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Meaningful Engagement with Sound for Strengthening Communication Skills

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Overview

Meaningful experiences with sound, such as lifelong language use, musical training, and even short-term auditory training, shape the auditory system and selectively alter its responsiveness. The creation of sound-to-meaning relationships can fuel auditory plasticity, resulting in behavioral and neural changes in auditory function. These neural changes reflect the highly integrated coupling of sensory and cognitive processes that support our ability to hear and communicate (Figure 27–1). When effective sensory-cognitive links do not form, such as with auditory processing disorders, language impairments, and learning impairments, efficient sound processing fails to develop and the auditory system gets repeated practice with abnormal sound representation. Thus, auditory-based deficits associated with these impairments are likely due to a complex feedback loop between cognitive processes and sensory encoding that is perpetuated by impaired associations between sounds and their meanings. In auditory experts such as bilinguals and musicians, links between sound and meaning are enhanced, leading to stronger auditory processing. Because auditory plasticity can be driven by positive, meaningful interaction with sound, persons with auditory processing, language, or learning disorders can benefit from training once they establish

proper interactions with sound. In this chapter we review the evidence that meaningful experience with sound can alter behavioral and neural auditory function, discuss different forms of auditory training and their documented impact on auditory system physiology, and highlight their application as remediation strategies for auditory processing disorders (APD).

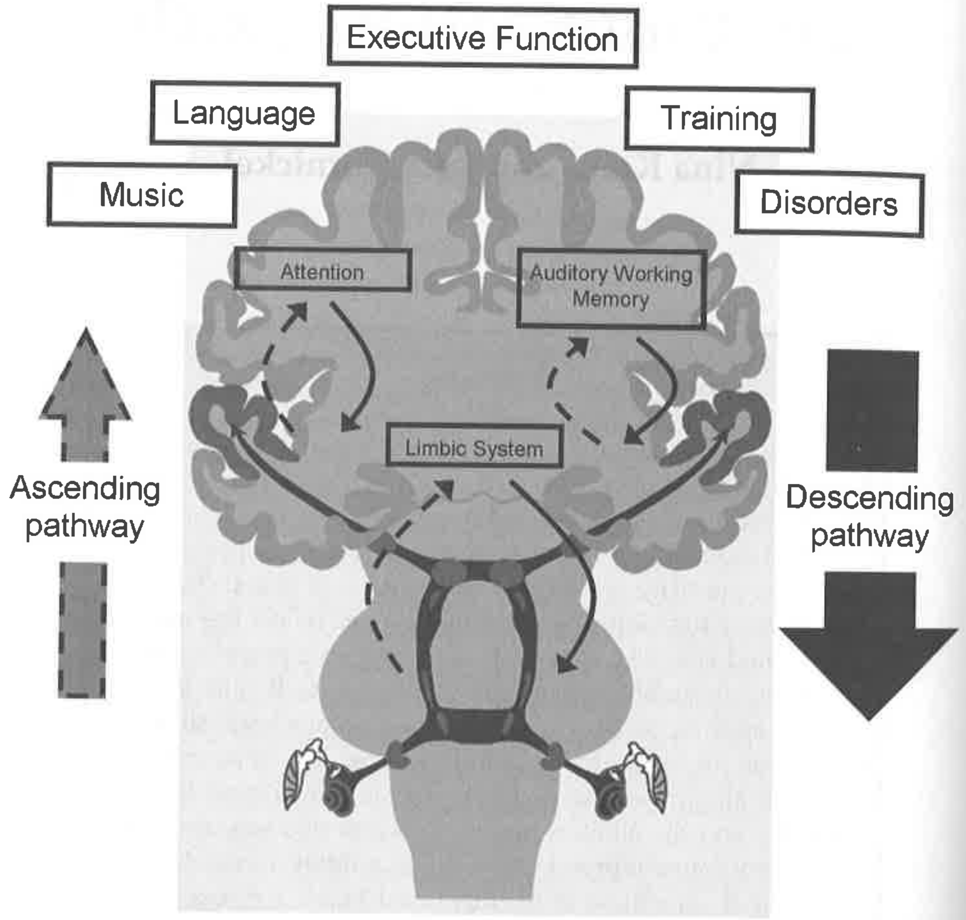

Figure 27–1. The auditory system dynamically reflects interactions among sensory and cognitive processes. The responsiveness of the auditory system to sound is not only dependent on the ascending neural transmission, but also on other physiological and cognitive factors. Auditory processing is impacted by both life-long and short-term experience with sound, such as musical training, language use, short-term training, and disordered language. Auditory attention, auditory working memory, and activity of the limbic system are likely mechanisms for engendering neural plasticity. There are greater descending cortical projections than ascending projections, highlighting the importance of cognitive-sensory interactions for the adaptation of the auditory system with experience.

Introduction

Auditory Plasticity Through Active Engagement with Sound

Neural plasticity reflects how the nervous system adapts to new environments and augments response properties based on the relevance of specific sounds. Auditory learning is supported by a reciprocal network of afferent and efferent pathways (Bajo, Nodal, Moore, & King, 2010; Huffman & Henson, 1990; Suga, Gao, Zhang, Ma, & Olsen, 2000; Xiao & Suga, 2002). Neural plasticity observed in animals, both in cortical and subcortical structures, is the strongest when stimuli are behaviorally meaningful (e.g., when animals are trained to respond to sound for a reward) or emotional centers of the brain are activated in parallel to the sound stimulation (Atiani, Elhilali, David, Fritz, & Shamma, 2009; Fritz, Elhilali, & Shamma, 2005a, 2005b; Gao & Suga, 2000; Kilgard, Vazquez, Engineer, & Pandya, 2007). Moreover, enhanced specificity of neural response properties correlates with behavioral performance on the task (Atiani et al., 2009). These types of learning engender changes in neural receptivity and sensitivity, priming neurons to fire preferentially to trained stimuli (Atiani et al., 2009; Fritz et al., 2005a, 2005b; Gao & Suga, 2000; Kilgard et al., 2007), and strengthen the ability of the auditory system to faithfully represent meaningful sounds. Although analogous single and multiunit response recordings are difficult or impossible to obtain in humans, physiologic data and functional imaging reveal training-related plasticity throughout life.

