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cABR: A Biological Probe of Auditory Processing

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Overview

Symptoms of auditory processing disorders (APD), including impaired perception of sound in challenging listening conditions, are often associated with poor language and communication skills that negatively impact learning and academic achievement in noisy classrooms (Bamiou, Musiek, & Luxon, 2001; Chermak, 2002; Dawes & Bishop, 2009; Keith, 1999; Smoski, Brunt, & Tannahill, 1992). Because of the importance of auditory processing for successful communication and language development, viable measures are needed to assess these skills. Present assessment batteries generally rely on behavioral measures which can be impacted by subject factors such as alertness/fatigue and co-occurring disorders (Baran, 2007). As illustrated in this chapter, the auditory brainstem response (ABR) to speech informs the biological mechanisms that subserve auditory processing. In addition to reflecting communication skills such as speech-in-noise perception, ABRs to complex sounds (cABRs) index the effects of lifelong and short-term meaningful interaction with sound. The auditory system is highly integrated and we define auditory processing based on this synthesis of sensory, cognitive, and emotional components. Our view is that auditory processing disorders result when efficient interactions with sound fail to occur and sound-to-meaning relationships are not established. It is acknowledged that there is no consensus on the defini-

tion of APD and no gold standard measure for assessing APD. Therefore, we argue that the clinical presentation of APD, such as difficulty listening, academic problems, and poor understanding of speech in noise, is the best working definition of APD. Because the cABR reflects these skills, it contributes to our understanding of the biological bases of APD and to the armamentarium for assessing them. As auditory processing and the neural representation of sound can be modified by meaningful interaction with sound, it is likely that repeated impaired interaction with sound, such as in APD, perpetuates auditory dysfunction. Similarly, this plasticity of the auditory system suggests that neural and communication deficits can be remediated with training. We discuss how cABRs yield unique and objective information about auditory neural function, thereby informing our understanding and assessment of auditory processing disorders. We also highlight links between auditory brainstem responses to complex stimuli and common symptoms of auditory processing disorders, such as poor speech-in-noise and psychophysical perception (e.g., temporal gap detection), particularly in children with reading disorders who often exhibit these auditory processing impairments. We suggest that auditory brainstem responses to complex stimuli, by reflecting sensory and cognitive influences on auditory function, provide a biological snapshot of auditory processing itself. We conclude by recommending auditory brainstem responses to complex stimuli as objective measures of training-related neural change during remediation.

Introduction

Auditory processing impairments exist in cases of neurological dysfunction such as seizure disorders, traumatic brain injury, and lesions, and similarly it is thought that children with APD without frank neurological disorders have disordered or immature nervous systems (Chermak & Musiek, 2011). Moreover, children with suspected APD show a similar pattern of performance as children with temporal lobe lesions on tasks of auditory processing (Jerger, Johnson, & Loiselle, 1988), suggesting that disordered nervous systems are characteristic of APD in children (Chermak & Musiek, 2011). Approximately two-thirds of APD cases are thought to be due to neural abnormalities such as polymicrogyri (underdeveloped cells) in the left hemisphere and corpus callosum, but it is suggested that one-third of cases are due to neural immaturity (Chermak, 2002), which is likely system-wide and affects both cortical and subcortical structures. Recent research also shows that children with language and communication impairments common in APD have deficient auditory brainstem responses to speech and speechlike sounds relative to typically developing peers (Anderson, Skoe, Chandrasekaran, & Kraus, 2010; Banai et al., 2009; Basu, Krishnan, & Weber-Fox, 2010; Billiet & Bellis, 2011; Chandrasekaran, Hornickel, Skoe, Nicol, & Kraus, 2009; Chandrasekaran & Kraus, 2012; Filippini & Schochat, 2011; Hornickel, Skoe, Nicol, Zecker, & Kraus, 2009; Hornickel, Anderson, Skoe, Yi, & Kraus, 2012; King, Warrier, Hayes, & Kraus, 2002; Rocha-Muniz, Befi-Lopes, & Schochat, 2012; Strait, Hornickel, & Kraus, 2011; Wible, Nicol, & Kraus, 2004), suggesting that APD may also include auditory brainstem dysfunction.

What Is the cABR?

Since the 1970s, ABRs to click stimuli (brief broadband stimuli) have been utilized for objective, noninvasive assessments of hearing and the integrity of the auditory pathway (Hall, 2006; Hood, 1998; Musiek, Shinn, & Jirsa, 2007; Sininger, 2007). The ABR, which reflects synchronous electrical activity in the nuclei of the auditory pathway, is collected on the scalp using electrodes (Sininger, 2007; Skoe & Kraus, 2010). A hallmark of the ABR is its robust consistency and reliability within an individual in the absence of meaningful engagement with sound. For example, click-ABR response timing varies only fractions of a millisecond within an individual for responses collected on the same day, across days, and across years (Edwards, Buchwald, Tanguay, & Schwafel, 1982; Issa & Ross, 1995; Lauter & Oyler, 1992). Because the auditory brainstem is remarkably faithful in its representation of stimulus characteristics, research and clinical assessment have recently incorporated more naturalistic and complex stimuli such as speech, music, and environmental sounds in evoking ABRs. We use the term complex ABR (cABR) to represent ABRs collected to stimuli with more complex acoustic characteristics and presentation schemes than a standard click stimulus. cABRs allow for the identification of fine-grained auditory processing deficits associated with real-world communication skills that are not apparent in click-evoked responses.

The cABR faithfully tracks the acoustic parameters of the stimulus that are important for both speech and music communication, including pitch, timing, and harmonics. As a consequence, the response waveform visibly mimics the stimulus features (Figure 7–1; Skoe & Kraus, 2010), and an acoustic playback of the cABR audibly sounds like the stimulus[1] (Galbraith, Arbagey, Branski, Comerci, & Rector, 1995). In speech, timing and harmonic cues are important for distinguishing and discriminating consonants and vowels (Blumstein & Stevens, 1979; Delattre, Liberman, & Cooper, 1955; Miller & Nicely, 1955; Summerfield & Haggard, 1977), pitch cues are important for understanding prosody and intonation (Bachorowski & Owren, 1995; Ladefoged, 2006), and pitch and the highest harmonics are important for identifying

