 7*.

Collins, M. J., Cullen, J. K., & Berlin, C. I. (1981). Auditory signal processing in a hearing-impaired subject with residual ultra-audiometric hearing. *Audiology, 20*(4), 347–361.

Conway, C. M., Pisoni, D. B., & Kronenberger, W. G. (2009). The importance of sound for cognitive sequencing abilities: The auditory scaffolding hypothesis. *Current Directions in Psychological Science, 18*(5), 275–279.

Crandell, C. C., Smaldino, J. J., & Flexer, C. (Eds.). (2005). *Sound field amplification: applications to speech perception and classroom acoustics* (2nd ed.). Clifton Park, NY: Thomson Delmar Learning.

Crinion, J., Turner, R., Grogan, A., Hanakawa, T., Noppeney, U., Devlin, J. T., . . . Usui, K. (2006). Language control in the bilingual brain. *Science, 312*(5779), 1537–1540.

Cunningham, J., Nicol, T., Zecker, S. G., Bradlow, A., & Kraus, N. (2001). Neurobiologic responses to speech in noise in children with learning problems: Deficits and strategies for improvement. *Clinical Neurophysiology, 112*(5), 758–767.

de Boer, J., & Thornton, A. R. D. (2008). Neural correlates of perceptual learning in the auditory brainstem: Efferent activity predicts and reflects improvement at a speech-in-noise discrimination task. *Journal of Neuroscience, 28*(19), 4929–4937.

DeBonis, D., & Moncrieff, D. (2008). Auditory processing disorders: An update for speech-language pathologists. *American Journal of Speech-Language Pathology, 17*, 4–18.

DiSarno, N. J., Schowalter, M., & Grassa, P. (2002). Classroom amplification to enhance student performance. *TEACHING Exceptional Children, 34*(6), 20–26.

Dragicevic, C. D., Aedo, C., León, A., Bowen, M., Jara, N., Terreros, G., Robles, L., & Delano, P. (2015). The olivocochlear reflex strength and cochlear sensitivity are independently modulated by auditory cortex microstimulation. *J. Assoc. Res. Otolaryngol*. 16, 223–240.

DuPaul, G. J., Anastopoulos, A. D., Power, T. J., Reid, R., Ikeda, M. J., & McGoey, K. E. (1998). Parent ratings of attention-deficit/hyperactivity disorder symptoms: Factor structure and normative data. *Journal of Psychopathology and Behavioral Assessment, 20*(1), 83–102.

Elmer, S., Hänggi, J., Meyer, M., & Jäncke, L., 2013. Increased cortical surface area of the left planum temporale in musicians facilitates the categorization of phonetic and temporal speech sounds. *Cortex*. http://dx.doi.org/10.1016/j.cortex.2013.03.007.

Eggermont, J. J., & Komiya, H. (2000). Moderate noise trauma in juvenile cats results in profound cortical topographic map changes in adulthood. *Hearing Research, 142*(1), 89–101.

Engineer, N. D., Percaccio, C. R., Pandya, P. K., Moucha, R., Rathbun, D. L., & Kilgard, M. P. (2004). Environmental enrichment improves response strength, threshold, selectivity, and latency of auditory cortex neurons. *Journal of Neurophysiology, 92*(1), 73–82.

Evans, G. W., & Kantrowitz, E. (2002). Socioeconomic status and health: the potential role of environmental risk exposure. *Annual Review of Public Health, 23*(1), 303–331.

Evans, G. W., Bullinger, M., & Hygge, S. (1998). Chronic noise exposure and physiological response: A prospective study of children living under environmental stress. *Psychological Science, 9*(1), 75–77.

Fausti, S. A., Wilmington, D. J., Gallun, F. J., Myers, P. J., & Henry, J. A. (2009). Auditory and vestibular dysfunction associated with blast-related traumatic brain injury. *Journal of Rehabilitation Research & Development, 46*(6).

Fey, M. E., Richard, G. J., Geffner, D., Kamhi, A. G., Medwetsky, L., Paul, D., . . . Schooling, T. (2011). Auditory processing disorder and auditory/language interventions: An evidence-based systematic review. *Language, Speech and Hearing Services in Schools, 42*, 246–264.

