



## Biological impact of music and software-based auditory training

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### ABSTRACT

Auditory-based communication skills are developed at a young age and are maintained throughout our lives. However, some individuals – both young and old – encounter difficulties in achieving or maintaining communication proficiency. Biological signals arising from hearing sounds relate to real-life communication skills such as listening to speech in noisy environments and reading, pointing to an intersection between hearing and cognition. Musical experience, amplification, and software-based training can improve these biological signals. These findings of biological plasticity, in a variety of subject populations, relate to attention and auditory memory, and represent an integrated auditory system influenced by both sensation and cognition.

**Learning outcomes:** The reader will (1) explain that the auditory system is malleable to experience and training, (2) identify the ingredients necessary for auditory learning to successfully be applied to communication, (3) recognize that the auditory brainstem response to complex sounds (cABR) is a window into the integrated auditory system, and (4) identify examples of how cABR can be used to track the outcome of experience and training.

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### 1. Introduction

A variety of communication skills are employed in our everyday lives: reading and listening in noise among them. Enhancing and maintaining these skills leads to a more fulfilling existence as a communicating human being. Long-term activities such as musical training, short-term training – especially software-based auditory-skills training regimens, and a clear amplified signal are capable of increasing communication skills. An open question is how this is accomplished from a biological standpoint. The auditory system is highly integrated and interactive – no part of it operates in isolation. So, to answer this question is at present beyond the scope of what can be accomplished in humans. However, we have access, in humans, to a physiological measure that reflects the biological processing of sound in the integrated system. This measure, the auditory brainstem response to complex stimulation (cABR), responds to training and experience and tracks well with cognitive abilities such as attention and auditory working memory. This review discusses cABR and its relationship with communication-based skills, offers a model that explains the nature of training and experience's role in shaping communication skills, and points toward training strategies that might best profit the auditory system in its responsibility as the center of human communication.

The cABR, unlike the click ABR or the various cortical evoked responses, has the advantage of having a morphology that mimics – with considerable fidelity – that of the stimulus. In both the time and frequency domains, this similarity lends itself to a quantification of processing precision. The inferior colliculus, a major contributor to cABR, is a convergence center in the

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integrated auditory system. Viewed as the auditory analog to primary visual cortex (Nelken, 2008), it functions not only as an afferent route from periphery to higher processing centers, but also receives an abundance of downward corticofugal projections and is critical to learning (Bajo, Nodal, Moore, & King, 2010; Suga & Ma, 2003). Thus, while the cABR adheres closely to the stimulus, it is also modified slightly by factors unrelated to strict afferent processing. Specifically, and relevant to the topic of this paper, an individual's communication ability is revealed in these slight response modifications.

Two highly complex auditory phenomena that change the brain are language and music. There has been much research on how speakers of different languages have different processing patterns in the brain (Bidelman, Gandour, & Krishnan, 2011; Chandrasekaran, Krishnan, & Gandour, 2009; Näätänen et al., 1997); likewise for people with language difficulties such as dyslexia (Backes et al., 2002; Brunswick & Rippon, 1994; Galaburda, 1993; Habib, 2000; Shaywitz et al., 2002). Musicians' brains show differences compared to nonmusicians' brains both structurally (Gaser & Schlaug, 2003; Hyde et al., 2009; Pantev et al., 1998; Schlaug, 2001; Schneider et al., 2002) and functionally (Fujioka, Trainor, Ross, Kakigi, & Pantev, 2004; Kraus & Chandrasekaran, 2010; Parbery-Clark, Strait, Anderson, Hittner, & Kraus, 2011; Shahin, Bosnyak, Trainor, & Roberts, 2003; Strait, Chan, Ashley, & Kraus, 2011; Trainor, Shahin, & Roberts, 2009); and communication abilities are enhanced in people with musical training (Marques, Moreno, Castro, & Besson, 2007; Moreno et al., 2009; Schön, Magne, & Besson, 2004; Parbery-Clark, Skoe, Lam, & Kraus, 2009; Strait, Hornickel, & Kraus, 2011; Moritz, Yampolsky, Papadelis, Thomson, & Wolf, 2012).