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[1]For an audio demonstration, visit http://www.brainvolts.northwestern.edu and select Demonstration: Brainstem Responses to Complex Sounds.
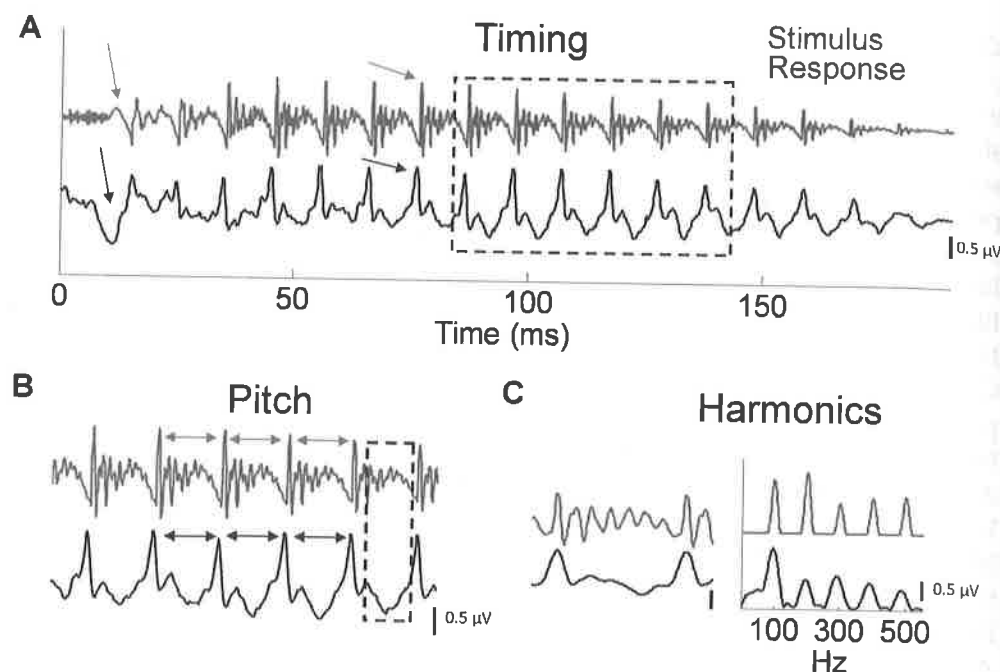
Figure 7–1. Auditory brainstem responses reflect stimulus timing, pitch, and harmonics. **A**. The speech-evoked auditory brainstem response (bottom trace, *black*) visually mimics the evoking stimulus, [da] (top trace, *gray*). Stimulus characteristics of timing (A), pitch (B) and harmonics (C) are represented in the response. Reprinted with permission from Skoe, E., and Kraus, N. (2010). Auditory brainstem response to complex sounds: A tutorial. *Ear and Hearing, 31*(3), 302–324.

who is speaking (Bachorowski & Owren, 1999; Ladefoged, 2006). Similarly, in music, spectrotemporal content marks instruments as being distinct (Caclin, McAdams, Smith, & Winsberg, 2005; Iverson & Krumhansl, 1993), pitch facilitates melody perception (de Cheveigne, 2005; Meddis & O'Mard, 1997), and timing contributes to the perception of tempo (Honing, 2001). In this chapter and in Chapter 27, Meaningful Engagement with Sound for Strengthening Communication Skills, we illustrate how the cABR can probe real-world listening and learning skills and how meaningful engagement with sound can alter neural function.

Experience-Dependent Malleability of the cABR

Evidence from studies in humans and animals indicates that the auditory system, as can be assessed by the cABR, is highly malleable with meaningful experience with sound, such as learning to discriminate tones for a reward or linking sounds with meaning when learning a language. For example, adults who have participated in lifelong musical training have enhanced auditory brainstem representation of both speech and music, even when the stimulus is presented in background noise (Bidelman, Krishnan, & Gandour, 2011; Lee,

Skoe, Kraus, & Ashley, 2009; Musacchia, Sams, Skoe, & Kraus, 2007; Parbery-Clark, Skoe, & Kraus, 2009; Parbery-Clark, Anderson, Hittner, & Kraus, 2012; Strait, Kraus, Skoe, & Ashley, 2009). These neural enhancements likely underlie musicians' better speech-in-noise perception and psychophysical performance relative to nonmusicians (Parbery-Clark, Skoe, Lam, & Kraus, 2009; Parbery-Clark, Strait, Anderson, Hittner, & Kraus, 2011; Strait, Kraus, Parbery-Clark, & Ashley, 2010). Language exposure can also shape how the auditory brainstem responds to complex stimuli (Krizman, Marian, Shook, Skoe, & Kraus, 2012). For example, native speakers of tonal languages (e.g., Mandarin Chinese, Thai), have stronger representations of complex, linguistically meaningful pitch contours than native English speakers (Krishnan, Gandour, Anathakrishnan, Bidelman, & Smalt, 2011; Krishnan, Gandour, & Bidelman, 2010; Krishnan, Swaminathan, & Gandour, 2009).

The connection between cABRs and auditory expertise suggests that focused attention to meaningful interactions with behaviorally relevant sounds, such as repeated discrimination, use, or manipulation, are needed to fine-tune auditory processing. The influence of meaningful interaction with sound on auditory processing in experts has implications for clinical disorders such as APD. Continual practice with impaired representations of sound, due to auditory processing disorders or learning impairments, likely negatively impacts auditory brainstem function (also discussed in Merzenich et al., 2002). The malleability of auditory brainstem function with mean-

ingful interaction with sound suggests these deficits may be fixable through focused auditory-based training (Hornickel, Zecker, Bradlow, & Kraus, 2012; Russo, Hornickel, Nicol, Zecker, & Kraus, 2010; Russo, Nicol, Zecker, Hayes, & Kraus, 2005). Response malleability can be seen for targeted auditory training that yields benefits in both the neural encoding and perception of speech in noise, a common symptom of APD (Russo et al., 2005; Song, Skoe, Banai, & Kraus, 2011b). As discussed below, the cABR to speech has been linked to speech-in-noise perception across the lifespan. Thus it could be used as an objective metric of auditory function that is free of most subject factors that can corrupt behavioral assessments. Importantly, impaired cABRs are also associated with poor speech-in-noise perception, which can impact communication and academic success. That these particular measures can be enhanced with training also suggests the cABR may be useful as a metric of training-related improvement.

Neural Correlates of Auditory Processing

Ingredients for Successful Speech-In-Noise Perception

Poor perception of speech in noisy environments is a common symptom of APD. Successful speech-in-noise (SIN) perception relies on utilizing multiple cues such as pitch, spatial location, loudness, temporal continuity, and linguistic content to successfully segment the speech stream from the competing background noise and track the speech

stream of interest over time (Best, Ozmeral, Kopco, & Shinn-Cunningham, 2008; Bregman, 1994; Oxenham, 2008; Shinn-Cunningham & Best, 2008). Vocal pitch is a particularly useful cue for separating speech from background noise when the speech target and competing noise are not spatially segregated (Bregman, 1994). In support of this, it has been shown that as the difference in vocal pitch increases between a target and competing background noise, performance in identifying the target improves (Assmann, 1999; Binns & Culling, 2007; Darwin & Hukin, 2000). Additionally, when tones are played interspersed, one or two sound streams can be perceived depending on the frequency difference between tone sets, with larger frequency differences resulting in the perception of two sound sources (Bregman, 1994). Similar stream segmentation can be found when stimuli differ temporally as we tend to group auditory events that occur at a short duration apart as being from the same source (Bregman, 1994).