Friederichs, E., & Friederichs, P. (2005). Electrophysiologic and psycho-acoustic findings following one-year application of a personal ear-level FM device in children with attention deficit and suspected central auditory processing disorder. *Journal of Educational Audiology, 12*, 31–36.

Fritz, J., Shamma, S., Elhilali, M., & Klein, D. (2003). Rapid task-related plasticity of spectrotemporal receptive fields in primary auditory cortex. *Nature Neuroscience, 6*(11), 1216–1223.

Fritz, J. B., Elhilali, M., David, S. V., & Shamma, S. A. (2007). Auditory attention—focusing the searchlight on sound. *Current Opinion in Neurobiology, 17*(4), 437–455.

Gaab, N., Gabrieli, J. D. E., Deutsch, G. K., Tallal, P., & Temple, E. (2007). Neural correlates of rapid auditory processing are disrupted in children with developmental dyslexia and ameliorated with training: An fMRI study. *Restorative Neurology and Neuroscience, 25*, 295–310.

Galambos, R., Sheatz, G., & Vernier, V. G. (1955). Electrophysiological correlates of a conditioned response in cats. *Science*.

Gatehouse, S., & Noble, W. (2004). The speech, spatial and qualities of hearing scale (SSQ). *International Journal of Audiology, 43*(2), 85–99.

Gao, E., & Suga, N. (2000). Experience-dependent plasticity in the auditory cortex and the inferior colliculus of bats: role of the corticofugal system. *Proceedings of the National Academy of Sciences, 97*(14), 8081–8086.

Geffner, D., & Ross-Swain, D. (2006). The Listening Inventory (TLI).

Gelfand, S. A. (2009). *Essentials of Audiology*. 3rd ed. New York, NY: Thieme.

Goines, L., & Hagler, L. (2007). Noise pollution: a modern plague. *Southern Medical Journal - Birmingham Alabama, 100*(3), 287.

Habibi, A., Cahn, B. R., Damasio, A., & Damasio, H. (2016). Neural correlates of accelerated auditory processing in children engaged in music training. *Developmental Cognitive Neuroscience, 21*, 1–14.

Hart, B., & Risley, T. R. (1995). *Meaningful differences in the everyday experience of young American children*. Baltimore, MD: Paul H Brookes Publishing.

Hayes, E., Warrier, C. M., Nicol, T., Zecker, S. G., & Kraus, N. (2003). Neural plasticity following auditory training in children with learning problems. *Clinical Neurophysiology, 114*, 673–684.

Hendler, T., Squires, N., & Emmerich, D. (1990). Psychophysical measures of central auditory dysfunction in multiple sclerosis: Neurophysiological and neuroanatomical correlates. *Ear and Hearing, 11*, 403–416.

Hornickel, J., Skoe, E., Nicol, T., Zecker, S., & Kraus, N. (2009). Subcortical differentiation of stop consonants relates to reading and speech-in-noise perception. *Proceedings of the National Academy of Sciences of the U S A, 106*(31), 13022–13027.

Hornickel, J., Zecker, S. G., Bradlow, A. R., & Kraus, N. (2012). Assistive listening devices drive neuroplasticity in children with dyslexia. *Proceedings of the National Academy of Sciences, 109*(41), 16731–16736.

Hornickel, J., & Kraus, N. (2013). Unstable representation of sound: A biological marker of dyslexia. *The Journal of Neuroscience, 33*(8), 3500–3504.

Hunter, L. L., Margolis, R. H., Rykken, J. R., Le, C. T., Daly, K. A., & Giebink, G. S. (1996). High frequency hearing loss associated with otitis media. *Ear and Hearing, 17*(1), 1–11.

Huttenlocher, P. R. (2009). *Neural plasticity: The effects of environment on the development of the cerebral cortex.* Boston, MA: Harvard University Press.

Ilari, B. S., Keller, P., Damasio, H., & Habibi, A. (2016). The development of musical skills of underprivileged children over the course of 1 year: a study in the context of an El Sistema-inspired program. *Frontiers in Psychology, 7.*

Jerger, S., Johnson, K., & Loiselle, L. (1988). Pediatric central auditory dysfunction: Comparison of children with a confirmed lesion versus suspected processing disorders. *American Journal of Otology, 9,* 63–71.

