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Auditory Pathway Encoding and Neural Plasticity in Children with Learning Problems

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Key Words

Auditory pathway · Perception · Learning · Evoked responses · Neural plasticity · Learning disorders

Abstract

An inability to process auditory information, especially speech, characterizes many children with learning and attention problems. Our working hypothesis is that these speech-sound perception problems arise, at least in some cases, from faulty representation of the speech signal in central auditory centers. Preconscious neurophysiologic representation of sound structure by central auditory pathway neurons can be reflected by subcortical and cortical aggregate neural responses. These neurophysiologic responses can be modified by perceptual learning. Our research has shown that some children with learning problems demonstrate abnormal perception and neural representation of certain speech sounds. Differences between normal and learning-impaired groups can be attributable to aspects of neural synchrony that are reflected in aggregate neural responses. Deficiencies in neural synchrony in these children are apparent in subcortical (as well as cortical) representations of speech-sound structure, and these timing deficits are related to performance on speech-sound perception and learning measures. Moreover, impaired perception and neurophysiologic encoding of speech sounds can be improved with cue enhancement and can be modified by perceptual learning associated with auditory training.

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Introduction

Understanding speech during everyday listening places many demands on the auditory system. Among these demands are the accurate representation of rapidly changing spectral information comprising the speech signal, and the separation of speech from background noise. Our research is aimed at understanding the basic biologic processes underlying speech-sound perception in quiet and noise. Specifically, we are interested in how neural activity gives rise to these processes in normal school-age children and in children with auditory learning problems. In addition, we are investigating the neurobiological processes involved in the perceptual learning of speech sounds in order to impact the design of training regimens that may assist those individuals who have difficulty perceiving speech sounds. Our group has used behavioral and neurophysiologic measures to investigate biologic processes involved in speech-sound perception and to delineate the nature and origin of auditory deficits affecting communication [Bradlow et al., 1999; Carrell et al., 1999; Cunningham et al., 2000b, 2001; Koch et al., 1999; King et al., 1999; Kraus et al., 1994a, b, 1996, 1998, 1999, 2000; McGee et al., 1996].

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Evoked potentials can reflect level-specific neural synchrony to speech-sound elements. The auditory brainstem response (ABR) depends on a high degree of synchronized firing between neurons. If there is excessive neural jitter, which might occur in an impaired auditory system, the separation of individual neural responses by even a fraction of a millisecond could cause responses to cancel each other out. The frequency following response (FFR) also depends on a high degree of neural synchrony. It reflects brainstem-generated, phase-locked responses to the speech stimulus' fundamental frequency and, to a lesser extent, its harmonics. Cortical responses reflect stimulus-locked synchronous firing across neural ensembles. P1/N1/N2 are elicited by stimuli presented in a simple repetitive sequence, whereas the mismatch negativity (MMN) is elicited by an acoustic change in a repetitive sequence. P1/N1/N2 and MMN each arise from different anatomic sources [Kraus et al., 1994a; Näätänen and Picton, 1987; Sams et al., 1991; Scherg et al., 1989] and represent different aspects of auditory function. That is, P1/N1/N2 and MMN (largely) reflect primary and nonprimary auditory pathway activity, respectively, and differ in their time course of maturation, patterns of hemispheric symmetry and responses to sound in background noise [Bellis et al., 2000; Cunningham et al., 2000b; Kraus et al., 1999; Ponton et al., 2000; Sharma et al., 1997; Martin et al., 1997]. Fine-grained speech-sound discrimination is associated with MMN [Kraus et al., 1993; Sams et al., 1985], whereas P1/N1/N2 are associated with other, more global aspects of auditory function such as the perception of syllables, words and sentences, and auditory short-term memory [Conley et al., 1999; Cunningham et al., 2000b]. Taken together, these aggregate neural responses can be used to acquire knowledge about speech-sound perception.