In addition, the temporal and harmonic cues important for distinguishing consonants (e.g., "d," "g," "b") are particularly confusing in background noise (Nishi, Lewis, Hoover, Choi, & Stelmachowicz, 2007), suggesting that temporal perception may also be particularly important for understanding the linguistic content of speech in noise. Because pitch and timing cues impact speech-in-noise perception, it is intuitive that speech-in-noise perception skill could be predicted by cABR measures of timing and pitch. These relationships may be particularly amplified when collecting cABRs to speech in the presence of background noise.

cABR Representation of Pitch Relates to Speech-in-Noise Perception

Across the life span, the representation of pitch cues in the cABR to speech is predictive of speech-in-noise (SIN) perception skill (Anderson, Parbery-Clark, Yi, & Kraus, 2011; Anderson, Skoe, Chandrasekaran, Zecker, & Kraus, 2010; Song, Skoe, Banai, & Kraus, 2011a). This has been demonstrated for participants who have normal hearing acuity and normal click-evoked ABRs. In these studies, cABRs were collected to the speech syllable [da], presented in quiet or in a multitalker background noise that mimics real-world conditions. Separately, SIN perception was assessed using commercially available clinical tests that require the participants to repeat target sentences arising from the same spatial location as the competing background noise, a condition in which pitch cues might be particularly useful. Poor SIN perceivers had significantly weaker representation of pitch cues in their cABRs (Figure 7–2A; Anderson et al., 2011; Song, Skoe, et al., 2011a). Differences in pitch representation between good and poor SIN perceivers became stronger as the number of talkers in the background noise increased (Song, Skoe, et al., 2011a). Importantly, the groups were matched on verbal and cognitive abilities, supporting the proposition that the results reflect fundamental differences in auditory processing of complex stimuli and not online working memory and attention differences known to impact SIN perception (Best et al., 2008; Shinn-Cunningham & Best, 2008).

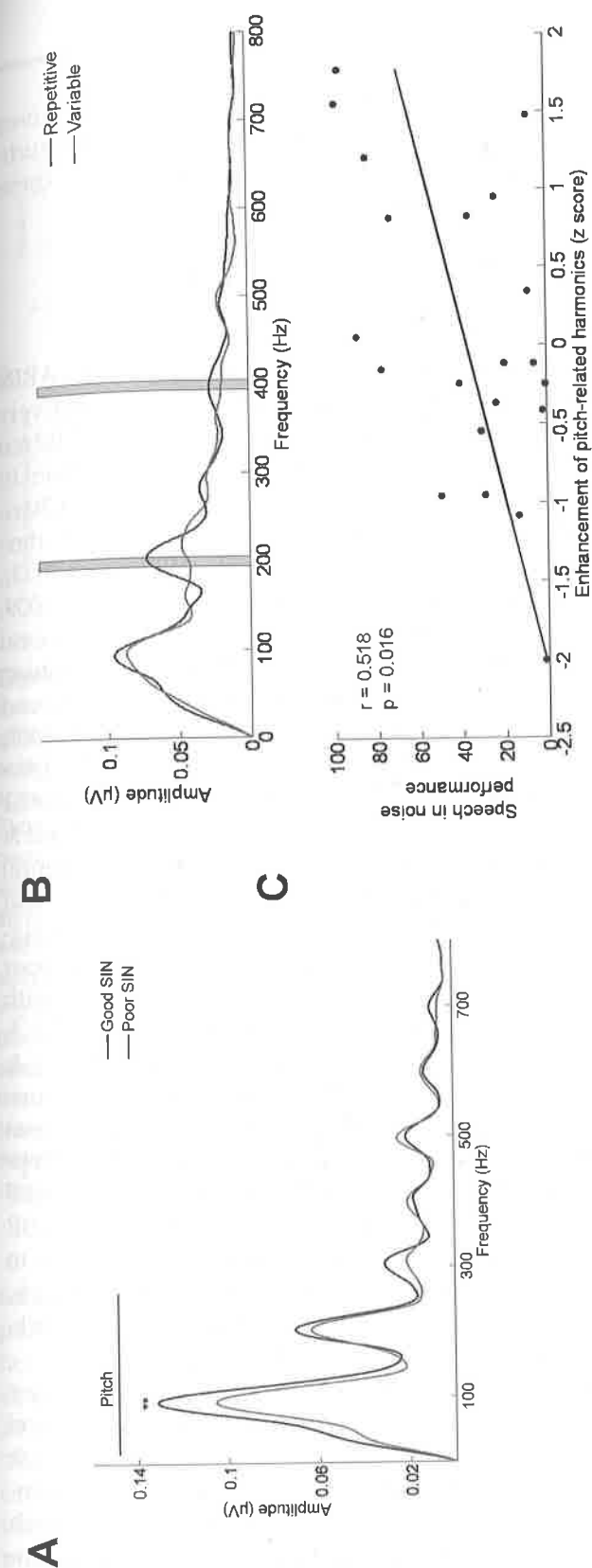Chandrasekaran and colleagues extended these findings to presentation

Figure 7–2. cABR representation of vocal pitch relates to speech-in-noise perception. **A.** Children who are above average speech-in-noise perceivers (*black*) have significantly greater subcortical representation of vocal pitch than do children who are poor speech-in-noise perceivers (*gray*). ** p < 0.01 Reprinted from Anderson, S., Skoe, E., Chandrasekaran, B., Zecker, S. G., and Kraus, N. (2010). Brainstem correlates of speech-in-noise perception in children. *Hearing Research, 270*(1–2), 151–157, Copyright 2010, with permission from Elsevier. **B.** Auditory brainstem responses to [da] in a predictable context (*black*) are larger than those to [da] in a variable, unpredictable context (*gray*), particularly for lower harmonics related to the perception of vocal pitch. **C.** The strength of enhancement of pitch-related harmonics in the predictable condition correlates with speech-in-noise perception, such that better speech-in-noise perceivers show a greater enhancement of pitch-related harmonics in the predictable condition. Reprinted from Chandrasekaran, B., Hornickel, J., Skoe, E., Nicol, T., and 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, Copyright 2009 with permission from Elsevier.

contexts that require the integration of pitch cues over time. In this study, the stimulus [da] was presented in a predictable context, occurring 100% of the time, and in an unpredictable context in which it was randomly intermixed with other speech syllables and occurred only 12.5% of the time. cABRs to [da] in the predictable presentation context had more robust representation of low, pitch-related harmonics, than cABRs to [da] in the unpredictable presentation context (Figure 7–2B; Chandrasekaran, et al., 2009). Notably, poor readers did not show this benefit from predictability (see also Strait et al., 2011). The magnitude of this difference in pitch-related harmonics between the two conditions positively correlated with SIN perception, with better perception being associated with greater neurophysiological enhancements in the predictable context (Chandrasekaran, et al., 2009). Taken together, these lines of work suggests that the representation of pitch cues, tracking of pitch cues over time, and enrichment of encoding with stimulus repetition may be indicative of strong SIN perception and learning ability.