Human auditory system function can be altered through both short-term and prolonged experience with sound, including language use and musical training. For example, through a lifetime of associating rapid changes in pitch with semantic meaning, native tonal language speakers have better auditory brainstem representation of dynamic vocal pitch contours than native English speakers (Krishnan, Gandour, & Bidelman, 2010; Krishnan, Xu, Gandour, & Cariani, 2005; Xu, Krishnan, & Gandour, 2006). Likewise, musicians are known to have enhanced sensitivity to their own instrument, more robust representation of musical notes in the auditory brainstem and cortex than nonmusicians, and better auditory processing skills than nonmusicians (Bidelman, Krishnan, & Gandour, 2011; Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Lee, Skoe, Kraus, & Ashley, 2009; Margulis, Mlsna, Uppunda, Parrish, & Wong, 2009; Micheyl, Delhommeau, Perrot, & Oxenham, 2006; Musacchia, Sams, Skoe, & Kraus, 2007; Pantev et al., 1998; Pantev, Roberts, Schulz, Engelien, & Ross, 2001; Strait, Chan, Ashley, & Kraus, 2012; Strait, Kraus, Parbery-Clark, & Ashley, 2010; reviewed in Kraus & Chandrasekaran, 2010). These auditory enhancements also impact speech processing, with musicians having better perception and neural encoding of speech, particularly in challenging listening conditions (Bidelman et al., 2011; Chartrand & Belin, 2006; Musacchia et al., 2007; Parbery-Clark, Skoe, & Kraus, 2009; Parbery-Clark, Skoe, Lam, & Kraus, 2009; Parbery-Clark, Strait, & Kraus, 2011; Strait, Kraus, Skoe, & Ashley, 2009; Wong, Skoe, Russo, Dees, & Kraus, 2007). The benefits of musicianship may even offset decreases in auditory function and speech-in-noise perception with aging (Parbery-Clark, Strait, Anderson, Hittner, & Kraus, 2011; Zendel & Alain, 2012). Auditory plasticity can also be seen for short-term auditory training (occurring over weeks or months), such as speech sound discrimination training or learning a pseudolanguage (Carcagno & Plack, 2011; Chandrasekaran, Kraus, & Wong, 2012; de Boer & Thornton, 2008; Song, Skoe, Wong, & Kraus, 2008). Children with language and learning impairments who show deficient neural responses can benefit from auditory training, with responses improving to such an extent that in some cases they are no longer distinguishable from those of typically developing peers after training (Friederichs & Friederichs, 2005; Gaab, Gabrieli, Deutsch, Tallal, & Temple, 2007; Hayes, Warrier, Nicol, Zecker, & Kraus, 2003; Hornickel, Zecker, Bradlow, & Kraus, 2012; Russo, Hornickel, Nicol, Zecker, & Kraus, 2010; Stevens, Fanning, Coch, Sanders, & Neville, 2008; Temple et al., 2003; Warrier, Johnson, Hayes, Nicol, & Kraus, 2004).

A key element determining the effectiveness of auditory training paradigms in enhancing communication skills and related auditory neurophysiology is meaningful interaction with sound. In the examples above, neural changes were seen for sounds that were actively manipulated in meaningful ways and that over time had become behaviorally important. We propose that auditory attention and the creation of sound-to-meaning relationships are crucial elements for eliciting communication-related neuroplasticity with training. Studies in both animals and humans reveal that attention drives learning and that learning requires attention to determine which stimuli are meaningful (Atiani et al., 2009; Goldstone, 1998; Seitz & Dinse, 2007). When tasks are engaging, challenge attention, employ working memory, present a variety of experiences with target sounds (e.g., multiple talkers), and require repeated practice on the auditory task, they will likely be particularly effective in engendering communication-related learning and neuroplasticity (Bavelier et al., 2011; Patel, 2011). In many cases the benefit from training goes beyond the trained stimuli and task (Moore, Rosenberg, & Coleman, 2005; Moreno et al., 2011; Moreno et al., 2009; Overy, 2003; Schellenberg, 2004; Song, Skoe, Banai, & Kraus, 2011; Stevens, et al., 2008; Tremblay, Kraus, Carrell, & McGee, 1997). It is likely that engaging auditory attention and establishing strong sound-to-meaning relationships enhances these mechanisms in the auditory system overall. Heightened auditory attention and improved linking of sound to meaning leads to the generalization of training-related benefits independently of focused auditory training. Based on this theory and evidence of auditory training generalizing to complex communication skills, we view auditory training as a viable approach to enhance and remediate deficient auditory processes important for communication in children with APD.

Auditory Training Impacts Behavior and Neural Function Important for Communication

Ingredients for Successful Learning

Perceptual learning and subsequent neural plasticity is likely a result of stimulus relevance being driven above a "learning threshold" (Seitz & Dinse, 2007; Wright & Sabin, 2007). One mechanism for enhancing stimulus relevance is directed attention (Goldstone, 1998; Seitz & Dinse, 2007); thus, successful training programs should emphasize meaningful interaction with sound by being engaging, motivating, and challenging, and by providing adequate practice and reinforcement of auditory skills (Bavelier et al., 2011). Behavioral relevance and limbic system engagement are known to drive auditory plasticity in animals (Atiani et al., 2009; Fritz, David, Radtke-Schuller, Yin, & Shamma, 2010; Fritz et al., 2005a, 2005b; Kilgard et al., 2007), and this is likely also true for humans. Numerous commercially available training programs, such as Earobics (Houghton Mifflin Harcourt Learning Technology, Boston, MA), Fast ForWord (Scientific Learning, Oakland, CA), Phonomena (Mindweavers Plc., Oxford, UK), Posit Science (Posit Science Corporation, San Francisco, CA) and LACE (Listening and Communication Enhancement; Neurotone, Redwood City, CA), use adaptive presentation methods and rewards to engage attention. Variability in the training (e.g., multiple talkers in a speech training program) not only increases attentional demands, but also facilitates greater generalization (e.g., to a new talker) and can target individual differences in learning success (Bradlow, Pisoni, Akahane-Yamada, & Tohkura, 1997; Perrachione, Lee, Ha, & Wong, 2011). Generalization to new stimulus conditions can also be elicited by training on easier, more general items (whereas training on harder items elicits specificity in learning for the item; Ahissar & Hochstein, 1997; Goldstone, 1998; Loebach & Pisoni, 2008), suggesting that participants learn task and stimulus related "rules" for successfully completing the training that they can then apply to new stimuli and tasks. Additional support for this comes from improved learning on harder tasks after having been exposed to easier tasks (Ahissar & Hochstein, 1997). Thus, active engagement with a variable and broad set of sound stimuli can lead to behavioral and neural enhancements, with the potential to generalize to untrained stimuli.