Speech Perception and Learning Problems

Almost 10% of children exhibit learning and reading disabilities [Torgeson, 1991]. Recent research has suggested that a subset of these children have difficulty with perception of certain fundamental acoustic differences within speech sounds [Brandt and Rosen, 1980; De Weirdt, 1988; Elliot et al., 1989; Kraus et al., 1996; Leonard et al., 1992; Mody et al., 1997; Stark and Heinz, 1996a; Sussman, 1993; Tallal and Piercy, 1974; Tallal and Stark, 1981; Werker and Tess, 1987]. Those perceptual deficits are associated with poor phonologic processing and poor reading skills [Fletcher et al., 1994; Godfrey et al., 1981; McBride-Chang, 1996; Reed, 1989]. Our hypothesis has been that, for some children, the difficulty in perceiving fundamental acoustic parameters stems from abnormalities in the neural representation of speech that occurs after peripheral sensory encoding but prior to conscious perception. Consistent with this view, we have demonstrated a fundamental, biologic basis for perceptual deficits in some children with learning problems at cortical and brainstem levels of the auditory pathway [Bradlow et al., 1999; Cunningham et al., 2000b, 2001; Kraus et al., 1996]. We have also shown that preattentive neural responses to sound can be improved with acoustically enhanced signals [Bradlow et al., 2000, 2001; Cunningham et al., 2001] and modified by short-term perceptual training [Hayes et al., 2001; Kraus et al., 1995; Tremblay et al., 1997, 1998].

Many individuals with learning problems (LP) demonstrate particular communication difficulties in noise [Bellis, 1996; Breedin et al., 1989; Chermak and Musiek, 1997; Jerger et al., 1987; Katz, 1992; Welsh et al., 1996], when stimuli are rapidly presented [Cestnick and Jerger, 2000; Farmer and Klein, 1995; Hari and Kiesila, 1996; Livingstone et al., 1991; Nagarajan et al., 1999; Tallal and Piercy, 1974], or when fine-grained discrimination is required [Bradlow et al., 1999; Elliot et al., 1989; Kraus et al., 1996; Wright et al., 1997]. Despite general acknowledgment that these factors excessively tax perception in this population, recent studies are just beginning to reveal neurobiological differences between normal and LP children when signals are presented in these challenging listening situations [Bradlow et al., 1999; Cestnick and Jerger, 2000; Cunningham et al., 2001; Kraus et al., 1996; Nagarajan et al., 1999; Wible et al., 2001].

Project on Listening, Learning and the Brain

In an ongoing project, we are investigating the correspondence between electrophysiologic responses and behavioral abilities in a large population of both normal and impaired children. Specifically examined is the relationship among psychophysical speech discrimination (listening), standardized measures of learning ability and academic achievement (learning), and neurophysiology (the brain).

Psychophysical Perception and Neurophysiologic Representation of Speech-Sound Differences

We have hypothesized that there is a biological basis for perceptual deficits in some of the LP children, and that disruption occurs in the representation of sound at a

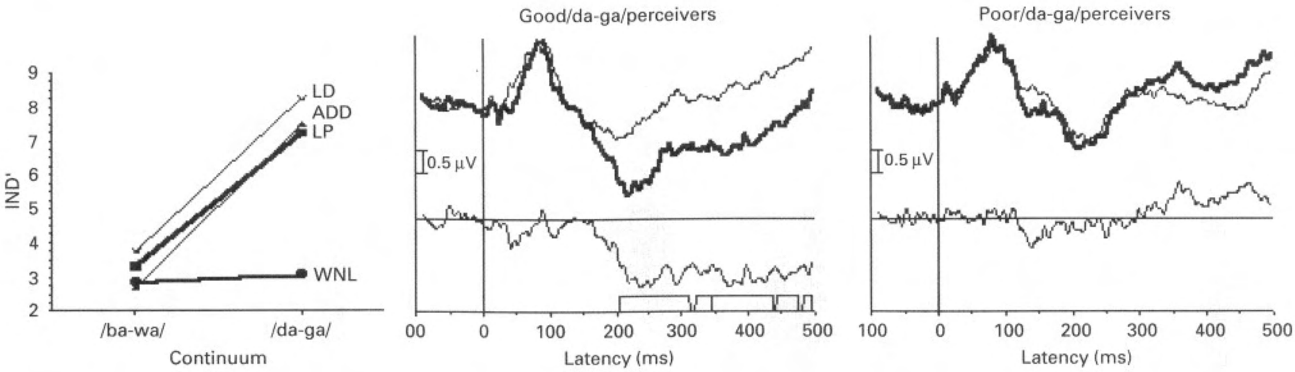

Fig. 1. Left: In LP children, perception was selectively worse for /da-ga/ than for /ba-wa/. Middle/right: MMN was evident for 'good' and absent for 'poor' /da-ga/ perceivers. Boxes below indicate the latency range over which a significant MMN occurs [from Kraus et al., Science, 1996].