Although children with APD are particularly impacted when speech occurs in competing background noise, documented symptoms of APD include difficulty following and remembering spoken instructions in quiet (Bamiou, et al., 2001; Smoski et al., 1992). Paralleling this, we find that neural differences between good and poor SIN perceivers occur even when speech stimuli are presented in quiet (Anderson, Skoe, Chandrasekaran, Zecker, et al., 2010; Chandrasekaran et al., 2009). Thus, neural deficiencies in nonchallenging listening conditions (i.e, quiet) can

still be symptomatic of APD, given the pervasive abnormalities in auditory function associated with these disorders.

Response Timing Relates to SIN Perception

The timing of speech-evoked cABRs can also be predictive of objectively assessed SIN perception in children and self-assessed SIN perception in older adults (Anderson, Skoe, Chandrasekaran, & Kraus, 2010; Anderson, Parbery-Clark, White-Schowch, & Kraus, 2012; Hornickel et al., 2009; Skoe, Nicol, & Kraus, 2011). Temporal cues are important for distinguishing consonants and for segregating sound streams (Bregman, 1994; Nishi et al., 2007; Summerfield & Haggard, 1977). However, the presence of background noise degrades neural synchrony (Burkard & Don, 2007), leading to delayed neural responses even in healthy adults and children. The extent of this delay is significantly greater in children with poor SIN perception relative to those with good SIN perception (Figure 7–3A & B; Anderson, Skoe, Chandrasekaran, & Kraus, 2010). Evidence from adult musicians also supports the link between neural delay in noise and SIN perception, as musicians have both enhanced SIN perception and more robust cABR timing in background noise relative to adult nonmusicians (Parbery-Clark, Skoe, & Kraus, 2009; Parbery-Clark, Skoe, Lam, et al., 2009).

Temporal acuity is also necessary for distinguishing consonant-vowel (CV) speech syllables (Summerfield & Haggard, 1977). The most spectrotemporally complex portion of a CV speech syllable, the rapid transition from a con-
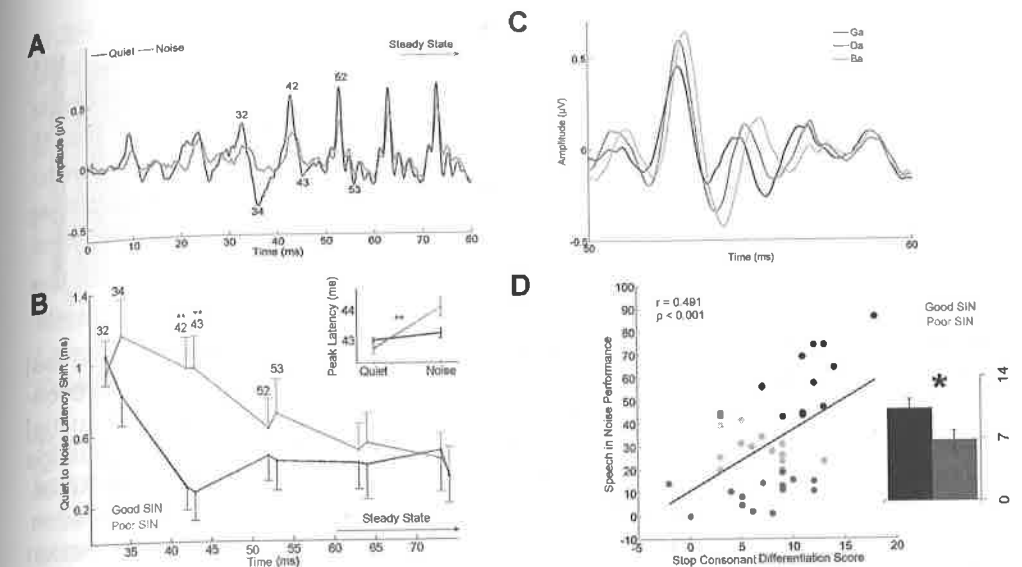

Figure 7–3. cABR timing relates to speech-in-noise perception. **A.** Responses to speech presented in background noise (*gray*) are degraded relative to responses to speech in quiet (*black*), being smaller in amplitude and slower. **B.** Poor speech-in-noise perceivers (*gray*) show larger noise-induced timing shifts than above-average speech-in-noise perceivers (*black*). Reprinted with permission from Anderson, S., Skoe, E., Chandrasekaran, B., and Kraus, N. (2010). Neural timing is linked to speech perception in noise. *Journal of Neuroscience, 30*(14), 4922–4926. **C.** Higher harmonics of speech syllables (>1000 Hz) are likely represented through peak timing, with stimuli with the highest harmonics ([ga] in *black*) eliciting earlier responses than stimuli with lower harmonics ([da] in *dark gray*), which also elicit earlier responses than those with the lowest harmonics ([ba] in *light gray*). **D.** Brainstem representation of these timing differences is predictive of speech-in-noise perception, with poor speech-in-noise perceivers having weaker neural differentiation of the three syllables. Above-average speech-in-noise perceivers (*black*) have better representation of the timing pattern than poor speech-in-noise perceivers (*dark gray*). Reprinted with permission from Hornickel, J., Skoe, E., Nicol, T., Zecker, S. G., and Kraus, N. (2009). Subcortical differentiation of stop consonants relates to reading and speech-in-noise perception. *Proceedings of the National Academy of Sciences, 106*(31), 13022–13027. *(continues)*

sonant to the following vowel, can be particularly degraded by background noise, contributing to consonant confusion (Miller & Nicely, 1955; Nishi et al., 2007). The rapid, high-frequency transitions that characterize different stop consonants result from differences in vocal tract configuration during speech production (Delattre et al., 1955; Miller