Jerger, J. (2009). The concept of auditory processing disorder: A brief history. In Cacace, A. & McFarland, D. (Eds.), *Controversies in central auditory processing disorder* (pp. 1–14). San Diego, CA: Plural.

Johnston, K., John, A., Kreisman, N., Hall, J., & Crandell, C. (2009). Multiple benefits of personal FM system use by children with Auditory Processing Disorder (APD). *International Journal of Audiology, 48*(6), 371–383.

Kamhi, A. G. (2011). What speech-language pathologists need to know about auditory processing disorder. *Language, Speech, and Hearing Services in Schools,* 42(3), 265–272.

Keith, R. W. (1999). Clinical issues in central auditory processing disorders. *Language, Speech, and Hearing Services in Schools, 30,* 339–344.

Keith, R. W. (2000). Development and standardization of SCAN-C test for auditory processing disorders in children. *Journal of the American Academy of Audiology, 11*(8), 438–445.

Kilgard, M. P., & Merzenich, M. M. (1998). Cortical map reorganization enabled by nucleus basalis activity. *Science, 279*(5357), 1714–1718.

Kilgard, M. P., Vazquez, J. L., Engineer, N. D., & Pandya, P. K. (2007). Experience dependent plasticity alters cortical synchronization. *Hearing Research, 229*(1), 171–179.

Kilgard, M. P. (2012). Harnessing plasticity to understand learning and treat disease. *Trends in Neurosciences, 35*(12), 715–722.

Killion, M. C., Niquette, P. A., Gudmundsen, G. I., Revit, L. J., & Banerjee, S. (2004). Development of a quick speech-in-noise test for measuring signal-to-noise ratio loss in normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America, 116*(4), 2395–2405.

Kim, K. H., Relkin, N. R., Kyoung-Min, L., & Hirsch, J. (1997). Distinct cortical areas associated with native and second languages. *Nature, 388*(6638), 171.

King, C., Warrier, C. M., Hayes, E., & Kraus, N. (2002). Deficits in auditory brainstem pathway encoding of speech sounds in children with learning problems. *Neuroscience Letters, 319*(2), 111–115.

Kraus, N., McGee, T. J., Carrell, T. D., & Zecker, S. G. (1996). Auditory neurophysiologic responses and discrimination deficits in children with learning problems. *Science, 273*(5277), 971.

Kraus, N., Strait, D. L., & Parbery-Clark, A. (2012). Cognitive factors shape brain networks for auditory skills: spotlight on auditory working memory. *Annals of the New York Academy of Sciences, 1252*(1), 100–107.

Kraus, N., & White-Schwoch, T. (2014). Music training: lifelong investment to protect the brain from aging and hearing loss. *Acoustics Australia, 42*(2).

Kraus, N. & Nicol, T. (2014). The cognitive auditory system: the role of learning in shaping the biology of the auditory system. In: Popper, A. N. & Fay, R. R (Eds.), *Perspectives on Auditory Research* (pp. 299–319). New York, NY: Springer Science and Business Media.

Kraus, N., & Chandrasekaran, B. (2010). Music training for the development of auditory skills. *Nature Reviews Neuroscience, 11*(8), 599–605.

Kraus, N., Hornickel, J., Strait, D. L., Slater, J., & Thompson, E. (2014). Engagement in community music classes sparks neuroplasticity and language development in children from disadvantaged backgrounds. *Frontiers in Psychology, 5.*

Kraus, N., & White-Schwoch, T. (2015). Unraveling the biology of auditory learning: a cognitive–sensorimotor–reward framework. *Trends in Cognitive Sciences, 19*(11), 642–654.

Kraus, N., Thompson, E. C., Krizman, J., Cook, K., White-Schwoch, T., & LaBella, C. R. (2016). Auditory biological marker of concussion in children. *Scientific Reports, 6,* 39009.

Kraus, N., Lindley, T., Colegrove, D., Krizman, J., Otto-Meyer, S., Thompson, E. C., & White-Schwoch, T. (2017). The neural legacy of a single concussion. *Neuroscience Letters, 646,* 21–23.