Some of these (positive) changes brought about by music experience and training are negatively mirrored by aging. As we age, there are declines in cognitive skills such as attention and memory (Andrés, Parmentier, & Escera, 2006; Bloss et al., 2011; Craik, Luo, & Sakuta, 2010; Nyberg et al., 2010; Wang et al., 2011; Zacks, Hasher, & Li, 2000), hearing in noise (Hargus & Gordon Salant, 1995; Souza, Boike, Witherell, & Tremblay, 2007), perceptual timing skills (Parbery-Clark, Strait, & Kraus, 2011; Zendel & Alain, 2012), and neural timing (Casparly, Ling, Turner, & Hughes, 2008; Humes, Kewley-Port, Fogerty, & Kinney, 2010; Lister, Maxfield, Pitt, & Gonzalez, 2011; Tremblay, Piskosz, & Souza, 2003).

We have a series of experiments that look at musicianship's effect on listening skills and biological processing in participants of all ages. We have explored the relationships between cABR and cognitive abilities such as attention and memory, with an eye toward illuminating how music confers a route to maintain these skills as we age. We also have investigated the use of assistive listening devices in the classroom to determine how a better, clearer signal impacts learning, communication, and neural processing. Coupled with these experiments are lines of research into software-based auditory training activities to determine whether short-term training can provide some of the benefits that long-term music training can provide in the three realms of perception, cognition, and physiology.

## 2. Long term experience (music)

Music affects language. For example, a musician's ability to hear speech in noise is generally superior to a nonmusician's (Parbery-Clark, Skoe, & Kraus, 2009; Parbery-Clark, Strait, Anderson, et al., 2011; Zendel & Alain, 2012). Musicians also excel at other verbal-based skills including reading (Chan, Ho, & Cheung, 1998; Forgeard, Winner, Norton, & Schlaug, 2008; Ho, Cheung, & Chan, 2003; Moreno et al., 2011; Strait, Hornickel, et al., 2011). The OPERA hypothesis (Patel, 2011), with the letters of its acronym, posits some of the reasons why musicianship is linked to language ability. The common levels of auditory biological processing (i.e. overlap) that music and speech share is one of the biggest. Also, the precision that learning and playing music demands exercises the auditory system more than speech does. The often strong positive emotions involved in performing music involve limbic areas of the brain which are known to be a precursor to auditory learning in animals (Kilgard & Merzenich, 1998; Weinberger, 2007). Task repetition and attention round out the forces invoked by music which initiate cortical plasticity. In turn, the entire integrated auditory system is thereby strengthened.

However, the influence of music training on cortical structure and function, and on perceptual and communicative skills, is not the whole story. In the last several years, cABR has uncovered subcortical effects of musical training across the life span as well. For example, the similarity of the cABR to its evoking stimulus – in this case speech – is greater in child (Strait et al., in preparation) and young-adult (Parbery-Clark, Skoe, Lam, et al., 2009) musicians (Fig. 1, top). This measure of fidelity is also well correlated with both hearing-in-noise ability and auditory working memory, but not visual working memory (Fig. 1, bottom). A second cABR measure, the difference in phase in responses to two different stop consonants (ba, ga), also is enhanced in musicians (Parbery-Clark, Tierney, Strait, & Kraus, 2012). Again, this musician enhancement parallels that seen in good listeners in noise (Skoe, Nicol, & Kraus, 2011) (Fig. 2).

We believe that years of musical training, with its emphasis on memorization of sound, visual patterns, and auditory-motor sequences, leads to a strengthening of auditory memory – the ability to remember, manipulate (e.g., reorder), and recite lists of words, numbers or sentences. The improved memory affects realms outside of music by transferring to other communication skills such as hearing in noise. Strengthened cognitive skills improve auditory centers in the cortex, which, in turn, trickle down via the corticofugal efferent system to a more finely tuned auditory brainstem. But can this chain of events be initiated in a shorter time frame?

## 3. Classroom amplification devices

In collaboration with a Chicago school for learning-disabled children, we have performed communication skills and neurophysiological testing on children with reading impairments (RI) prior to and after one year of school. Half of the cohort