& Nicely, 1955). Due to the tonotopic organization of the auditory system (Gorga, Kaminski, Beauchaine, & Jesteadt, 1988; Pickles, 1988), the auditory brainstem appears to represent the differences among consonants through response timing (Hornickel et al. 2009; Johnson et al., 2008; Skoe et al. 2011). In this way, responses to a CV stimulus
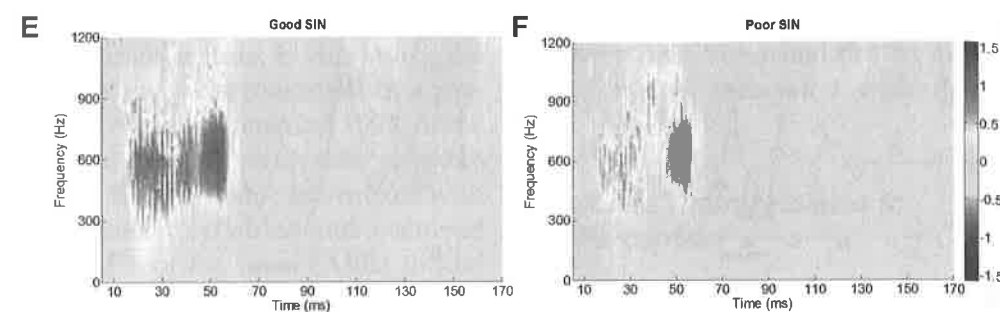
Figure 7–3. *(continued)* **E**. Phase differences between responses to [ga] and [ba] are large (*darker*) for good speech-in-noise perceivers but are weak for poor speech-in-noise perceivers, **F**. Phase differences between responses (with responses to [ba] phase lagging responses to [ga], *darker*) are seen in the first formant frequency range and during the formant transition only. Reprinted from Skoe, E., Nicol, T., and Kraus, N. (2011). Cross-phaseogram: Objective neural index of speech sound differentiation. *Journal of Neuroscience Methods*, *196*(2), 308-317, Copyright 2011, with permission from Elsevier.
*p < 0.05 **p < 0.01

with higher formant frequencies (e.g., [ga]) elicit earlier responses than a CV syllable with lower formant frequencies (e.g., [ba]; Hornickel et al., 2009; Johnson, Nicol, Zecker, et al., 2008). The magnitude of this timing difference is predictive of SIN perception (Figures 7–3C and 7–3D; Hornickel et al., 2009; Skoe et al. 2011; Tierney, Parbery-Clark, Skoe, & Kraus, 2011). Children with better SIN perception have larger timing differences among responses to contrastive speech sounds, indicating greater subcortical (i.e., brainstem) differentiation of the sounds (Figures 7–3D, 7–3E and 7–3F; Hornickel et al., 2009; Skoe et al., 2011). The failure to accurately encode different meaning-bearing speech contrasts has obvious implications for the understanding of speech in background noise.

It is important to point out that relationships between cABRs and SIN perception in children are seen exclusively in the response to the formant transition of the [da] syllable and not during the response to the steady-state vowel. Formant transitions are the most acoustically complex segment of a stop-consonant syllable because they include multiple frequency sweeps covering hundreds of hertz over only a fraction of a second (Delattre, et al., 1955). Formant transitions also yield linguistic information for interpreting speech streams by serving to differentiate consonants and vowels (Blumstein & Stevens, 1979; Delattre et al., 1955; Miller & Nicely, 1955; Summerfield & Haggard, 1977). It is well documented that children with language and learning impairments have difficulty perceiving rapidly presented formant transitions and that they also have difficulty categorizing speech based on these cues (Adlard & Hazan, 1998; Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008; Serniclaes & Sprenger-Charolles, 2003; Tallal, Miller, Jenkins, & Merzenich, 1997; Tallal & Piercy, 1974, 1975). Thus, we suggest that the relationships among

cABR pitch, cABR timing, and SIN perception are found in the formant transition region because it is the most linguistically meaningful and acoustically complex portion of the syllable that is particularly vulnerable to degradation in background noise.

Neural Correlates of SIN Are Largely Distinct from the Neural Correlates of Reading

The research discussed above has helped to establish that subcortical representation of the elemental components of speech, such as pitch and timing, can provide a neural signature of SIN perception (Anderson et al., 2011; Anderson, Skoe, Chandrasekaran, & Kraus, 2010; Anderson, Skoe, Chandrasekaran, Zecker, et al., 2010; Chandrasekaran, et al., 2009; Chandrasekaran & Kraus, 2012; Hornickel et al., 2009; Skoe et al., 2011; Tierney et al., 2011). Numerous studies have found that reading is also linked to deficient auditory brainstem function. cABR measures of timing, harmonics, neural consistency, and utilization of stimulus regularities predict reading and reading-related abilities in children (Anderson, Skoe, Chandrasekaran, & Kraus, 2010; Banai et al., 2009; Banai, Nicol, Zecker, & Kraus, 2005; Basu et al., 2010; Billiet & Bellis, 2011; Chandrasekaran et al., 2009; Hornickel et al., 2012; Hornickel et al., 2009; Johnson, Nicol, Zecker, and Kraus, 2007; Rocha-Muniz et al., 2012; Strait et al., 2011; Wible et al., 2004). See Chandrasekaran and Kraus, 2012 for a review of these relationships. Although reading and SIN perception do share common neural correlates, recent analytical modeling has corroborated that both communication skills are represented by

unique neural signatures. By simultaneously assessing relationships among multiple neural and behavioral metrics, structural equation modeling was used to determine the neural predictors of measures of SIN perception and measures of reading. When modeling the relationship between cABR measures and SIN measures, the model with the greatest predictive power for SIN perception was one that included cABR measures of pitch, tracking of pitch cues over time, and response timing in noise. Importantly, the cABR measures that best predicted SIN performance differed from those that best accounted for reading skill, which included harmonic encoding and response timing (Hornickel, Chandrasekaran, Zecker, & Kraus, 2011). Thus, the neural measures that relate to SIN perception are distinct from those that relate to reading, supporting the proposition that SIN perception has a unique neural signature. If cABRs are to be used in a clinical setting, the unique neural correlates of SIN perception should be targeted in order to determine SIN-specific auditory brainstem dysfunction that might be particularly indicative of APD.

As an illustrative example, we describe a case study representative of child with suspected APD. This 12-year-old boy was falling short academically and was easily distractible. He had above average intelligence and reading skills; however, his speed of processing and ability to maintain attention were weak. He also had particular difficulties with the perception of speech in noise and performed poorly on behavioral measures of APD such as dichotic listening. When assessing his cABR to speech stimuli, we found that he had particularly poor representation of the pitch of the stimuli

and his response showed an excessive time delay when speech was presented in background noise. He also showed impaired neural differentiation of three stop-consonants via response timing and reduced utilization of stimulus regularities. However, he did not show impaired representation of higher speech harmonics commonly seen in poor readers, consistent with his proficient reading skill. Thus, his neural responses fit a pattern of deficits in the representation of pitch and timing in noise seen for children with poor SIN perception but not a pattern of deficits common to poor readers and match his skills in reading and deficits in SIN perception. Thus, the cABR measures provided a biologic basis for his auditory distractibility and impaired perception of speech in noise.