Kraus, N., Anderson, S., & White-Schwoch, T. (2017). *The Frequency-Following Response.* Springer International Publishing, Cham, Switzerland.

Kraus, N., & White-Schwoch, T. (2017). Neurobiology of everyday communication: what have we learned from music? *The Neuroscientist,* 23(3), 287–298.

Krishnan, A. (2002). Human frequency-following responses: representation of steady-state synthetic vowels. *Hearing Research,* 166(1), 192–201.

Krizman, J., Marian, V., Shook, A., Skoe, E., & Kraus, N. (2012). Subcortical encoding of sound is enhanced in bilinguals and relates to executive function advantages. *Proceedings of the National Academy of Sciences, 109*(20), 7877–7881.

Krizman, J., Skoe, E., Marian, V., & Kraus, N. (2014). Bilingualism increases neural response consistency and attentional control: Evidence for sensory and cognitive coupling. *Brain and Language, 128*(1), 34–40.

Krizman, J., Slater, J., Skoe, E., Marian, V., & Kraus, N. (2015). Neural processing of speech in children is influenced by extent of bilingual experience. *Neuroscience Letters, 585,* 48–53.

Krizman, J., Bradlow, A. R., Lam, S. S. Y., & Kraus, N. (2017). How bilinguals listen in noise: linguistic and non-linguistic factors. *Bilingualism: Language and Cognition, 20*(4), 834–843.

Kujawa, S. G., & Liberman, M. C. (2009). Adding insult to injury: cochlear nerve degeneration after "temporary" noise-induced hearing loss. *Journal of Neuroscience, 29*(45), 14077–14085.

Lee, K. M., Skoe, E., Kraus, N., & Ashley, R. (2009). Selective subcortical enhancement of musical intervals in musicians. *Journal of Neuroscience, 29*(18), 5832–5840.

León, A., Elgueda, D., Silva, M. A., Hamamé, C. M., & Delano, P. H. (2012). Auditory cortex basal activity modulates cochlear responses in chinchillas. *PLoS One* 7:e36203.

Liberman, M. C., Epstein, M. J., Cleveland, S. S., Wang, H., & Maison, S. F. (2016). Toward a differential diagnosis of hidden hearing loss in humans. *PLoS One, 11*(9), e0162726.

Marler, J. A., & Champlin, C. A. (2005). Sensory processing of backward-masking signals in children with language-learning impairment as assessed with the auditory brainstem response. *Journal of Speech, Language, and Hearing Research, 48*(1), 189–203.

Marmel, F., Parbery-Clark, A., Skoe, E., Nicol, T., & Kraus, N. (2011). Harmonic relationships influence auditory brainstem encoding of chords. *Neuroreport,* 22(10), 504–508.

McFarland, D. J., & Cacace, A. T. (1995). Modality specificity as a criterion for diagnosing central auditory processing disorders. *American Journal of Audiology, 4,* 36–48.

Merzenich, M. M., Jenkins, W. M., Johnston, P., Schreiner, C., Miller, S. L., & Tallal, P. (1996). Temporal processing deficits in language-learning impaired children ameliorated by training. *Science, 271*(5245), 77–81.

Moore, D., Rosenberg, J. F., & Coleman, J. S. (2005). Discrimination training of phonemic contrasts enhances phonological processing in mainstream school children. *Brain and Language, 94*, 72–85.

Moore, D. R. (2006). Auditory processing disorder (APD): Definition, diagnosis, neural basis, and intervention. *Audiological Medicine*, *4*(1), 4–11.

Moore, D. R., Ferguson, M. A., Edmondson-Jones, A. M., Ratib, S., & Riley, A. (2010). Nature of auditory processing disorder in children. *Pediatrics*, *126*(2), e382–e390.

Moore, D. R., Rosen, S., Bamiou, D. E., Campbell, N. G., & Sirimanna, T. (2013). Evolving concepts of developmental auditory processing disorder (APD): a British Society of Audiology APD special interest group 'white paper.' *International Journal of Audiology*.