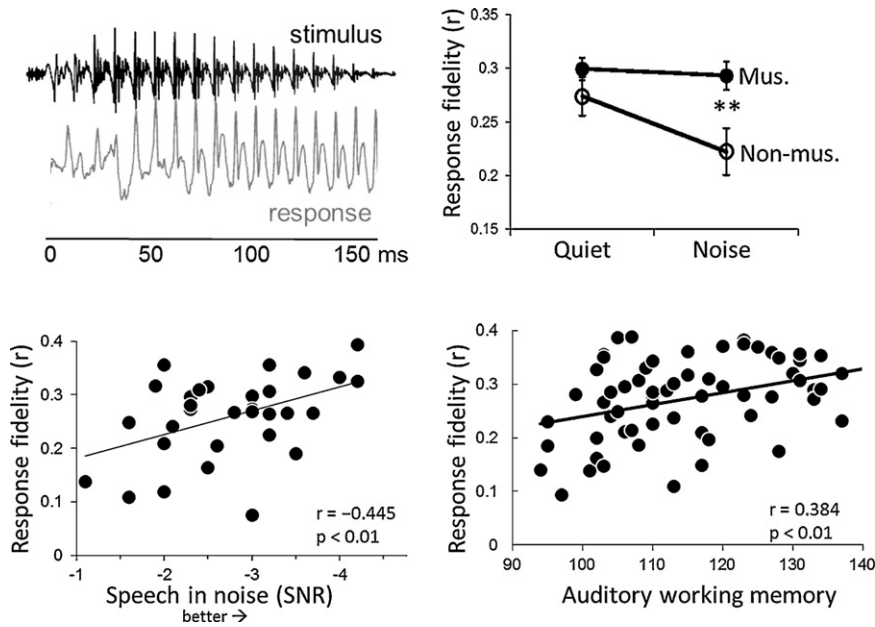


Fig. 1. Top left: The stimulus (black) and resultant cABR (gray) are similar in their features. This similarity enables the application of conventional cross-correlation techniques in order to assess response fidelity. Top right: When “da” is presented in a noise-free background, musicians and nonmusicians have about the same response fidelity. However, the addition of background noise reduces the fidelity of the nonmusician response. Bottom: Response-in-noise correlations with the stimulus are related to hearing in noise ability (left) and auditory working memory (right).

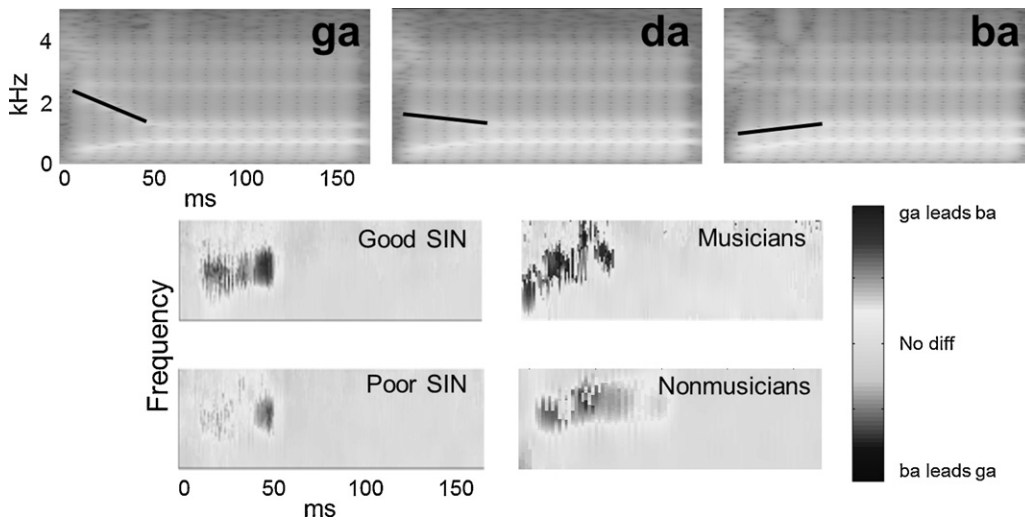


Fig. 2. Top: Spectrograms of synthesized stop-consonant-vowel syllables. The black lines trace the second formant trajectory that distinguishes ga, da and ba. Bottom: Cross-phaseograms depict, in color, the timing differences between pairs of responses (Skoee et al., 2011). Here, when comparing responses to ga and ba, warm colors signify portions of the response that are earlier to ga, a result of the higher-frequency second formant content in the first 50 ms. The extent to which this timing shift occurs is greater in good speech-in-noise (SIN) perceivers (left) and experienced musicians (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