preconscious, preattentive level. Our results support these hypotheses and provide evidence of neural asynchrony in sound representation at both brainstem and cortical levels [Bradlow et al., 1999; Cunningham et al., 2000b, 2001; King et al., 2001; Kraus et al., 1996].

On a behavioral task assessing fine-grained perception along /da-ga/ and /ba-wa/ continua, LP subjects performed significantly worse than normal subjects [Kraus et al., 1996]. Perception was selectively worse for /da-ga/ (change in third-formant onset frequency) than for /ba-wa/ (change in formant transition duration). This pattern indicates that LP children are better able to discriminate synthetic speech stimuli that differ in the temporal domain than stimuli that differ spectrally at stimulus onset. The discrepancy between /da-ga/ and /ba-wa/ in LP subjects is important in that the better performance on /ba-wa/ indicates that attention-motivation factors did not preclude good performance on the task. Overall, perceptual deficits cut across diagnostic categories, occurring in LP children with diagnoses of learning disability, attention deficit hyperactivity disorder, combined learning/attention disorder, and dyslexia. This supports the notion that there is a common perceptual deficit in a subset of children with various clinical diagnoses.

An association between perception and neurophysiologic mechanisms has been established as illustrated in figure 1. Good perception of /da-ga/ is associated with robust cortical responses to stimulus change (MMN), whereas poor discrimination is associated with diminished responses [Bradlow et al., 1999; Kraus et al., 1996]. Children in both groups had MMNs in response to the /ba-wa/ stimulus contrast, consistent with their good discrimination of those stimuli. The psychophysical and electrophysiologic data together provide evidence for a preattentive, biological basis for learning problems in some children.

Brainstem and Cortical Asynchrony to Speech Sounds

Our data on normal (NL) and LP children indicate that brainstem responses to speech syllables differ for NL compared to LP children [King et al., 2001]. In addition, we have investigated brainstem and cortical encoding of speech sounds presented in background noise [Cunningham et al., 2001]. Subjects were children with LP and age-matched normal controls. LP subjects performed significantly worse than normal children on measures of auditory processing, reading, spelling, and fine-grained discrimination along a /da-ga/ continuum. Speech perception in noise (discrimination along an /ada-aga/ continuum) was significantly worse in the LP children.

Results are summarized in figure 2. ABR, FFR and P1/N1/N2 were elicited by /da/, presented in quiet and in background noise [Cunningham et al., 2001]. In noise, LP children exhibited significantly prolonged wave V latencies. A fast Fourier transform of the FFR revealed reduced energy in certain frequency bands (250–750 Hz) in the LP children compared to normals. Correlations between the stimulus and response waveforms in noise were significantly lower for the LP group. Overall, the data indicate that synchrony of auditory brainstem neurons differs between NL and LP children. Consequently certain learning deficits may originate from a disorder in auditory neural timing already seen at the brainstem level. In addition, cortical responses revealed that LP chil-