Moore, D., Hunter, L., & Munro, K. (2017). Benefits of extended high-frequency audiometry for everyone. *The Hearing Journal*, *70*(3), 50–52.

Mulders, W. H. A. M., & Robertson, D. (2000). Evidence for direct cortical innervation of medial olivocochlear neurones in rats. *Hearing Research, 144*(1), 65–72.

Musacchia, G., Sams, M., Skoe, E., & Kraus, N. (2007). Musicians have enhanced subcortical auditory and audiovisual processing of speech and music. *Proceedings of the National Academy of Sciences*, *104*(40), 15894–15898.

Musacchia, G., Strait, D., & Kraus, N. (2008). Relationships between behavior, brainstem and cortical encoding of seen and heard speech in musicians and nonmusicians. *Hearing Research*, *241*(1), 34–42.

Musiek, F. E., Bellis, T. J., & Chermak, G. D. (2005). Nonmodularity of the central auditory nervous system: implications for (central) auditory processing disorder. *American Journal of Audiology*, *14*(2), 128–138.

Musiek, F. E., & Chermak, G. D. (Eds.). (2013). *Handbook of central auditory processing disorder, volume I: auditory neuroscience and diagnosis* (Vol. 1). Plural Publishing, San Diego.

Nelken, I., & Ulanovsky, N. (2007). Mismatch negativity and stimulus-specific adaptation in animal models. *Journal of Psychophysiology*, *21*(3–4), 214–223.

Nilsson, M., Soli, S. D., & Sullivan, J. A. (1994). Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. *The Journal of the Acoustical Society of America*, *95*(2), 1085–1099.

Nittrouer, S., & Burton, L. T. (2005). The role of early language experience in the development of speech perception and phonological processing abilities: Evidence from 5-year-olds with histories of otitis media with effusion and low socioeconomic status. *Journal of Communication Disorders*, *38*(1), 29–63.

Noreña, A. J., & Eggermont, J. J. (2005). Enriched acoustic environment after noise trauma reduces hearing loss and prevents cortical map reorganization. *Journal of Neuroscience*, *25*(3), 699–705.

Noreña, A. J., & Eggermont, J. J. (2006). Enriched acoustic environment after noise trauma abolishes neural signs of tinnitus. *Neuroreport*, *17*(6), 559–563.

Ota, Y., Oliver, D. L., & Dolan, D. F. (2004). Frequency-specific effects on cochlear responses during activation of the inferior colliculus in the Guinea pig. *Journal of Neurophysiology*, *91*(5), 2185–2193.

Pantev, C., Roberts, L. E., Schulz, M., Engelien, A., & Ross, B. (2001). Timbre-specific enhancement of auditory cortical representations in musicians. *Neuroreport*, *12*(1), 169–174.

Parbery-Clark, A., Skoe, E., Lam, C., & Kraus, N. (2009). Musician enhancement for speech-in-noise. *Ear and Hearing*, *30*(6), 653–661.

Parbery-Clark, A., Strait, D. L., Anderson, S., Hittner, E., & Kraus, N. (2011). Musical experience and the aging auditory system: implications for cognitive abilities and hearing speech in noise. *PLoS One*, *6*(5), e18082.

Parbery-Clark, A., Anderson, S., Hittner, E., & Kraus, N. (2012). Musical experience offsets age-related delays in neural timing. *Neurobiology of Aging*, *33*(7), 1483-e1.

Parbery-Clark, A., Tierney, A., Strait, D. L., & Kraus, N. (2012). Musicians have fine-tuned neural distinction of speech syllables. *Neuroscience*, *219*, 111–119.

Patel, A. D. (2011). Why would musical training benefit the neural encoding of speech? The OPERA hypothesis. *Frontiers in Psychology*, *2*.

Patel, A. D. (2014). Can nonlinguistic musical training change the way the brain processes speech? The expanded OPERA hypothesis. *Hearing Research*, *308*, 98–108.

Perrot, X., & Collet, L. (2014). Function and plasticity of the medial olivocochlear system in musicians: a review. *Hearing Research*, *308*, 27–40.