of children wore FM assistive listening devices (Phonak EduLink). These devices amplified the teacher’s voice so that ambient classroom noises were less distracting. Such devices have been shown to improve reading and communication skills (Blake, Field, Foster, Platt, & Wertz, 1991; DiSarno, Schowalter, & Grassa, 2002; Flexer, Kemp Biley, Hinkley, Harkema, & Holcomb, 2002; Johnston, John, Kreisman, Hall, & Crandell, 2009; Purdy, Smart, Baily, & Sharma, 2009; Rosenberg et al., 1999), teacher perception of student learning (Purdy et al., 2009), and neural measures of attention (Friederichs & Friederichs, 2005). Here, unlike the non-FM-device-wearing RI controls in the same classroom, the FM-device wearers significantly improved on measures of reading and phonological awareness. Consistent with the observed variability that characterizes performance in people with RI, a cABR measure of response consistency–intra-session response replicability – was also improved in

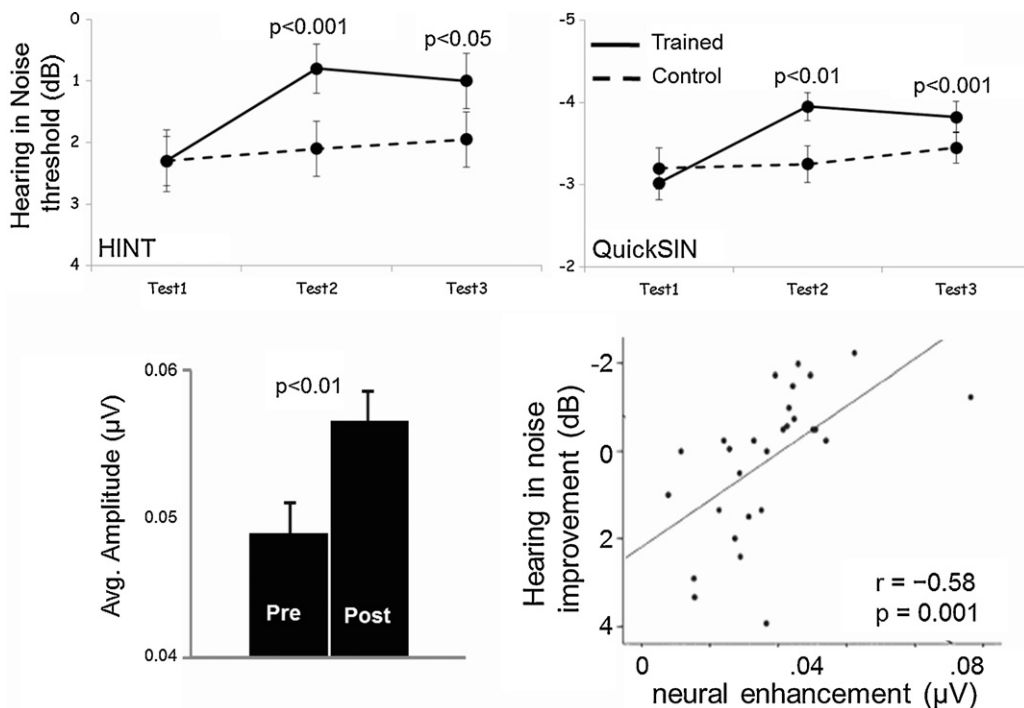
FM-device wearers, and the improvement on this measure was positively correlated with the extent of phonological-awareness improvement. Interestingly, the children in the experimental group who had the least consistent cABRs prior to the year of FM device usage showed the largest improvements in reading measures (Hornickel, Zecker, & Kraus, 2012). The changes seen in the cABR and their relationship with objective measures of reading skills serve as evidence that corticofugal-driven plasticity in the integrated auditory system is responsive to clear speech signals in the course of just one year. In the classroom, students wore the devices all day long while learning was occurring. Are similar communication gains possible in a focused training setting?

#### 4. Short term training

Given the effect of long-term musical experience on the cABR, medium-term classroom amplification, and the effects that training is known to have on projections to the inferior colliculus (Bajo et al., 2010), we asked whether shorter-term training might also affect this measure of auditory system integration. We looked at this in three subject populations – children on the autism spectrum, normal young adults, and older adults – using three different software-based training programs. All designs followed the same basic procedure: Participants underwent cognitive- and communication-skill testing and cABR testing. Then, they underwent their respective training programs for the prescribed number of weeks. Finally, after training, the pre-training battery was repeated. Each experimental group was paired with a non-trained control group and the two adult studies had a follow-up test session to gauge the persistence of training effects.