Psychophysical Temporal Processing and cABR Measures

Hallmark symptoms of APD include impaired perception of stimuli in challenging listening conditions and deficits in sound localization, pattern detection, and temporal processing (Bamiou et al., 2001; Chermak, 2002; Dawes & Bishop, 2009; Keith, 1999; Smoski et al., 1992). The American Speech-Language-Hearing Association's definition of auditory processing impairments includes temporal aspects of audition, specifically temporal integration, temporal ordering, and temporal masking (ASHA, 1996). Temporal processing is assessed behaviorally through gap detection tasks (a temporal gap between two stimuli is reduced until no longer perceptible) and backward masking tasks (the level of a noise burst following a tone is manipulated to make the tone

imperceptible; Hartley, Wright, Hogan, & Moore, 2000; Shinn, Chermak, & Musiek, 2009). It is argued that temporal processing deficits may underlie learning and language impairments due to the rapidity of consonant-vowel formant transitions (Delattre, et al., 1955; Tallal, et al., 1997). For learning impaired children, perceptual deficits can be ameliorated by increasing the length of the formant transition (Tallal & Piercy, 1975). As temporal processing can impact speech perception in noise, children with language-based learning impairments are also adversely affected by competing background noise (Bradlow, Kraus, & Hayes, 2003; Ziegler, Pech-Georgel, George, & Lorenzi, 2009). Temporal processing deficits may be one common impairment among children with language, learning, and auditory processing disorders that universally impacts speech perception both in quiet and background noise.

Behavioral and neural measures of temporal processing skills are linked. In cABRs to speech, children with poor backward masking thresholds and language learning impairments have slower timing in response to the onset and offset of the formant transition of a speech syllable (Figures 7–4A and 7–3B; Johnson, et al., 2007). The inability of the nervous system to faithfully capture the cessation of a sound may result in poor backward masking thresholds, reflecting an inability to distinguish two stimuli (i.e., the target tone and following noise) as being temporally distinct (Johnson et al., 2007; Phillips, 1999). Neural deficiencies in sound detection could lead to impairments in distinguishing speech from background noise (i.e., grouping the two signals as one through misidentified
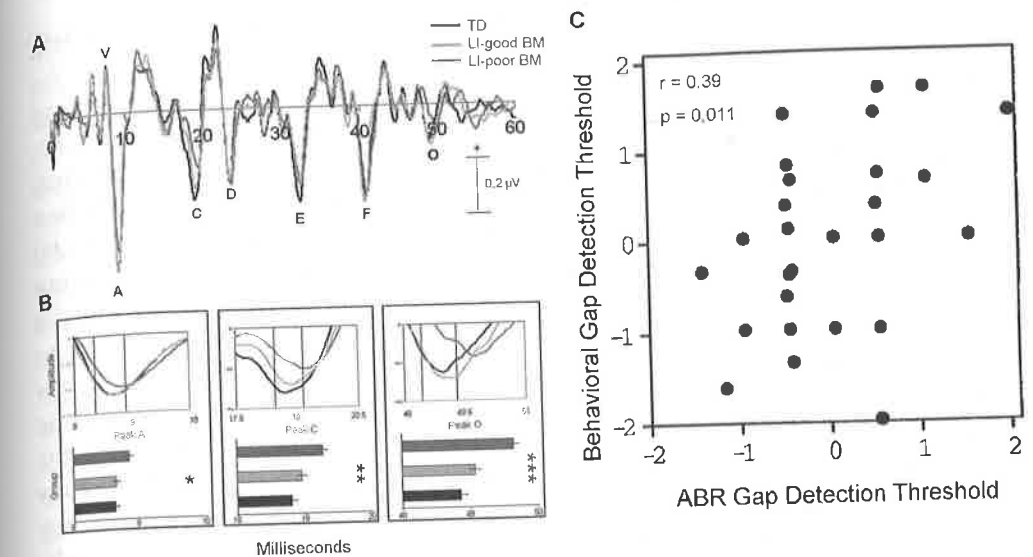
Figure 7–4. cABR measures relate directly to temporal processing. **A.** Auditory brainstem responses to [da] for typically developing children (TD, *black*), learning impaired children with normal backward masking thresholds (LI-good BM, *light gray*), and learning impaired children with poor backward masking thresholds (LI-poor *dark gray*). **B.** LI-poor BM (*dark gray*) have later brainstem responses than LI-good BM children (*gray*) and TD peers (*black*), particularly for the response to the offset of the syllable (Peak O). Responses of the LI-good BM children (*light gray*) do not differ from those of TD children (*black*). Reprinted by permission of MIT Press Journals from Johnson, K., Nicol, T., Zecker, S. G., and Kraus, N. (2007). Auditory brainstem correlates of perceptual timing deficits. *Journal of Cognitive Neuroscience, 19*, 376–385, Copyright 2007 Massachusetts Institute of Technology. **C.** Although gap detection thresholds determined by ABRs are slightly better than behavioral thresholds, the two thresholds are correlated in healthy young adults suggesting they measure two manifestations of the same skill. Note: In panel C, the effects of stimulus level have been partialled out and these values reflect residuals. Reprinted from Werner, L. A., Folsom, R. C., Mancl, L. R., and Syapin, C. L. (2001). Human auditory brainstem response to temporal gaps in noise. *Journal of Speech, Language, and Hearing Research, 44*, 737–750, Copyright 2001 American Speech-Language-Hearing Association. http://jslhr.asha.org/cgi/content/abstract/44/4/737
*p < 0.05 **p < 0.01 ***p < 0.001

temporal cues) and confusing speech even when it is successfully separated from the noise. The inability to differentiate speech sounds may lead to "smearing" of speech, which could lead to the development of language focused on a slower temporal scale (i.e., syllables) rather than a faster temporal scale (i.e.,

phonemes) that is important for linguistic meaning (Merzenich et al., 2002).

Like cABRs to speech, subcortical responses to backward masking and gap detection stimuli relate to behavioral thresholds (Marler & Champlin, 2005; Werner, Folsom, Mancl, & Syapin, 2001). Language-impaired children had

higher backward masking thresholds relative to typically developing peers when assessed behaviorally; similarly their cABR thresholds were higher, as determined by the reliable presence of a response to a tone followed by a masker (Marler & Champlin, 2005). Additionally, at a sufficiently loud level for all children to have a reliable response, the language-impaired children had significantly later neurophysiological responses than their typically developing peers (Marler & Champlin, 2005). In a similar vein, Werner and colleagues assessed gap detection thresholds behaviorally and electrophysiologically. In typically functioning adults, subcortical thresholds were slightly better than behavioral thresholds, but only by a fraction of a millisecond, and the two thresholds were significantly correlated (Figure 7–4C; Werner et al., 2001).