Polley, D. B., Steinberg, E. E., & Merzenich, M. M. (2006). Perceptual learning directs auditory cortical map reorganization through top-down influences. *Journal of Neuroscience*, *26*(18), 4970–4982.

Purdy, S. C., Farrington, D. R., Moran, C. A., Chard, L. L., & Hodgson, S. A. (2002). A parental questionnaire to evaluate children's Auditory Behavior in Everyday Life (ABEL). *American Journal of Audiology*, *11*(2), 72–82.

Purdy, S. C., Smart, J. L., Baily, M., & Sharma, M. (2009). Do children with reading delay benefit from the use of personal FM systems in the classroom? *International Journal of Audiology*, *48*, 843–852.

Rajan, R. (1990). Electrical stimulation of the inferior colliculus at low rates protects the cochlea from auditory desensitization. *Brain Research*, *506*(2), 192–204.

Rappaport, J., Gulliver, M., Phillips, D., Van Dorpe, R., Maxner, C., & Bhan, V. (1994). Auditory temporal resolution in multiple sclerosis. *Journal of Otolaryngology*, *23*(5), 307–324.

Reed, A., Riley, J., Carraway, R., Carrasco, A., Perez, C., Jakkamsetti, V., & Kilgard, M. P. (2011). Cortical map plasticity improves learning but is not necessary for improved performance. *Neuron*, *70*(1), 121–131.

Rocha–Muniz, C. N., Befi-Lopes, D. M., & Schochat, E. (2012). Investigation of auditory processing disorder and language impairment using the speech-evoked auditory brainstem response. *Hearing Research*, *294*(1), 143–152.

Rosenberg, G. G., Blake-Rahter, P., Heavner, J., Allen, L., Redmond, B. M., Phillips, J., & Stigers, K. (1999). Improving classroom acoustics (ICA): A three-year FM sound field classroom amplification study. *Journal of Educational Audiology*, *7*, 8–28.

Ruggles, D. R., Freyman, R. L., & Oxenham, A. J. (2014). Influence of musical training on understanding voiced and whispered speech in noise. *PLoS One*, *9*(1), e86980.

Russo, N., Nicol, T., Zecker, S. G., Hayes, E., & Kraus, N. (2005). Auditory training improves neural timing in the human brainstem. *Behavioural Brain Research*, *156*, 95–103.

Schneider, P., Sluming, V., Roberts, N., Bleeck, S., Rupp, A. (2005). Structural, functional, and perceptual differences in Heschl's gyrus and musical instrument preference. *Annals of the New York Academy of Sciences*, *1060*, 387–394.

Sergeyenko, Y., Lall, K., Liberman, M. C., & Kujawa, S. G. (2013). Age-related cochlear synaptopathy: an early-onset contributor to auditory functional decline. *Journal of Neuroscience*, *33*(34), 13686–13694.

Shahin, A. J., Roberts, L. E., Chau, W., Trainor, L. J., & Miller, L. M. (2008). Music training leads to the development of timbre-specific gamma band activity. *Neuroimage*, *41*(1), 113–122.

Skoe, E., & Kraus, N. (2010). Auditory brainstem response to complex sounds: a tutorial. *Ear and Hearing*, *31*(3), 302.

Skoe, E., & Kraus, N. (2012). A little goes a long way: how the adult brain is shaped by musical training in childhood. *Journal of Neuroscience*, *32*(34), 11507–11510.

Skoe, E., Krizman, J., Spitzer, E., & Kraus, N. (2013). The auditory brainstem is a barometer of rapid auditory learning. *Neuroscience*, *243*, 104–114.

Skoe, E., Krizman, J., Anderson, S., & Kraus, N. (2013). Stability and plasticity of auditory brainstem function across the lifespan. *Cerebral Cortex*, *25*(6), 1415–1426.

Slater, J., Tierney, A., & Kraus, N. (2013). At-risk elementary school children with one year of classroom music instruction are better at keeping a beat. *PLoS One*, *8*(10), e77250.

Slater, J., Strait, D. L., Skoe, E., O'Connell, S., et al. (2014). Longitudinal effects of group music instruction on literacy skills in low-income children. *PLoS One*, *9*(11), e113383.