In children with autism spectrum disorder (ASD), we wondered whether the typical attribute of poor voice pitch production and perception would have a cABR correlate. Two “ya” syllables with rising and falling pitch contours, resembling the tones of voice used for questions and statements, respectively, were used as stimuli. Previous work had revealed that ASD children have cABRs with poor pitch tracking: That is, the fundamental periodicity of the response does not adhere closely to the pitch of the evoking stimulus (Russo et al., 2008). A small cohort of ASD children participated in 5–10 weeks of “Fast ForWord” training (Scientific Learning Corp.), a program that combines adaptive perceptual discrimination exercises with cognitive demands. A marked reduction in pitch error – the deviation of the response from the stimulus – was observed in one of the participants. Another aspect of the cABR, specifically timing to the syllable “da”, was improved in three participants relative to the non-trained controls (Russo, Hornickel, Nicol, Zecker, & Kraus, 2010).

In a much larger group of college-age subjects, we likewise looked for training-induced changes in hearing-in-noise abilities and subcortical function. LACE training (Neurotone), which is specifically targeted toward increasing participants’



**Fig. 3.** Top: A short-term training program (LACE) resulted in gains in speech-in-noise perception ability both immediately after concluding the program (test 2) and 6 months later (test 3). P values are test 2 vs. test 1 and test 3 vs. test 1 for trained group. Control group did not significantly improve. Bottom: Magnitude of spectral encoding of speech fundamental frequency and second harmonic was greater post-training for the experimental group (left) and the extent of the increase correlated with the improvement in a speech-in-noise measure (right).

ability to hear speech in noise, was administered to 28 young adults. Compared to their pre-training ability, LACE-trained participants increased their ability to understand speech in noise, as measured by QuickSIN (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004) and HINT (Nilsson, Soli, & Sullivan, 1994), relative to a matched untrained control group ( $n = 32$ ) (Fig. 3, top). These improvements coincided with an increase in cABR encoding of the fundamental frequency ( $F_0$ ) and second harmonic ( $H_2$ ) of a syllable “da” when it was presented in multi-talker background noise (Fig. 3, bottom left) (Song, Skoe, Banai, & Kraus, 2011) and a decrease in response timing. There was a significant correlation between hearing-in-noise improvement and cABR  $F_0$  and  $H_2$  encoding enhancement (Fig. 3, bottom right).

In ongoing work in older adults, we likewise are investigating communication skills and brainstem encoding following directed training. In this case, the training program was Brain Fitness (Posit Science), which purports to improve communication, hearing, and memory skills. This program, which is a variant of Fast ForWord, was administered over an 8-week period to an experimental group, while quizzes on educational programming, viewed for the same duration, were administered to a control group. Cognitive and perceptual abilities, including auditory memory, hearing in noise ability, and backward masking performance, were improved in the experimental group only. A cABR measure of timing in noise likewise became faster in the majority of Brain Fitness recipients, indicating that age-related neural timing delays were offset; controls did not improve (Anderson & Kraus, 2011; Anderson, Parbery-Clark, Choi, & Kraus, 2012).

Taken together, training programs in three different populations have provided evidence that directed training on the order of weeks can not only benefit perceptual and behavioral communication outcomes but also rewire biological processing in the integrated auditory system. As speculated above in the discussion of music-training’s role in influencing cABR, we believe that the impetus of the change lay in the cognitive demands that the training required. The exercising of attention and memory skills required for performing the tasks strengthened these cortical processes and, in turn, focused the auditory processing of the brainstem structures involved in cABR generation. The brainstem, in turn, with its improved acuity sends a more robust signal “up” to cortical processing structures, completing a positive feedback loop (Kraus & Chandrasekaran, 2009).