Use of cABRs in the Assessment of APD

Given the evidence that cABRs are linked to psychophysical and communication skills known to be deficient in children with APD, cABRs can yield information about auditory processing not available to clinicians through behavioral metrics. This is particularly true for infants and young children who are unable to complete complex behavioral tasks and in cases when concomitant disorders may obscure results. Although primary testing batteries for APD are behavioral in nature, there is no gold-standard test for diagnosing APD. Even the best formed behavioral tests can be confounded by subject factors such as attention, motivation, alertness/fatigue, and co-occurring disorders such as language impairments,

learning impairments, or attention deficits (Baran, 2007).

In diagnosing APD, cABRs may contribute additional proof of dysfunction and reveal particular biological deficits (Rocha-Muniz et al., 2012). In a study of children with developmental dyslexia, 70% were classified as having APD via behavioral assessment and the remaining 30% had deficient cABRs to speech without sufficiently poor behavioral performance to meet diagnostic criteria (Billiet & Bellis, 2011). Thus, for children with auditory-based communication impairments, cABR measures can be particularly revealing of auditory processing deficits that are missed by behavioral assessments. Given the link between APD and communication skills, such as SIN perception, and language-based learning impairments (Sharma, Purdy, & Kelly, 2009), cABR measures can contribute unique information in APD assessment batteries that is objective and tied to real-world communication skills. Additionally, because cABR measures are reflective of behaviorally obtained psychophysical thresholds (Marler & Champlin, 2005; Werner et al., 2001), neural assessments could replace behavioral assessments in cases when a subject cannot respond accurately or when other subject factors would make the behavioral assessment unreliable. Importantly, as neural responses to measures such as gap detection appear to be mature in infancy but behaviorally measured responses do not reach adult levels until later childhood (Shinn et al., 2009; Werner et al., 2001), cABR metrics may be used for early identification of auditory processing impairments in very young children.

The cABR to speech is largely mature by the age of five (Johnson, Nicol, &

Kraus, 2008) and is stable during the school-age years (Hornickel, Knowles, & Kraus, 2012). As atypical cABRs can occur despite normal click-evoked responses, which are mature by age two (Hood, 1998; Ponton, Eggermont, Kwong, & Don, 2000; Salamy, 1984; Sininger, 2007), deficient cABRs seen in children with language and learning impairments may reflect neural immaturity. It is also possible that the cABR can fail to mature due to continued reinforcement of inappropriate sound-to-meaning relationships throughout development. Thus the auditory brainstem may be a site of dysfunction for some children with APD, likely reflecting an interaction of neural immaturity perpetuated by continued impaired interactions with sound and physical neural dysfunction.

Use of cABRs in the Management and Remediation of APD

cABRs to speech are replicable and reliable within individuals in the absence of auditory intervention or training (Hornickel, Knowles, et al., 2012; Song, Nicol, & Kraus, 2011). However, meaningful interaction with sound, such as repeated manipulation of sound or creation of sound-to-meaning relationships, can alter auditory brainstem function (Figure 7–5). Changes in function can be seen with lifelong experience, such as musical training and language use (Kraus & Chandrasekaran, 2010; Krishnan et al., 2009; Krishnan, Xu, Gandour, & Cariani, 2005; Krizman et al., 2012; Musacchia et al., 2007; Parbery-Clark, Skoe, & Kraus, 2009; Strait et al., 2009; Xu, Krishnan, & Gandour, 2006) and short-term training in laboratory settings or remediation programs (Carcagno & Plack, 2011; de Boer &

Thornton, 2008; Hornickel, Zecker, et al., 2012; Russo et al., 2010; Russo et al., 2005; Song, Skoe, et al., 2011b; Song, Skoe, Wong, & Kraus, 2008). Auditory training for children with learning impairments can lead to improvements in previously deficient cABRs to speech (Hornickel, Zecker, et al., 2012; Russo et al., 2010; Russo et al., 2005). We suggest that children with APD similarly would show improvements in subcortical auditory function after auditory training. (Descriptions of different types of auditory training, documented improvements with auditory training, and applications to APD are discussed in Chapter 27, Meaningful Engagement with Sound for Strengthening Communication Skills.)

Because changes in cABRs are primarily seen with active engagement with sound, auditory attention is likely an important contributing factor to neural change. Descending input from higher cortical areas is necessary for learning-related plasticity in subcortical areas (Bajo, Nodal, Moore, & King, 2010; Gao & Suga, 2000) and plasticity is driven by meaningful associations with sounds (Atiani, Elhilali, David, Fritz, & Shamma, 2009; Fritz, Elhilali, & Shamma, 2005a; Kilgard, Vazquez, Engineer, & Pandya, 2007). For example, ferrets trained to identify tones showed auditory cortical plasticity only in response to the trained (behaviorally-relevant) tones (Fritz et al., 2005a; Fritz, Elhilali, & Shamma, 2005b). Moreover, greater neural response selectivity toward the target tones was linked to increased activity in frontal cortical areas thought to underlie executive control (Atiani et al., 2009; Fritz, David, Radtke-Schuller, Yin, & Shamma, 2010; Fritz, et al., 2005a). Consistent with the OPERA (Overlap, Precision, Emotion,
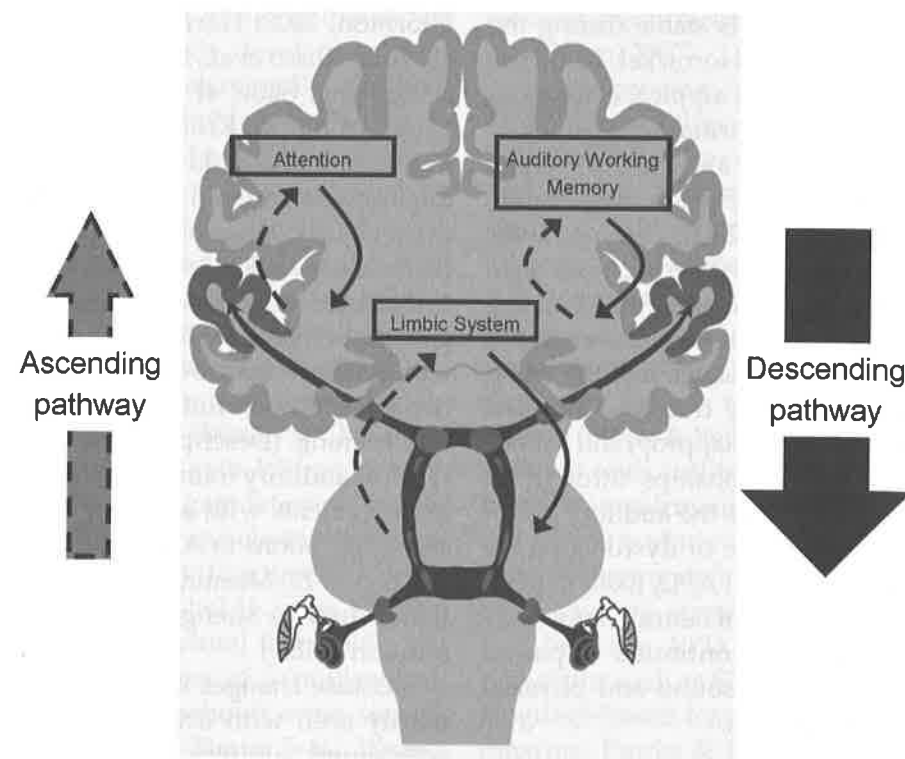
Figure 7–5. The auditory system dynamically reflects interactions between sensory and cognitive processes. The responsiveness of the auditory system to sound is dependent not only on the ascending neural transmission, but also on other physiological and cognitive factors. Auditory processing is impacted by both lifelong 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. Importantly, there are greater descending cortical projections than ascending cortical projections, highlighting the importance of cognitive-sensory interactions for the adaptation of the auditory system with experience.