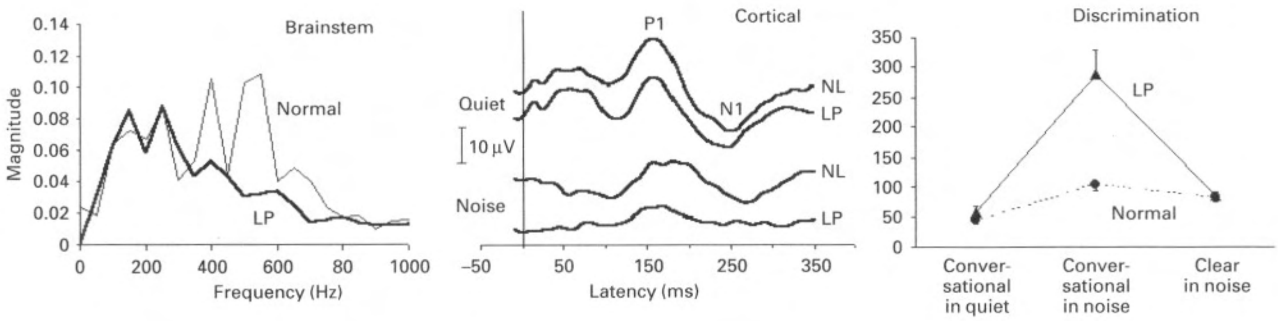

Fig. 2. Left: Magnitude of the spectral content of FFR shown by FFT in NL and LP children. Groups differed significantly in noise (between 450 and 750 Hz), not in quiet. Middle: Cortical potentials did not differ between NL and LP children in quiet, but were significantly smaller in LP subjects in noise. Right: Mean JNDs for NL and LP children along /ada-aga/ continua. LP children had poorer speech discrimination in noise and regained normal performance with cue-enhanced 'clear' stimuli [from Cunningham et al., Clin Neurophysiol, 2001].

dren showed significantly reduced P2-N2 amplitude to stimuli in noise. This demonstration of deficient neural representation of speech-in-noise at brainstem and cortical levels in LP children indicates that deficiencies in neural representation exist at multiple levels of the auditory pathway. In another study [Bradlow et al., 2000], LP children performed significantly worse than NL children in the perception of sentences in noise. Finally, preliminary data describe the effects, both singular and combined, of repeated stimulus repetition and background noise on cortical potentials [Wible et al., 2001]. The neural representation of repeated speech stimuli has been found to be diminished in LP children and was related to behavioral measures of auditory processing.

Cue Enhancement

The perceptual benefits of 'clear' or acoustically enhanced speech have been established [Jerger, 1999; Payton et al., 1994; Picheny et al., 1985; Smith and Levitt, 1999; Uchanski et al., 1996], and some features have been incorporated into commercially available auditory training programs designed for LP children. The effects of 'clear' speech in noise were investigated in LP and NL children [Cunningham et al., 2001]. The acoustic cues that are enhanced during 'clear' speech include an increased amplitude of consonant burst and a lengthened stop-gap duration [Picheny et al., 1986].

ABR, FFR and P1/N1/N2 potentials were obtained to enhanced /da/ stimuli (with amplification of the release burst intensity) presented in background noise [Cunningham et al., 2001]. Cue enhancement elicited normal cortical responses in those LP children with deficient responses to unenhanced signals. This implies that the neural representation of acoustic events can be improved by specific cue enhancement.

Behaviorally, fine-grained discrimination in noise (along an /ada-aga/ continuum) was significantly worse in LP than normal children [Cunningham et al., 2001]. Yet, when 'clear' speech characteristics are added to the stimuli, perception improved. When each of the 'clear' speech enhancements was studied in isolation, increased release burst intensity was found to be a more important acoustic cue manipulation than lengthened stop gap duration. In addition, perception of sentences in noise in LP children improved dramatically when the same sentences are produced with 'clear' speech [Bradlow et al., 2000, 2001], expanding our findings to more real-world listening situations.

Plasticity and Speech-Sound Perceptual Learning

Speech perception abilities in humans are modified both by long-term experience with one's native language [Aslin et al., 1981; Cheour et al., 1998; Dehaene-Lambertz and Baillet, 1998; Jusczyk et al., 1984; Kuhl et al., 1992; Mehler et al., 1978; Näätänen et al., 1997; Werker et al., 1981], and by short-term directed auditory training in a laboratory or clinical environment [Bradlow and Pisoni, 1999; Pisoni et al., 1982], and speech perception can be modified by auditory training in language-impaired children [Ball and Blanchman, 1991; Bradley and Bryant, 1983; Merzenich et al., 1996; Schankweiler et al., 1995; Tallal et al., 1996]. Little is known about neural plasticity associated with perceptual learning in humans, although animal experiments have demonstrated that sensory cortex becomes restructured with training [Jenkins et al., 1990; Kraus et al., 1982; Merzenich and Jenkins, 1993; Recanzone et al., 1992, 1993]. Our research has demonstrated physiologic changes associated with auditory perceptual learning in humans. These changes are preattentive and can precede behavioral learning [Kraus et al., 1995; Tremblay et al., 1997, 1998, 2001].