## 5. Conclusion

The learning and maintenance of communication skills involves a highly interactive and integrated auditory system. Much as it describes the overlap between music and language, the OPERA hypothesis also can serve as an enumeration of the ingredients required for effective training and successful learning. Effective learning requires both sensory and cognitive components (Bavelier, Achtman, Mani, & Föcker, 2012; Berry et al., 2011); focusing on just the former risks the ‘curse of specialization.’ Learning takes place on multiple time frames: Both life-long endeavors, such as playing a musical instrument or speaking a second language (Krizman, Marian, Shook, Skoe, & Kraus, 2012), and shorter-term amplification and focused listening training tune the auditory system. In each, sound-to-meaning relationships are formed, driven by cognitive processes such as attention and memory. Along with emotion, cognition affects basic response properties of the auditory

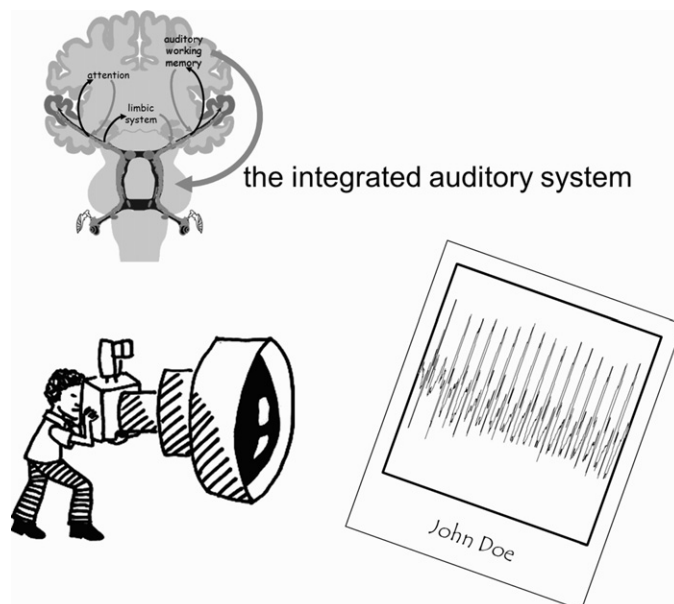


Fig. 4. Top: The integrated auditory system’s afferent (black) pathways are accompanied by downward-descending efferent (red) pathways that enable cognitive and emotional centers to exert influence on biological processing of sound. Bottom: cABR is a snapshot of auditory function, consisting of a combination of multiple sensory and executive processes which, together, impact everyday communication skills. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

system which can be accessed by cABR. Future longitudinal studies combining cortical physiology and imaging could be designed to solidify the supposition that cortical reorganization precedes subcortical tuning changes (Kraus & Chandrasekaran, 2010).

cABR, like other auditory brainstem response paradigms, is passively elicited. Yet, despite this, it is not a measure of passive processing. The cABR, as a nervous system index of sound processing, both reflects the encoding of the acoustics of sound and relates to executive function and everyday communication skills. Although inferential, this dual nature of cABR is consistent with the notion that “hearing” consists of the combination of multiple sensory and executive processes. cABR is a snapshot of the integrated auditory system—a system with strong afferent and efferent connections joining subcortical and cortical structures—revealing an auditory system molded by life experience (Fig. 4). These experiences enable auditory learning that promotes successful communication. The cABR, because it is so much more than a measure of one-way afferent encoding in the brainstem, has the potential for a variety of research questions plus wide-spread adoption into schools, clinics, industry, and other venues where there is an interest in assessing the biological basis of listening and monitoring the underlying changes wrought by education and training.

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## Appendix A. Continuing education

1. Performance on speech in noise tasks is
  - a. mediated by attention and working memory
  - b. reflected in brainstem function
  - c. better in musicians compared to non-musicians
  - d. mainly related to audiometric thresholds
  - e. a, b, and c
2. Brainstem response to complex sounds can be used for evaluation of auditory processes because
  - a. the response waveform resembles the stimulus waveform
  - b. the brainstem response is a snapshot of the integrated auditory system
  - c. latency differences of at least a millisecond are clinically significant
  - d. a and b
  - e. all of the above
3. Which of the following is true about auditory training?
  - a. adults are unable to materially improve their listening in noise
  - b. training for only a short period of time (~1–2 months) can change neural encoding in the brainstem
  - c. training has the same effect on all participants
  - d. training related changes are seen in the cortex but not the brainstem
  - e. c and d
4. Musical training has been shown to yield benefits in
  - a. working memory
  - b. speech-in-noise perception
  - c. neural encoding of speech
  - d. a and b
  - e. all of the above
5. The effects of noise on the brainstem response
  - a. include delays in peak timing
  - b. are particularly pronounced in the steady state region of the response
  - c. are less pronounced in children with poor speech-in-noise perception
  - d. result in increased amplitudes in children with good speech-in-noise perception
  - e. all of the above

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