Auditory Training Games and Programs

Changes in behavior and neural function in both children and adults have been seen after repeated practice with computer-based and lab-based training programs, even over the course of only a few days or weeks (Chandrasekaran et al., 2012; de Boer & Thornton, 2008; Merzenich et al., 1996; Moore et al., 2005; Song et al., 2011; Song et al., 2008; Tallal et al., 1996; Tremblay et al., 1997). Successful training programs integrate many of the key ingredients for effective training outlined above. Commercially available training games like Earobics, Fast ForWord, Phonomena, Posit Science, and LACE comprise tasks such as speech sound discrimination, rhyming judgment, pitch trajectory determination, memory games, grammar-based tasks, and perception of speech in noise; however, benefits can be seen even for untrained skills. These programs are usually computer-based with engaging and age-appropriate dynamic graphics, and employ adaptive procedures with feedback to create a challenging yet rewarding experience. Lab-based auditory training programs used to investigate training-related plasticity could include learning a pseudo-language via speech-to-picture matching tasks or repeated discrimination training on psychophysical stimuli near threshold (Chandrasekaran et al., 2012; de Boer & Thornton, 2008; Song et al., 2008; Tremblay et al., 1997; Wright, Sabin, Zhang, Marrone, & Fitzgerald, 2010). These types of lab-based programs also require attention to the task and contain numerous meaningful interactions with the stimuli, leading them to be effective in engendering learning.

Behavioral Improvements Generalize to Untrained Skills

Auditory training can yield benefits in both trained and untrained auditory processes. For example, typically developing children and children with language delays 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 language-impaired children, performance improved to age-appropriate levels (Merzenich et al., 1996; Tallal et al., 1996). Similar transfer effects are found for adults. Adults trained on discriminating non-native speech sound contrasts not only improved on the trained contrasts but also improved on the same contrast (i.e., voice-onset time) at a different place of articulation (Figure 27–2A; Tremblay et al., 1997). Thus, meaningful interaction with sound through auditory training programs can improve behavior on the trained stimuli, as well as on untrained stimuli, untrained tasks, and higher order language skills.

Neural Improvements with Short-Term Training

What neural changes accompany behavioral improvements following training? In typically developing young adults, training on speech discrimination can increase cortical sensitivity to previously indistinguishable contrasts, with generalization to untrained contrasts (Figure 27–2B; Tremblay et al., 1997). Importantly, cortical function can also improve for children with language and learning impairments, even when that neural function was initially deficient. Children with language impairments who lacked an N100 response, a cortical response indexing directed attention, showed enhancement in this response after participating in Fast ForWord training (Stevens et al., 2008). Other children with learning impairments who showed abnormal cortical activity during rhyming tasks or in response to rapidly presented stimuli had greater and more typical activity during these tasks after Fast ForWord training (Gaab et al., 2007; Temple et al., 2003). For these children neural activity after training did not differ from that of their typically developing peers (Gaab et al., 2007; Stevens et al., 2008; Temple et al., 2003), suggesting that neural deficiencies at pretest were remediated.

Training-related plasticity is also seen in the auditory brainstem. Young adults participating in the LACE program had improved brainstem responses to speech in noise concurrent with improved speech-in-noise perception (see Figure 27–2C; Song et al., 2011). After participating in Earobics, children with learning impairments also showed more robust responses to speech presented in background noise (Russo, Nicol, Zecker, Hayes, & Kraus, 2005). Similarly, children with autism spectrum disorders improved on auditory brainstem timing and representation of vocal pitch contours after training with Fast ForWord (Russo et al., 2010). Importantly, the degree of brainstem impairment at pretest also appears to predict improvement with auditory training. Children with learning impairments who had abnormal brainstem response timing showed improved cortical responses to speech after playing Earobics, as well as improved speech sound discrimination

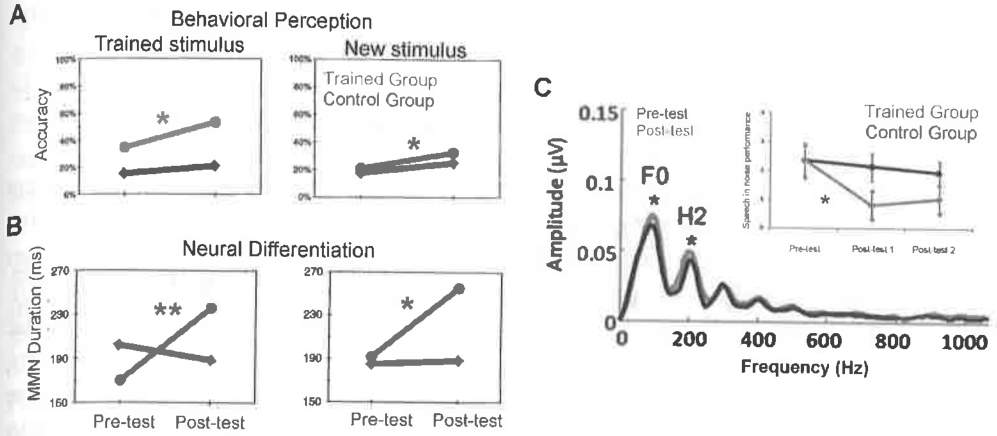

Figure 27–2. Auditory training yields benefits for trained and untrained stimuli and tasks, evident both behaviorally and neurally. **A.** English-speaking adults trained on a nonnative speech contrast (*gray*) improved on behavioral discrimination of the trained speech contrast (*left*) as well as a new speech contrast with similar acoustic features (*right*). Improvements were not seen for control participants (*black*). **B.** Improvements with training were also found for preconscious neural differentiation of trained speech sounds (*left*) and untrained speech contrasts (*right*). Again, changes were only seen for the trained group (*gray*) and not the control group (*black*). Reprinted with permission from Tremblay, K., Kraus, N., Carrell, T. D., and McGee, T. (1997). Central auditory system plasticity: Generalization to novel stimuli following listening training. *Journal of the Acoustical Society of America*, *102*, 3762–3773, Copyright 1997, Acoustic Society of America. **C.** Young adults who underwent LACE training for 8 weeks showed enhanced brainstem representation of vocal pitch when the speech syllable [da] was presented in background noise. This is illustrated as a stronger response to the fundamental frequency (F_0) and second harmonic (H_2) after training (*gray*). Participants who underwent LACE training (*gray*) also improved on clinical measures of speech-in-noise perception that were not explicitly trained as part of LACE whereas the control group (*black*) showed no change (*inset*). These improvements persisted for 6 months (Post-test 2). Reprinted with permission of Oxford University Press from Song, J. H., Skoe, E., Banai, K., and Kraus, N. (2011). Training to improve hearing speech in noise: Biological mechanisms. *Cerebral Cortex*, *122*, 1890–1898. *$p < 0.05$ **$p < 0.01$ ***$p < 0.001$.