Speech-Sound Training in Children with LP

Interest in perceptual training programs for people with LP has persisted throughout the years in the fields of education, psychology, speech and hearing, and learning disabilities [Orton, 1937]. More recently, there has been much interest in interactive computer-based auditory training programs [Diehl, 1999; Morrison, 1998; Tallal et al., 1998]. However, the efficacy of these programs is not uniform across children, and it is unclear which kind of training, for which profile of deficits, results in perceptual improvements. Studying children who undergo this training provides important insights into the neurophysiologic and perceptual changes associated with perceptual learning. It is important to determine which children might benefit from training, and how training may alter the neural representation of sound at various levels of the auditory pathway.

We are investigating the effects of commercial computer-based auditory training programs on behavioral and neurophysiologic measures in children with LP [Hayes et al., 2001; Zhang et al., 2000]. Subjects are tested before and after participation in these programs on learning, perceptual, and neurophysiologic measures. Preliminary results indicate improvement on measures of perception and learning, and changes in cortical potentials to stimuli presented in quiet and in noise. These changes did not occur in an untrained control group. Results have direct bearing on the interpretation of brain/behavior changes associated with auditory training programs and require considerable additional systematic study.

Animal Studies

The distinctive roles of the auditory midbrain, thalamus and cortex have been directly explored in an animal model using identical stimuli used in human studies. First, elemental acoustic parameters of synthetic speech stimuli were reflected in auditory pathway responses [McGee et al., 1996]. Second, the encoding of stimulus change (mismatch negativity) has been shown to occur predominantly in the nonprimary thalamocortical pathway. Third, different acoustic contrasts appear to be encoded at distinct places along the auditory pathway [Kraus et al., 1994a, b; Sharma et al., 1994]. Processing certain rapid spectrotemporal difference appears to require the auditory cortex. Fourth, when stimuli were presented in background noise, neural representation of the consonant portion was affected to a greater extent than the vowel portion of the stimulus [Cunningham et al., 1999, 2000a, 2001]. The percent decrease in the onset response that can be attributed to the effects of noise was greatest at cortical compared to subcortical locations. At the midbrain, noise reduced the magnitude of low frequency spectral components (FFT analysis), whereas higher frequency components remained unchanged, mirroring FFT findings in NL children using the same stimuli [Cunningham et al., 2001]. Fifth, the effects of 'clear' speech parameter manipulations were assessed in neurophysiologic responses in the midbrain, thalamus, and epidural cortex [Cunningham et al., 2000a]. Onset response amplitudes increased as the stop gap duration or burst intensity alone were varied. Combined manipulations resulted in maximal effects and were not a simple linear sum of the response of each manipulation alone. In background noise, 'clear' speech stimuli elicited an onset response (absent in unenhanced signals). The increase in the onset response that can be attributed to the effect of cue enhancement was greater at cortical than subcortical levels. Cue enhancements did not affect the representation of steady-state portions of the response. Overall, animal data on the neural representation of speech in noise complement the human studies and provide information about physiologic mechanisms underlying the perception of speech in NL and LP children.

Summary

LP children demonstrate abnormal perception and neural representation of fine-grained stimulus differences. Differences between normal and LP groups can be attributable to aspects of neural synchrony that are reflected in aggregate neural responses. Deficiencies in neural synchrony in these children are already apparent in subcortical representation of speech-sound structure, and these timing deficits are related to speech-sound perception and learning measures. Thus, neural representation of certain speech features – independent of cognitive and attentional influences – underlies certain learning and reading disorders. Moreover, impaired perception and neurophysiologic encoding of speech sounds in LP children can be improved with cue enhancement and perceptual learning.

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