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Neuroscience Letters 319 (2002) 111–115

Neuroscience Letters

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Deficits in auditory brainstem pathway encoding of speech sounds in children with learning problems

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Received 28 September 2001; received in revised form 28 November 2001; accepted 5 December 2001

Abstract

Auditory brainstem responses were recorded in normal children (NL) and children clinically diagnosed with a learning problem (LP). These responses were recorded to both a click stimulus and the formant transition portion of a speech syllable /da/. While no latency differences between the NL and LP populations were seen in responses to the click stimuli, the syllable /da/ did elicit latency differences between these two groups. Deficits in cortical processing of signals in noise were seen for those LP subjects with delayed brainstem responses to the /da/, but not for LPs with normal brainstem measures. Preliminary findings indicate that training may be beneficial to LP subjects with brainstem processing delays.

Keywords: Learning impairment; Auditory brainstem response; Speech; Training; Development; Neural encoding; Auditory

Many children are diagnosed each year with learning disabilities. Approximately 9% of children in the United States are diagnosed with reading and learning disabilities, while 5% are diagnosed with an attentional disorder [18]. For a number of these children, an inability to process auditory information, especially speech, characterizes their learning problems [2,10,17]. By the time these children begin school, much of the critical time for language development has already passed and they lag behind their peers in a variety of skills. Our working hypothesis is that a subset of children who struggle to learn have basic differences in the way their brains encode the acoustic structure of complex signals, such as speech, when compared to their normal counterparts. Deficits in specific speech discrimination tasks have been correlated with abnormal cortical processing in learning-impaired children [8,14].

Many acoustic events, including speech, have a complex structure with multiple frequencies changing across the time-course of the signal. Some aspects of speech, such as onset bursts and formant transitions, change very rapidly, lasting for only a few milliseconds. Other features, such as vowel segments and fundamental frequency, have longer durations and are thus neurally encoded over a longer time interval. Highly synchronized neural activity, a fundamental neurobiologic process that underlies many sensory, motor and cognitive events [1,9,16], encodes temporal characteristics of auditory signals [4,15]. In the auditory system, the brainstem is uniquely organized to encode rapid timing changes in auditory signals with such exquisite accuracy that differences in neural representation on the order of tenths of a millisecond are clinically significant [7,13]. While substantial data have been obtained revealing how brainstem neurons encode simple acoustic signals like clicks and tones [11], little research has been done to assess the accuracy of brainstem representation of timing events for more complex signals such as speech.

The experimental aim of this study was to compare speech-evoked auditory brainstem responses (ABRs) in normal children and children diagnosed with a learning impairment to determine if there are neurophysiologic timing differences between these two populations. Measures of speech sound perception and neurophysiologic measures from the cortex were used to interpret differences in ABRs seen in the learning-impaired subjects. Finally, an initial assessment was made of the relationship between brainstem timing deficits and efficacy of commercial auditory training in a subset of the learning-impaired children.

Subjects were 8–12 years old and included 33 normal

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0304-3940/02/$ - see front matter
PII: S0304-3940(01)02556-3

children (NL) and 54 children diagnosed with learning impairment (LP). All subjects had normal hearing (threshold <20 dB HL for octaves from 500 to 4000 Hz). Each LP subject had a formal diagnosis of a learning disability or attentional disorder prior to entering the study. Inclusion of a broad range of learning disabilities is based on previous research showing that perception/encoding deficits cut across diagnostic categories [8,14]. All subjects were tested on study-internal standardized measures of learning and academic achievement. These measures included subtests from the Woodcock–Johnson Psycho-Educational Battery, Revised (Auditory Processing, Listening Comprehension, Incomplete Words, Sound Blending, Memory for Words and Cross-Out), and Reading and Spelling subtests from the WRAT3 Test Battery. As expected, NLs scored significantly better than LPs on all standardized measures of learning ($P < 0.03$, all tests). The IQ of each subject was assessed with the Brief Cognitive Scale from the Woodcock–Johnson Psycho-Educational Battery. All subjects had IQs above 85, and the average IQ of LPs fell within the normal range (average IQ: LP = 102, NL = 117). All subjects and their parents or guardians gave oral and written informed consent. Institutional Review Board approval for this study was obtained from Northwestern University.