that resembled that of typically developing children (Hayes et al., 2003; King, Warrier, Hayes, & Kraus, 2002). Children with learning impairments but without abnormal auditory brainstem responses did not show this change in cortical activity with training (Hayes et al., 2003), suggesting that neural measures may be useful for predicting which participants will reap the greatest benefit from training.

Generalizability of Auditory Training

There is mounting evidence that auditory training through focused discrimination, manipulation, and retention of target stimuli can lead to behavioral and neural changes for both trained and untrained sounds that generalize to real-world communication skills. In all cases, we attribute the neural and behavioral improvements to an active engagement with sound. As a result of training, the auditory system likely changes how it engages with and uses sound (e.g., through changes in auditory attention), leading to benefits for a wide array of communication skills (de Boer & Thornton, 2008; Merzenich et al., 1996; Moore et al., 2005; Song et al., 2011; Song et al., 2008; Tallal et al., 1996; Tremblay et al., 1997). Because targeted auditory training can generalize across different tasks and to more complex cognitive and communicative skills, likely through global changes in auditory function, we might then infer that forms of auditory training not specifically targeting speech and communication may also yield improvements in speech representation and processing through similar mechanisms. Studies of assistive listening devices and musical training (discussed below) suggest this is the case.

Classroom FM Systems

FM (frequency-modulation) systems are one of the more commonly prescribed treatment devices for children with APD (Chermak, 2002; Keith, 1999). The systems strive to enhance acoustic signals in the classroom by reducing the impact of background noise on the auditory signal reaching a child's ear. The talker of interest (e.g., a teacher) wears a microphone and a broadcasting transmitter that sends a high fidelity audio signal to speakers situated around the classroom or to earpieces worn by individual students. While the systems do not greatly amplify the teacher's voice, they effectively enhance the signal-to-noise ratio of the teacher's voice relative to background noise in the classroom (Crandell, Smaldino, & Flexer, 2005). Although the American Speech-Language-Hearing Association has published guidelines for classroom acoustics, with noise levels below 35 dB SPL and reverberation times approximately 0.5 seconds or less, internal and external noise often combine to create classrooms with >60 dB SPL of background noise, roughly the level of a busy traffic intersection (American Speech-Language-Hearing Association, 2005; Shield & Dockrell, 2003; Hornickel et al., 2012). Because young children are especially sensitive to background noise, noisy classrooms can be particularly detrimental to learning (Jamieson, Kranjc, Yu, & Hodgetts, 2004). The impact of noise is even more pronounced in children with language and learning impairments (Boets, Ghesquiere, van Wieringen, & Wouters, 2007; Bradlow, Kraus, & Hayes, 2003; Brady, Shankweiler, & Mann, 1983; Ziegler, Pech-Georgel, George, & Lorenzi, 2009), suggesting they are at a particular disadvantage in noisy classrooms.

Behavioral Improvements in Attention and Academic Performance

FM system use improves attentive behavior in class for children with learning impairments, APD, and even those who are typically developing (Blake, Field, Foster, Platt, & Wertz, 1991; DiSarno, Schowalter, & Grassa, 2002; Purdy, Smart, Baily, & Sharma, 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 students rated their own hearing in difficult situations as better (Purdy et al., 2009). Increases in attention were also seen for extended use of an FM system (20 weeks) by children with learning impairments, particularly for observed eye-contact and teacher-rated motivation to participate in group activities (Blake et al., 1991). In a large scale study of FM system use in typically developing classrooms, Rosenberg and colleagues found that children in classrooms fitted with FM systems showed greater improvement in listening and attention skills and also improved more rapidly in these skills than their peers in classrooms without FM systems. Improvements were greatest for the youngest students. This is likely because they have weaker linguistic knowledge to compensate for degraded listening conditions and consequently benefitted more from the enhanced acoustic input (Rosenberg et al., 1999). These documented improvements in observed and perceived attention suggest FM systems may be effective in engendering learning and alleviating auditory processing impairments by improving audio quality, directing auditory attention, and increasing meaningful interaction with sound.

FM systems can also benefit academic performance. 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 (Johnston et al., 2009). This suggests that the children who wore the FM systems learned how to effectively employ the FM system, which translated to improved speech discrimination. FM benefits also extend to reading-related skills. Preschool children who used FM systems in conjunction with a specialized phonological curriculum had better phonemic segmentation than peers who did not wear the FM system but were also participating in the specialized curriculum (Figure 27–3A; Flexer, Biley, Hinkley, Harkema, & Holcomb, 2002). Likewise, first grade students in classrooms with FM systems showed greater gains in literacy than their peers in classrooms without FM systems (Darai, 2000). These improvements were greatest for children who were bilingual or had learning impairments (Darai, 2000).