Repetition, Attention) hypothesis proposed by Dr. Aniruddh Patel, we suggest that cognitive and executive skills such as attention and working memory serve to drive these descending influences in humans when responding to meaningful sounds. The OPERA hypothesis for learning-related plasticity with musical training postulates that both emotion and attention are crucial for robust learning and it suggests that changes in cABRs are driven by active interaction with sound through engagement of executive functions such as attention and working memory (Atiani et al., 2009; Fritz et al., 2010; Krizman et al., 2012; Patel, 2011).

Although attention is an important component of auditory training success, children with APD tend to have weaker auditory attention, weaker auditory memory, and greater internal variability than their typically developing peers (Keith, 1999; Moore, Ferguson, Edmondson-Jones, Ratib, & Riley, 2010; Riccio, Cohen, Garrison, & Smith, 2005). For example, poor performance on a dichotic listening task common to APD batteries (Staggered Spondaic Word Test) correlated with poor sentence repetition (Riccio et al., 2005), implying children with APD may have deficient verbal memory resulting in impairments in distinguishing competing speech streams. Additionally, children with the worst performance on psychophysical measures of backward masking, frequency discrimination, and simultaneous masking had the most variable performance on these measures, which was more predictive of parent-rated SIN skills than psychophysical thresholds (Moore et al., 2010). Variability in performance may stem from attentional factors or an inability to consistently parse spectral and temporal information regarding stimulus differences, and is likely a combination of the two.

In children, computer-based training programs can yield benefits for complex language and reading-related skills and engender neuroplasticity, sometimes without showing concurrent improvements on the trained tasks (Moore, Rosenberg, & Coleman, 2005; Stevens, Fanning, Coch, Sanders, & Neville, 2008). A recent evaluation of both computer-based training versus individualized speech-language therapy found equivalent benefits for children in all groups in receptive and expressive language, with improvement on phonological awareness only for children who participated in language-focused training (Gillam et al., 2008). Beyond concluding there are insufficient data to assess the efficacy of training programs, the authors suggest this indicates auditory training is ineffective. An alternative interpretation is that auditory training can be as effective as one-on-one therapy. Moore and colleagues suggest that improvements in language skills are mediated by increased attention, focus, and meaningful engagement with sound (Moore et al., 2005), consistent with the notion that the improvements in language function observed for all forms of training studied by Gillam and colleagues (Gillam et al., 2008) were due to overall enhancements of attention and analytical thinking skills. Thus, auditory-based training may improve auditory attention and reduce internal variability in children with APD. If training paradigms for APD are engaging, motivating, and increase auditory attention and meaningful interactions with sound, they have the capacity to alter auditory function through descending cortical input that may serve to enhance deficient auditory processing in children. We expect that improvements in neural function after training would be evident in the cABR.

Summary

We have discussed the relationships between cABR characteristics and listening skills such as speech-in-noise perception and temporal processing. We have illustrated how auditory brainstem representation of vocal pitch and timing predicts speech-in-noise perception across the life span and relates

to psychophysical perception. These relationships suggest that the cABR is a biological correlate of real-world communication skills. Given that children with APD are known to have deficits in both speech-in-noise perception and psychophysical perception, cABR measures may contribute a unique and objective metric to the assessment of APD. cABRs can also provide unique insight into the biological mechanisms of auditory processing. To the extent that they encapsulate a biological snapshot of the cognitive and sensory interactions that comprise human hearing, cABRs may serve as a model of auditory processing. Future research will determine whether cABRs collected during infancy and the preschool years are predictive of later language and communication skill. Because the cABR is malleable with focused experience with sound, cABRs can be used to assess neural plasticity before and after auditory training in children with APD. In sum, the cABR gives insight into the fidelity of neural encoding of complex and meaningful sounds, such as speech, that can be directly applicable to assessment, monitoring, and understanding of auditory processing.

Key Points

- cABRs faithfully mimic stimulus characteristics and are reliable from test to retest.
- cABRs may be useful clinically for assessing mechanisms of auditory dysfunction in children with suspected APD.
- cABRs are predictive of real-world listening and communication skills such as speech-in-noise perception.
- cABRs are malleable with training, revealing changes in neural function through meaningful interaction with sound.

Study Questions

1. List three characteristics of brainstem responses that make them appealing for clinical use.

2. List the characteristics of the stimulus that are represented in the speech-evoked brainstem response.

3. Discuss the pros and cons of behavioral APD testing batteries.

4. Discuss why vocal pitch may be a particularly useful cue for speech-in-noise perception.

5. ABRs:
   a. Are collected on the scalp
   b. Reflect stimulus characteristics
   c. Reflect incoming auditory stimulation only
   d. a and b
   e. a and c

6. The speech-evoked ABR appears to be mature by age
   a. 2 years
   b. 5 years
   c. 6 months
   d. 8 years

7. Relative to nonmusicians, adult musicians have enhanced
   a. Speech-in-noise perception
   b. Speech-evoked ABRs
   c. Music-evoked ABRs
   d. a and c
   e. All of the above

8. Successful tracking of a speech stream in noise does NOT rely on which of the following
   a. Pitch
   b. Loudness
   c. Temporal continuity
   d. Linguistic content
   e. Spatial location
   f. None of the above

9. Speech-in-noise perception has been found to relate to cABR representation of
   a. Pitch
   b. Timing
   c. Harmonics
   d. Benefit in pitch representation from stimulus repetition
   e. a, b, and c
   f. a, b, and d
   g. b and d

10. Auditory brainstem function can be impacted by
    a. Short-term auditory training
    b. Lifelong experience
    c. Neither a nor b
    d. a and b

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