ABRs were elicited by the formant transition portion of a synthesized speech syllable /da/ (referred to as /da/ below) and by an acoustic click. The /da/ stimulus consisted of the first 40 ms of a five-formant synthetic speech syllable /da/ used in previous experiments in our laboratory [3]. This portion of the syllable contained the formant transition of the stimulus without the vowel portion. The fundamental frequency ramped up from 103 to 121 Hz, and F1 ramped up from 220 to 720 Hz. F2 and F3 ramped down from 1700 to 1240 Hz, and from 2580 to 2500 Hz, respectively. F4 and F5 remained constant at 3600 and 4500 Hz. Rise and fall times were 5 ms. This /da/ stimulus was presented with alternating polarities to the right ear through insert earphones at 80 dB SPL at a stimulus rate of 11.1/s. ABR recordings were made from a Cz electrode placed centrally on the scalp (10–20 electrode system, right earlobe reference, forehead ground). Responses were filtered on-line from 100 to 2000 Hz and recorded over a 60 ms post-stimulus time period. Three thousand repetitions were collected for each stimulus polarity (condensation and rarefaction). Responses to each polarity of the /da/ stimulus were averaged separately and added together to create a mainly neural response representing brainstem activity [5]. Responses to click stimuli were collected in the same manner as the /da/ stimulus except that the 100 μs clicks were presented at a rate of 31.1/s at a level of 68 dB HL.

All subjects had normal responses to click stimuli (wave V latency between 5.6 and 6.0 ms) with no latency difference between the NL and LP groups ($t = 0.73$, $P = 0.47$). Fig. 1a shows the average brainstem response from NL subjects to /da/. To compare the peak latencies of the NL and LP groups, it was first necessary to determine which peaks in the waveform could be measured reliably in normal children. A maximum SD of 0.5 ms from the mean was set as the criterion for considering a peak reliable. Peaks marked A, C and F met this criterion. Peak A is the onset response to the stimulus, and Peaks C and F are part of the frequency following response (FFR) elicited by the fundamental frequency of the stimulus. When comparing the latency values of all LP children to those of NL children, only Peak A was significantly different between the two groups (NL: mean 7.47 ms, SD 0.23 ms; LP: mean 7.61 ms, SD 0.31 ms; $t = 2.27$, $P = 0.026$). These findings indicate that at least some of the learning-impaired children have abnormalities in the acoustic representation of a speech sound as low as the auditory brainstem.

In order to compare individual LP subjects to a normative data set, Peak A latency values of the NL subjects were used to determine the normal range. The normal range for clinical validity of ABRs to clicks is typically the mean plus 1 SD. We therefore calculated the normal range of onset response latencies to /da/ as the mean plus 1 SD of NL onset latencies (7.70 ms). Using this criterion, 20 out of 54 LP subjects had delayed onset latencies to /da/, even though they had normal ABRs to click stimuli. All of the LP subjects with delayed onset latencies also had delayed latencies for Peaks C and F

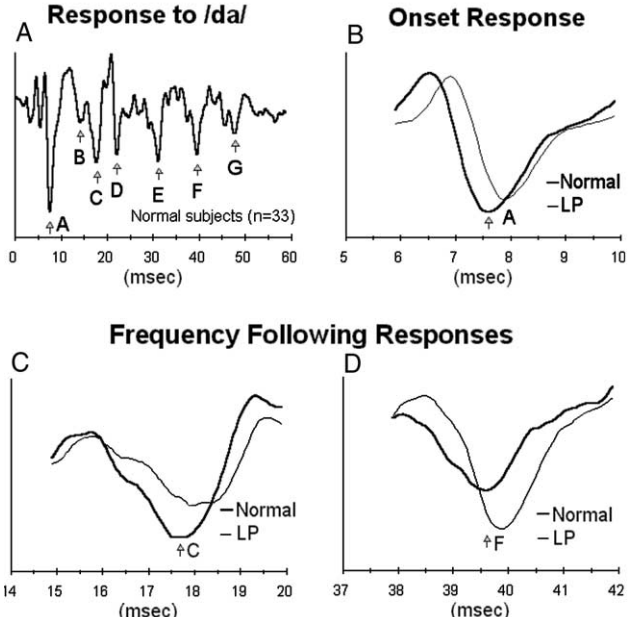

Fig. 1. (A) ABR to the formant transition portion of the synthesized speech syllable /da/ recorded from a group of normal children ($n = 33$). The initial negative peak (Peak A) is the response to the stimulus onset. The remaining peaks correspond to the frequency following response, synchronized to the fundamental frequency of the stimulus (Peak A: mean 7.47 ms, SD 0.23 ms; Peak C: mean 17.7 ms, SD 0.39 ms; Peak F: mean 39.5 ms, SD 0.47 ms). (B) Onset response to the /da/ recorded from normal (NL, thick line) and learning-impaired children with delayed onset latencies ($n = 20$) (LP-del, thin line). (C,D) Peaks C and F from the frequency following response recorded from normal (thick line) and learning-impaired (thin line) children.