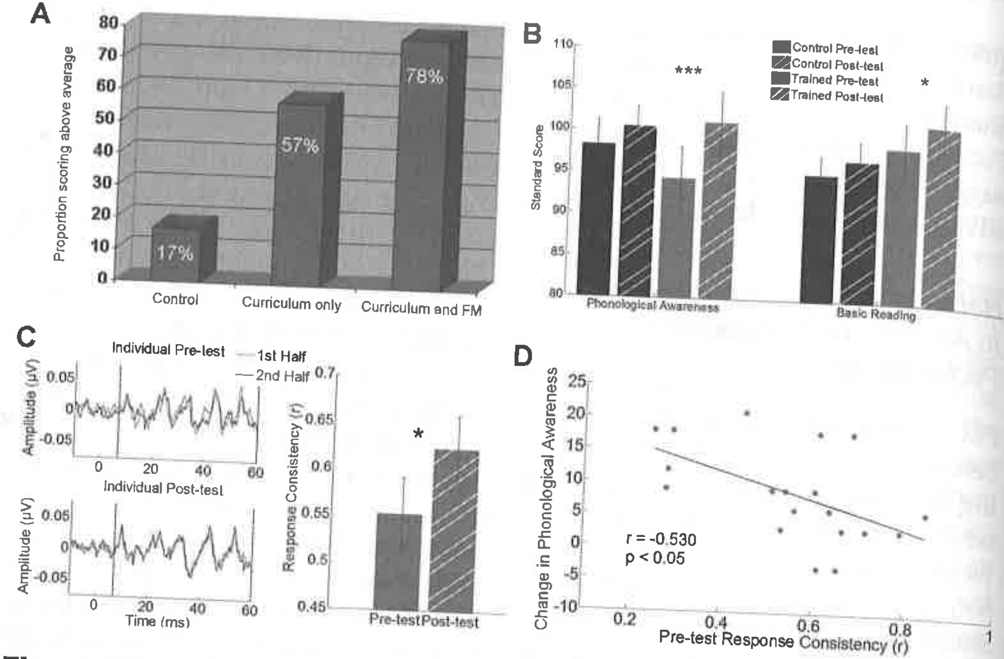

Figure 27–3. FM system use in children reduces risk for learning impairments and improves reading and neural responses to speech. **A**. Preschool children who participated in a special phonological curriculum while using an FM system were more likely to perform above average on phonemic segmentation (*right bar*) than children in the phonological curriculum only (*middle bar*) or children in no special curriculum (*left bar*). Additionally, the children who used the FM system were less likely to be classified as "at-risk" for reading impairments based on their performance on the phonemic segmentation task. Reprinted with permission from Flexer, C., Biley, K. K., Hinkley, A., Harkema, C., and Holcomb, J. (2002). Using sound-field systems to teach phonemic awareness to pre-schoolers. *Hearing Journal, 55*(3), 38–44. **B**. In school-age children with reading impairments, FM system use for one year yielded improvements in phonological awareness and reading (*gray bars*) that was not seen for reading-impaired children who did not use the FM system (*black bars*). **C**. Response consistency, the fidelity of the response from trial-to-trial throughout the recording, also improved after FM use for one year (*gray bars*). The pretest and post-test responses from a representative individual illustrate the enhancements in the consistency of the response after FM system use (the analysis region is marked by hashed lines). **D**. Improvements in phonological awareness were the greatest for children with the weakest response consistency before FM system use. Reprinted with permission from Hornickel, J., Zecker, S. G., Bradlow, A. R., and Kraus, N. (2012). Assistive listening devices drive neuroplasticity in children with dyslexia *Proceedings of the National Academy of Sciences*. DOI: 10.1073/pnas.1206628109. $^{*}p < 0.05$ $^{**}p < 0.01$ $^{***}p < 0.001$. 2012

A recently completed study in elementary school-age children found similar effects. Reading-impaired children who wore personal FM systems for one school year improved on phonological awareness and reading while their reading-impaired peers did not (Figure 27–3B; Hornickel et al., 2012). Notably, all of the children were attending the same private schools for children with severe reading impairments. Thus, the benefits seen here are more likely due to FM system use than academic curriculum, since academic environment was controlled for. These results suggest that FM system use can positively impact reading-related skills through increases in auditory attention, likely by enhancing auditory processing skills relevant to speech discrimination and phonological awareness that are commonly deficient in children with language and learning impairments (Boets et al., 2011; Goswami et al., 2011; Tallal, Miller, Jenkins, & Merzenich, 1997).

Neural Enhancements with FM System Use

To the best of our knowledge, the impact of FM system use on neural function has only been assessed in two studies. Friederichs and Friederichs found enhancements in neural markers of attention after one year of FM system use by children with APD. Electrophysiological responses to attended tones that were presented infrequently were enhanced, suggesting more robust neural activity reflecting attention after FM system use. These neural improvements coincided with improved frequency discrimination and improved teacher-rated attentiveness. No changes were seen for children with APD who did not wear the FM system (Friederichs & Friederichs, 2005). Enhanced brainstem representation of speech sounds is also observed in children with reading impairments following FM system use for one academic year. Children who wore an FM system showed more consistent responses to speech syllables throughout the recording session (i.e., reduced trial-by-trial variability), whereas control children in the same academic environment did not (Figure 27–3C; Hornickel et al., 2012). These training-related effects were restricted to the response to the formant transition of the syllables, the most acoustically complex and linguistically important part of the syllable (see Chapter 7, cABR: A Biological Probe of Auditory Processing). Improvements in the consistency of the response after FM system use correlated with changes in phonological awareness, an important skill for successful reading acquisition (Boets et al., 2011; Boets, Wouters, Van Wieringen, De Smedt, & Ghesquiere, 2008; Paul, Bott, Heim, Wienbruch, & Elbert, 2006; Schulte-Korne, Deimel, Bartling, & Remschmidt, 1999); participants with the greatest improvement on the neural measure improved most on phonological awareness (Hornickel et al., 2012). Additionally, children with the poorest response consistency at pretest showed the greatest benefit from the enhanced acoustic input and heightened auditory attention provided by the FM system, showing the largest gains in phonological awareness (Figure 27–3D). We suggest that inconsistent neural processing of sound underlies and reflects the variability in auditory processing that contributes to poor phonological awareness in children with auditory-based learning impairments. FM system use appears to address these deficits by directing and enhancing auditory attention to meaningful sounds during the school day through enhanced signal-to-noise ratios. Neither changes in neural function nor relationships between neural function and behavior were seen for children with reading impairments who did not use the FM system but attended the same school, indicating that it was auditory-based training in particular that was effective in altering neural function in children with language-based learning impairments.

Enhanced Attention Impacts Auditory Function

As suggested above through observed improvements in classroom attention and self-rating of ease with difficult listening conditions, FM systems likely engage and enhance students' auditory attention to promote learning. Unlike stimulus-based training (discussed above), FM systems manipulate the incoming, real-world, meaningful speech of the teacher during classroom instruction. Because FM systems are focusing students' attention on the meaningful speech of their teacher, they may be used throughout the school day without requiring time away from the curriculum and, unlike computer-based training, FM systems can benefit whole classrooms at once. That FM system use also appears to benefit reading, reading-related skills, speech-in-noise (SIN) perception, and neural function suggests FM system use can be a particularly effective and wide-reaching remediation strategy for children with APD, reading impairments, and learning impairments. By increasing auditory attention to meaningful speech during classroom instruction while learning is taking place, FM systems likely contribute to strengthened sound-to-meaning associations, occurring both implicitly (i.e., facilitating the integration of speech with meaning) and also explicitly through the targeted curriculum (e.g., phonemic training).