Slater, J., Skoe, E., Strait, D. L., O'Connell, S., et al. (2015). Music training improves speech-in-noise perception: Longitudinal evidence from a community-based music program. *Behavioural Brain Research*, *291*, 244–252.

Smith, J. C., Marsh, J. T., & Brown, W. S. (1975). Far-field recorded frequency-following responses: evidence for the locus of brainstem sources. *Electroencephalography and Clinical Neurophysiology*, *39*(5), 465–472.

Smith, J. C., Marsh, J. T., Greenberg, S., & Brown, W. S. (1978). Human auditory frequency-following responses to a missing fundamental. *Science*, *201*(4356), 639–641.

Smith, S. B., & Cone, B. (2015). The medial olivocochlear reflex in children during active listening. *International Journal of Audiology*, *54*(8), 518–523.

Sohmer, H., Pratt, H., & Kinarti, R. (1977). Sources of frequency following responses (FFR) in man. *Electroencephalography and Clinical Neurophysiology*, *42*(5), 656–664.

Song, J. H., Skoe, E., Wong, P. C. M., & Kraus, N. (2008). Plasticity in the adult human auditory brainstem following short-term linguistic training. *Journal of Cognitive Neuroscience*, *20*(10), 1892–1902.

Song, J. H., Skoe, E., Banai, K., & Kraus, N. (2011). Training to improve hearing speech in noise: biological mechanisms. *Cerebral Cortex*, *122*, 1890–1898.

Song, J. H., Skoe, E., Banai, K., & Kraus, N. (2012). Training to improve hearing speech in noise: biological mechanisms. *Cerebral Cortex*, *122*, 1890–1898.

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*(3), 1282–1290.

Steptoe, A., & Feldman, P. J. (2001). Neighborhood problems as sources of chronic stress: development of a measure of neighborhood problems, and associations with socioeconomic status and health. *Annals of Behavioral Medicine*, *23*(3), 177–185.

Strait, D. L., Parbery-Clark, A., Hittner, E., & Kraus, N. (2012). Musical training during early childhood enhances the neural encoding of speech in noise. *Brain and Language*, *123*(3), 191–201.

Strait, D. L., O'Connell, S., Parbery-Clark, A., & Kraus, N. (2013). Musicians' enhanced neural differentiation of speech sounds arises early in life: developmental evidence from ages 3 to 30. *Cerebral Cortex*, *24*(9), 2512–2521.

Strait, D. L., & Kraus, N. (2014). Biological impact of auditory expertise across the life span: musicians as a model of auditory learning. *Hearing Research*, *308*, 109–121.

Tallal, P. (2004). Improving language and literacy is a matter of time. Nature Reviews *Neuroscience*, *5*(9), 721–728.

Tallal, P., Miller, S. L., Bedi, G., Byma, G., Wang, X., Nagarajan, S. S., . . . Merzenich, M. M. (1996). Language comprehension in language-learning impaired children improved with acoustically modified speech. *Science*, *271*(5245), 81–84.

Takesian, A. E., Kotak, V. C., & Sanes, D. H. (2012). Age-dependent effect of hearing loss on cortical inhibitory synapse function. *Journal of Neurophysiology*, *107*(3), 937–947.

Tazeau, Y. N., & Hamaguchi, P. M. (2012). Disorders and deficits that co-occur or look like APD. *Auditory Processing Disorders: Assessment, Management and Treatment*, 91–116.

Temple, E., Deutsch, G. K., Poldrack, R. A., Miller, S. L., Tallal, P., Merzenich, M. M., & Gabrieli, J. D. E. (2003). Neural deficits in children with dsylexia ameliorated by behavioral remediation: Evidence from functional MRI. *Proceedings of the National Academy of Sciences*, *100*(5), 2860–2865.

Tierney, A. T., Krizman, J., & Kraus, N. (2015). Music training alters the course of adolescent auditory development. *Proceedings of the National Academy of Sciences*, *112*(32), 10062–10067.

Tierney, A., Krizman, J., Skoe, E., Johnston, K., & Kraus, N. (2013). High school music classes enhance the neural processing of speech. *Frontiers in Psychology*, *4*.