of the FFR (Peak C: NL mean 17.7, SD 0.39; LP-delayed mean 18.1, SD 0.61; $t = 2.81$, $P = 0.006$; Peak F: NL mean 39.5, SD 0.47; LP-delayed mean 40.0, SD 0.65; $t = 2.63$, $P = 0.01$) (Fig. 1b–d). In contrast, of the 34 LP subjects with normal onset latencies to /da/, all but two also had normal latency values for the FFR peaks. These findings indicate that the children who have delays in brainstem onset latency are the same children who have latency delays in the FFR.

Performance on speech sound perception was also assessed. Each subject's ability to discriminate synthesized 100 ms speech syllables along two continua was determined. A 41-step continuum from /da/ to /ga/ differed only in onset frequency of the third formant (/da/ = 2580 Hz, /ga/ = 2180 Hz). A 31-step /ba/ to /wa/ continuum, differing only in the length of the first and second formant transitions (/ba/ = 10 ms, /wa/ = 40 ms), was used as a control condition to ensure that all subjects were able to understand and perform the task. Discrimination was tested using the Parameter Estimation by Sequential Tracking (PEST) algorithm. The program was used to step along continua from the endpoints (/ga/ or /ba/), to arrive at a just noticeable difference (JND) (relative to anchors /da/ or /wa/) that was correctly identified 70% of the time.

Similar to previous findings from this laboratory, no significant difference in JND scores was found between NLs and LPs for the /ba/–/wa/ continuum ($t = 1.11$, $P = 0.27$), but NLs had significantly better JND scores than LPs for the /da/–/ga/ continuum ($t = 2.27$, $P = 0.026$) [8]. Comparisons of /da/–/ga/ JND scores between LP subjects with delayed versus normal brainstem onset responses to /da/ revealed no differences between these two groups ($t = 0.73$, $P = 0.47$). Thus, a relationship between deficits in auditory brainstem timing mechanisms and speech sound perception was not evident.

To determine if timing deficits in responses from the auditory brainstem had an effect on later (cortical) potentials, P1/N1/P2/N2 cortical responses to the /da/ stimulus presented in quiet and in background noise were analyzed. The same /da/ stimulus described for the brainstem potentials was presented to the right ear through insert earphones at 80 dB SPL at a rate of 1.7/s. Responses were recorded in quiet and in noise (0 dB signal-to-noise ratio). Responses to 1000 stimulus presentations at each noise level were recorded from Cz, (nasal reference, forehead ground) and averaged on-line. Responses were bandpass filtered on-line between 0.05 and 100 Hz.

No cortical latency or amplitude differences were seen between LPs with normal and delayed brainstem onset latencies to /da/ ($P > 0.05$, all tests). Cortical waveforms recorded in quiet and noise were correlated with one another to assess timing differences between the two waveforms. LPs with delayed brainstem onset latencies to /da/ had significantly lower correlations ($r = 0.52$) than LPs with normal onset latencies ($r = 0.77$, $t = 2.4$, $P = 0.02$). This was apparently due to disruptions in the timing of their responses in noise. Therefore, it seems that the presence of noise selectively degrades cortical responses in the subset of LP subjects who have deficits in brainstem neural synchrony.

A subset of the LP subjects ($n = 17$) received acoustic-phonetic training through a widely used commercially available training program. This program targets deficits in auditory perception by using acoustically enhanced signals to facilitate learning. Children participating in the training program attended daily 1 h training sessions for approximately 8 weeks. Training was conducted by an independent agency and consisted of supervised work with Earobics Step I and Step II software (Cognitive Concepts, Inc., Evanston, IL). (Our laboratory has no conflict of interest or any official relationship with Cognitive Concepts, Inc.) The software provides training on phonological awareness, auditory processing and language processing skills through multilevel interactive games. Specifically, the programs consist of exercises in quiet and in noise that incorporate phoneme discrimination, auditory memory, sequencing and attention, rhyming and sound blending skills. In some exercises, the rapid transitions of the speech stimuli are elongated. Auditory stimuli are presented bilaterally through headphones and children indicated the number of sounds or phonemes in a stimulus by clicking on pictures and letters on the screen.