Musical Training

Lifelong musicianship is known to alter auditory system function and enhance auditory skills. Musicians have better psychophysical perception and SIN perception than nonmusicians, more robust brainstem responses to music, speech, and speech in background noise, and greater neural specialization relative to nonmusicians (Bidelman et al., 2011; Chartrand & Belin, 2006; Elbert et al., 1995; Kraus & Chandrasekaran, 2010; Lee et al., 2009; Margulis et al., 2009; Micheyl et al., 2006; Musacchia et al., 2007; Pantev et al., 1998; Pantev et al., 2001; Parbery-Clark, Skoe, & Kraus, 2009; Parbery-Clark et al., 2009; Parbery-Clark et al., 2011; Parbery-Clark, Strait, & Kraus, 2011; Strait, Chan, Ashley, & Kraus, 2012; Strait et al., 2010; Strait et al., 2009; Wong et al., 2007). The impact of musical training on auditory function is correlated with years of practice, with greater length of practice and earlier starting age relating to better performance and stronger neurophysiological responses (Elbert et al., 1995; Forgeard, Winner, Norton, & Schlaug, 2008; Ho, Cheung, & Chan, 2003; Musacchia et al., 2007; Pantev et al., 1998; Parbery-Clark et al., 2009; Wong et al., 2007). Additionally, musical training can yield changes in neural function and behavior for children who do not significantly differ from nonmusical peers at pretest or are randomly assigned to musical versus artistic or drama training (Hyde et al., 2009; Moreno et al., 2011; Moreno et al., 2009; Schellenberg 2004; Schlaug, Norton, Overy, & Winner, 2005). Thus, it appears that repetition through extensive and continuous practice is a contributing factor in musician-related benefits and suggests that musician/nonmusician differences are not simply due to inherent genetic differences between musicians and nonmusicians. Even musical training in childhood that has been discontinued can still lead to enhancements in adult brainstem representation of tones relative to no musical training, suggesting that even limited musical experience can have long lasting neural consequences (Skoe & Kraus, 2012).

Given that musical training does not specifically target language processing, how might musical training lead to enhancements in speech perception and processing? Dr. Aniruddh Patel suggests five aspects of musical training that contribute to generalization to speech: overlap, precision, emotion, repetition, and attention (coined the "OPERA hypothesis"). In his model, music and speech likely activate the same neural structures, particularly in the auditory brainstem, so focused musical practice will reciprocally strengthen neurons that also respond to speech. Although speech consists of rapid frequency sweeps, comprises transient elements, and is on a much faster time scale than music, linguistic redundancies, such as contextual cues, allow us to correctly interpret speech even when degraded by competing sounds or reverberation. Because music does not have the same contextual redundancy as speech, much more attention must be paid to the minute acoustics, suggesting that music demands more precise auditory encoding than speech. In addition, playing and listening to music is often enjoyable, leading to positive emotional associations and meaningfulness. Last, musical training requires a large amount of repetition and focused auditory attention during practice, increasing interaction with meaningful sound (Patel, 2011). Through these mechanisms musical training can impact auditory function and communication skills after both lifelong and short-term experience.

Behavioral Improvements in Academic and Cognitive Skills

In children, musical skill is related to communication skills, with musical training enhancing these and other cognitive skills (Anvari, Trainor, Woodside, & Levy, 2002; Forgeard, Schlaug, Norton, Rosam, & Iyengar, 2008; Forgeard et al., 2008; Ho et al., 2003; Lamb & Gregory, 1993; Moreno et al., 2011; Moreno et al., 2009; Schellenberg, 2004; Strait, Hornickel, & Kraus, 2011). In preschool and school-age children, pitch and rhythm perception are correlated with phonological awareness and reading (Anvari et al., 2002; Forgeard et al., 2008; Huss, Verney, Fosker, Mead, & Goswami, 2011; Lamb & Gregory, 1993; Strait et al., 2011). Analytical modeling suggests that rhythm perception significantly predicts variance in reading ability, mediated by auditory working memory and the subcortical representation of speech (Figure 27–4A; Strait, Hornickel, et al., 2011). Importantly, auditory processing skills such as rhythm perception, frequency discrimination, and temporal judgment assessed in infancy or preschool are predictive of later reading achievement

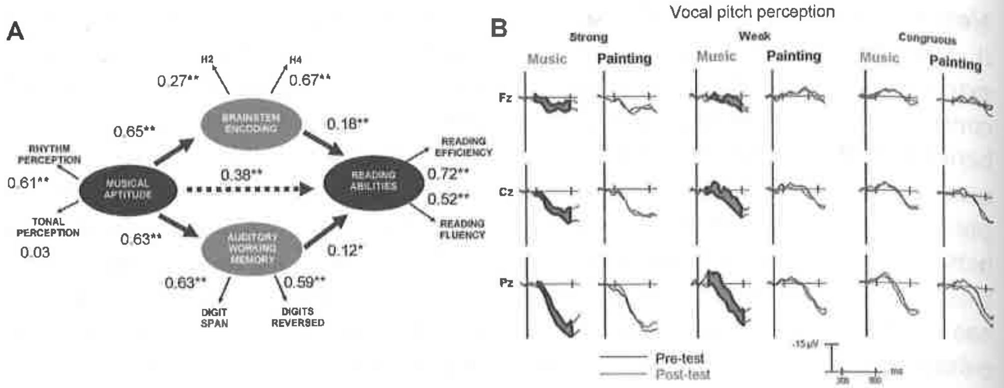

Figure 27–4. Musical skill impacts reading and communication in children through neural mechanisms. **A.** Jointly, rhythm aptitude, auditory working memory and attention, and subcortical pattern detection account for 38% of the variance in reading ability in children. Values reported are variance accounted for by relationships among variables (*r*-squared). Reprinted with permission from Strait, D. L., Hornickel, J., and Kraus, N. (2011). Subcortical processing of speech regularities predicts reading and music aptitude in children. *Behavioral and Brain Functions*, *7*, 44. **B.** Children participating in musical training (*gray, left columns*) show larger responses to incongruities in vocal pitch after training relative to pretraining (*differences marked with gray*). Children who participated in painting training (*black, right columns*) showed no change in responses from pre-test to post-test. Neural enhancements in the musically trained group are particularly strong for detecting weak pitch incongruities (*middle panel*). Reprinted with permission of Oxford University Press from Moreno, S., Marques, C., Santos, A., Santos, M., Castro, S. L., and Besson, M. (2009). Musical training influences linguistic abilities in 8-year-old children: More evidence for brain plasticity. *Cerebral Cortex*, *19*, 712–723. $^{*}p < 0.05$ $^{**}p < 0.01$ $^{***}p < 0.001$.