Tremblay, K., Kraus, N., Carrell, T. D., & McGee, T. (1997). Central auditory system plasticity: Generalization to novel stimuli following listening training. *Journal of the Acoustical Society of America*, *102*, 3762–3773.

Vander Werff, K. R. (2012). Auditory dysfunction among long-term consequences of mild traumatic brain injury (mTBI). *SIG 6 Perspectives on Hearing and Hearing Disorders: Research and Diagnostics*, *16*(1), 3–17.

Vander Werff, K. R., & Rieger, B. (2017). Brainstem evoked potential indices of subcortical auditory processing after mild traumatic brain injury. *Ear and Hearing*, *38*(4), e200–e214.

Vitela, A. D., Monson, B. B., & Lotto, A. J. (2015). Phoneme categorization relying solely on high-frequency energy. *The Journal of the Acoustical Society of America*, *137*(1), EL65–EL70.

Watson, C. S., & Kidd, G. R. (2002). On the lack of association between basic auditory abilities, speech processing, and other cognitive skills. *Seminars in Hearing*, *23*, 83–93.

Webb, A. R., Heller, H. T., Benson, C. B., & Lahav, A. (2015). Mother's voice and heartbeat sounds elicit auditory plasticity in the human brain before full gestation. *Proceedings of the National Academy of Sciences*, *112*(10), 3152–3157.

Webster, D. B. (1977). Neonatal sound deprivation affects brain stem auditory nuclei. *Archives of Otolaryngology*, *103*(7), 392–396.

Webster, D. B., & Webster, M. (1979). Effects of neonatal conductive hearing loss on brain stem auditory nuclei. *Annals of Otology, Rhinology & Laryngology*, *88*(5), 684–688.

White-Schwoch, T., Carr, K. W., Anderson, S., Strait, D. L., & Kraus, N. (2013). Older adults benefit from music training early in life: biological evidence for long-term training-driven plasticity. *Journal of Neuroscience*, *33*(45), 17667–17674.

White-Schwoch, T., & Kraus, N. (2017). The Janus face of auditory learning: how life in sound shapes everyday communication. In *The Frequency-Following Response* (pp. 121–158). Springer International Publishing.

Whitton, J. P., & Polley, D. B. (2011). Evaluating the perceptual and pathophysiological consequences of auditory deprivation in early postnatal life: a comparison of basic and clinical studies. *Journal of the Association for Research in Otolaryngology*, *12*(5), 535–547.

Wible, B., Nicol, T., & Kraus, N. (2004). Atypical brainstem representation of onset and formant structure of speech sounds in children with language-based learning problems. *Biological Psychology*, *67*(3), 299–317.

Wible, B., Nicol, T., & Kraus, N. (2005). Correlation between brainstem and cortical auditory processes in normal and language-impaired children. *Brain, 128*(2), 417–423.

Winer, J. A. (2005). Three systems of descending projections to the inferior colliculus. *The Inferior Colliculus, 1*, 231–247.

Wittekindt, A., Kaiser, J., & Abel, C. (2014). Attentional modulation of the inner ear: a combined otoacoustic emission and EEG study. *Journal of Neuroscience, 34*(30), 9995–10002.

Wong, P. C., Skoe, E., Russo, N. M., Dees, T., & Kraus, N. (2007). Musical experience shapes human brainstem encoding of linguistic pitch patterns. *Nature Neuroscience, 10*(4), 420.

Woodcock, R. W., & Johnson, M. B. (1989). *Woodcock-Johnson tests of cognitive ability.* DLM Teaching Resources.

Xiao, Z., & Suga, N. (2002). Modulation of cochlear hair cells by the auditory cortex in the mustached bat. *Nat. Neurosci. 5*, 57–63.

Xu, H., Kotak, V. C., & Sanes, D. H. (2007). Conductive hearing loss disrupts synaptic and spike adaptation in developing auditory cortex. *Journal of Neuroscience, 27*(35), 9417–9426.

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*(7), 547–558.

Zhang, W., & Dolan, D. F. (2006). Inferior colliculus stimulation causes similar efferent effects on ipsilateral and contralateral cochlear potentials in the guinea pig. *Brain Research, 1081*(1), 138–149.