(Benasich & Tallal, 2002; Boets et al., 2011; Boets et al., 2008; Corriveau, Goswami, & Thomson, 2010; David, Wade-Woolley, Kirby, & Smithrim, 2007). Musical training during childhood is also shown to enhance cognitive and communication skills, with benefits similar to those seen for adult musicians. Children with multiple years of musical practice have stronger motor learning, pitch and melodic perception, vocabulary, verbal memory, and nonverbal reasoning than children without musical training, even when the effects of nonverbal intelligence, age, and education level are controlled for (Forgeard et al., 2008; Ho et al., 2003). These studies suggest that training-related benefits are proportional to the extent of musical training and not dependent on pre-existing skill (Forgeard et al., 2008; Ho et al., 2003; Norton et al., 2005). Relative to other artistic extracurricular activities such as painting or drama training, children undergoing musical training showed improvements in IQ, reading, and pitch discrimination, particularly for pitch discrimination of small incongruities in melodies or sentences (Moreno et al., 2011; Moreno et al., 2009; Schellenberg, 2004). Musical training also benefits children with dyslexia, yielding improved phonological awareness and spelling scores (Overy, 2003). It appears that the benefits of musical training can be gained quite quickly over weeks and months, even in young children, and can positively impact developing language and academic skills.

Neural Enhancements with Musical Experience

As in adult musicians, children who undergo musical training or have stronger musical aptitude show enhancements in auditory neurophysiology relative to nonmusical children (Hyde et al., 2009; Moreno et al., 2011; Moreno et al., 2009; Schlaug et al., 2005; Strait et al., 2011; Trainor, Shahin, & Roberts, 2003). Children with stronger musical aptitude showed enhanced auditory brainstem representation of vocal pitch when speech was presented in a predictable context (Strait et al., 2011), a measure previously correlated with SIN perception (Chandrasekaran, Hornickel, Skoe, Nicol, & Kraus, 2009). Taking advantage of repetition within a stimulus stream to enhance encoding, in conjunction with auditory working memory and attention, is thought to mediate the relationship between rhythm aptitude and reading ability (Strait et al., 2011). Improvements in neural metrics after musical training also mirror the improvements seen in behavior. Children with musical training but not painting training have enhanced cortical responses reflecting the detection of weak pitch incongruities in both melodies and speech, commensurate with their reduced error in detecting these incongruities on the behavioral test (Figure 27–4B; Moreno et al., 2009). Children with musical training also have larger responses to tones produced by their instrument than nonmusician children, similar to differences seen between adult musicians and nonmusicians (Trainor et al., 2003). Functional and structural changes are also found after one year of intensive musical training, primarily in the auditory cortices and association areas, corpus callosum, and precentral gyrus (i.e., motor planning; Hyde et al., 2009; Schlaug et al., 2005). Interestingly, in one study the control group participated in their regular, once-weekly 40-minute musical program at school, consisting of singing, drumming, and playing bells, yet this limited exposure was not sufficient to drive neural changes (Hyde et al., 2009). As the extent of practice appears to be important for music-related benefits in children (Forgeard et al.,2008; Ho et al., 2003), so too does the amount and type of training on a regular basis, suggesting there may be a minimum threshold of exposure and engagement that must be met for musical training to impart such pervasive benefits, similar to learning on psychophysical tasks (Seitz & Dinse, 2007; Wright & Sabin, 2007).

Impact of Musical Training in Disordered Populations

It is clear that musical training can impact both auditory skills and auditory neurophysiology in a positive way that can generalize to communication and literacy skills (Anvari et al., 2002; Forgeard, Schlaug, et al., 2008; Forgeard, Winner, et al., 2008; Ho et al., 2003; Hyde et al., 2009; Lamb & Gregory, 1993; Moreno et al., 2011; Moreno et al., 2009; Schellenberg, 2004; Strait, Hornickel, et al., 2011). There is evidence that musical training can yield improvements in children with impaired literacy (dyslexia), highlighting musical training as a possible remediation strategy for children with communication disorders. Dyslexic children who underwent classroom music lessons showed gains in spelling and phonological awareness, thought to be one of the strongest contributing factors to learning to read (Boets et al., 2011; Boets et al., 2008; Overy, 2003; Paul et al., 2006; Schulte-Korne et al., 1999). These children had impaired rhythm perception initially and, unlike the control group, showed no correlation between rhythm perception and spelling (Overy, 2003). These results, in conjunction with Goswami and colleagues' findings that children with dyslexia have poor rhythm and vocal stress perception (Goswami et al., 2011; Huss et al., 2011), suggest that children with dyslexia may have impaired syllable segmentation skills as evidenced by weaker rhythm perception and production. As pattern detection and syllable segmentation in ongoing speech are important for language learning (Saffran, 2003; Saffran, Aslin, & Newport, 1996), poor processing of speech rhythm has obvious implications for language learning and later literacy. After undergoing musical training, children with dyslexia did show improvements in rhythm perception (Overy, 2003), suggesting that these deficits can be remediated through musical training. Although studies of neural changes in dyslexic children following musical training have not been completed, studies showing neural changes with other forms of auditory training suggest that musical training could also elicit neuroplasticity in children with communication disorders, including APD (Gaab et al., 2007; Hayes et al., 2003; Hornickel et al., 2012; Russo et al., 2010; Russo et al., 2005; Stevens et al., 2008; Temple et al., 2003). Musical training enhances the very aspects of auditory processing that are deficient in children with APD, such as backward masking, temporal processing, and SIN perception (Bamiou, Musiek, & Luxon, 2001; Chermak, 2002; Dawes & Bishop, 2009; Keith, 1999; Micheyl et al., 2006; Parbery-Clark, Skoe, Lam, et al., 2009; Parbery-Clark, Strait, Anderson, et al., 2011; Smoski, Brunt, & Tannahill, 1992; Strait et al., 2010; Zendel & Alain, 2012). Additionally, these changes are linked to enhancements in auditory neural structure and function (Hyde et al., 2009; Moreno et al., 2011; Moreno et al., 2009; Musacchia et al., 2007; Parbery-Clark, Skoe, & Kraus, 2009; Parbery-Clark, Strait, & Kraus, 2011; Schlaug et al., 2005; Strait et al., 2009; Trainor et al., 2003), suggesting that impaired auditory function and structure may be ameliorable with musical training. Musical training is also engaging and enjoyable, involves social interaction, and yields benefits even after a short period of training, making it a viable intervention technique with great potential for engendering learning and plasticity.

Auditory Training for Children with APD

Children with APD have deficits in auditory processing skills that often manifest in the neural representation of complex sounds like speech (see Chapter 7, cABR: A Biological Probe of Auditory Processing). Short-term auditory training can impact auditory function, leading to improvements in skills that are commonly deficient in children with APD. Software-based training, FM system use, as well as musical training can improve speech and language skills, even in children with deficient neural processing (Darai, 2000; Flexer et al., 2002; Gaab et al., 2007; Hayes et al., 2003; Hornickel et al., 2012; Overy, 2003; Stevens et al., 2008; Temple et al., 2003). Children with APD, who have known impairments in understanding speech in challenging listening situations, auditory processing and integration, and likely also atypical auditory brainstem responses to complex stimuli, could benefit from targeted auditory training through one of the paradigms described above. Notably, training-related changes in behavior and neural function appear to be maintained over time (Moore et al., 2005; Song et al., 2011). This suggests that children with deficient auditory neural function may gain long-lasting benefits from auditory training, leading to a fundamental change in communication skills and auditory processing. Additionally, neural metrics of auditory function might serve to predict which children would reap the greatest benefit from auditory training, as those individuals with the largest impairments at pretest have been shown to have the greatest gains at posttest (de Boer & Thornton, 2008; Hayes et al., 2003; Hornickel et al., 2012). Neural metrics can also be used to assess function before and after training to determine the effect and extent of training on auditory neurophysiology.

One common and very important aspect of the various training programs described above is that they are engaging and require heightened auditory attention to meaningful stimuli. Studies of auditory training in animals have found that training-related plasticity is greatest for sounds that are behaviorally meaningful, either in a trained task or when paired with stimulation of pleasure centers. Moreover, plasticity is linked to activation in the prefrontal cortex, an area of the brain thought to be important for executive control, and correlated with behavioral performance (Atiani et al., 2009; Fritz et al., 2010; Fritz et al., 2005; Kilgard et al., 2007). We suggest that auditory attention in humans allows for the creation of sound-to-meaning relationships, through explicit pairings of sound with meaning (e.g., learning a pseudolanguage) and also through emotional ties (e.g., enjoyment in playing a musical instrument and playing an exciting reward game). By enhancing the behavioral importance of sound stimuli, descending cortical influence on subcortical structures, known to be critical for auditory learning (Bajo et al., 2010), could be increased. While the brain is malleable, plasticity is not elicited immediately or to all stimuli; rather it requires repetition and meaningfulness of sounds being trained (Fritz et al., 2005; Seitz & Dinse, 2007; Wright et al., 2010). The effectiveness of auditory training lies in the meaningful experience with sound; even if there is no improvement on the trained task, benefits in language skills and communication can be seen (Moore et al., 2005; Stevens et al., 2008). This is why such a wide array of auditory training regimens can impact similar auditory functions and yield benefits in speech and language function, even if speech is not specifically trained. We argue that it is meaningful interaction with sound and the creation of sound-to-meaning relationships that drives auditory neuroplasticity and, because these effects are not driven by internal factors such as pre-existing skill, even children with communication disorders can reap great benefits from auditory training.

Summary

Auditory training improves auditory processing skills, language and communication function, and auditory neural structure and function. Auditory training paradigms can take on a wide variety of forms, including speech-discrimination, language learning, enhanced auditory input (FM system use), and musical training. Benefits for language function can be seen even without evident learning on the trained task and when training does not focus on speech perception. Auditory attention and engagement with sound appear to be the crucial elements for successful learning, and auditory training paradigms that can maximize these attributes will likely be the most successful. Auditory training can benefit not only typically developing children and adults, but also those with communication impairments. Through auditory training it is possible for deficient auditory processing to even reach typically developing levels. It is through meaningful interaction with sound that this remediation is possible, and because changes in language and communication function can be seen even without active training on those skills, auditory training programs that are sufficiently engaging and employ meaningful, complex stimuli may engender positive changes in communication and auditory function. The converging evidence reviewed here gives cause for considerable optimism for the effectiveness of auditory training for treating APD by enhancing meaningful interaction with sound.

Key Points Learned

- The auditory system is malleable with experience throughout the life span.
- Meaningful interaction with sound drives training-related auditory plasticity.
- Training can yield benefits for both trained and untrained auditory processes.
- Training can ameliorate auditory deficits in children with communication disorders.

Study Questions

1. Provide examples of lifelong experience with sound that may alter auditory function. Include at least two that are not discussed in this chapter.
2. Discuss two examples of how lifelong musical training affects neural function, giving examples of both the specificity and generalization of musical training.

3. Discuss why FM system use is effective in increasing auditory attention.
4. Based on your own experiences, which of the auditory training paradigms discussed above do you believe would be most effective in clinical practice?
5. Examples of generalization in speech-based auditory training include:
   a. Linguistic skills
   b. Untrained speech contrasts
   c. Sound localization
   d. Speech-in-noise perception
   e. a, b, c
   f. a, b, d
   g. All of the above
6. Classroom FM system use has been shown to benefit children with:
   a. APD
   b. Learning impairments
   c. Reading disorders
   d. No impairments
   e. a, b, c
   f. All of the above
7. Enhancements in cortical measures of attention have been seen for:
   a. Speech-sound training
   b. Passive exposure to music
   c. FM system use
   d. a and b
   e. All of the above
8. Which is not a component of the OPERA hypothesis (Patel, 2011)?
   a. Emotion
   b. Responsiveness
   c. Precision
   d. Attention
   e. Overlap
9. The benefits of musical training are:
   a. Speech-sound training
   b. Seen in children with less than one year of musical training
   c. Not seen for children who quit musical training
   d. a and c
   e. All of the above

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