Auditory brainstem and cortical neurophysiology, as well as speech sound perception, were evaluated before and after training to assess any training-related changes [6]. The auditory brainstem onset latency to /da/ did not change with training (pre = 7.70 ms, post = 7.68 ms, $t = 0.87$, $P = 0.40$). However, while LP children whose onset latencies were within the normal range did not show any change in their /da/–/ga/ speech perception, LP children with delayed onset latencies showed improved discrimination

Table 1
Mean and SD values on perceptual and electrophysiologic tasks that were assessed before and after subjects received training[a]

	Pre-train mean (1 SD)	Post-train mean (1 SD)	Wilc. Z (P)
/ba/–/wa/ JND			
LP-normal	11.57 (7.43)	9.52 (2.66)	− 0.53 (0.59)
LP-delayed	7.30 (3.60)	7.90 (3.10)	− 0.42 (0.67)
Controls	7.97 (1.61)	5.58 (2.31)	− 1.68 (0.09)
/da/–/ga/ JND			
LP-normal	13.23 (4.87)	13.77 (5.45)	0.65 (0.51)
LP-delayed	14.26 (4.63)	9.09 (4.02)	− 2.10 (0.03)
Controls	10.86 (3.78)	9.73 (5.05)	− 0.98 (0.33)
Q-N r values			
LP-normal	0.67 (0.11)	0.77 (0.06)	0.84 (0.40)
LP-delayed	0.37 (0.24)	0.87 (0.02)	2.0 (0.04)
Controls	0.71 (0.26)	0.68 (0.26)	− 0.84 (0.40)

[a] Subjects who received training from Cognitive Concepts, Inc. were grouped by their ABR onset latencies to /da/ (LP-normal and LP-delayed). In addition, there was a control group of LP subjects who did not receive training.

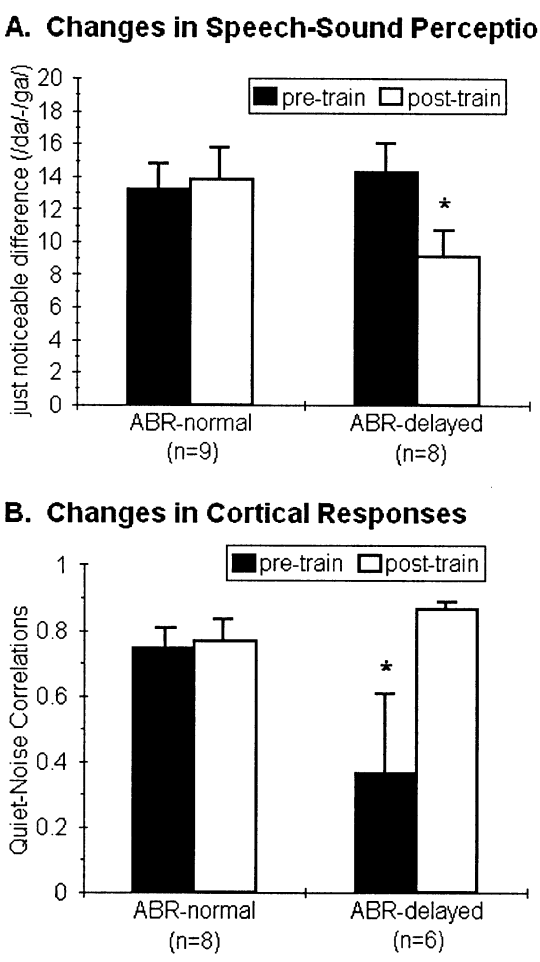

Fig. 2. (A) *LP scores for /da/–/ga/ discrimination task.* Prior to training, there was no difference between LP subjects with normal brainstem responses to /da/ versus LP subjects with delayed brainstem responses. However, following training the LP subjects with delayed brainstem responses to /da/ showed improvement in the discrimination task while scores for the LP subjects with normal brainstem recordings did not change. (B) *Quiet-to-noise correlations of cortical responses for LP subjects.* Prior to training, the LP subjects with normal ABR onsets showed better correlations of responses recorded in quiet and noise. Only the LP subjects with delayed latencies in the auditory brainstem recordings showed improvements in quiet-to-noise correlations following training.

with training (see Table 1 and Fig. 2a). Neither group showed perceptual changes on the /ba/–/wa/ discrimination task, which served as the control (see Table 1).

In addition to improvements in speech sound perception in quiet, LP children with delayed brainstem onset latencies also showed an increased resistance to the degrading effects of noise on cortical responses following training (Fig. 2b). Even in this small sample of subjects, LP children with normal auditory brainstem onset latencies had better correlations between cortical responses recorded in quiet versus noise prior to training. However, with acoustic-phonetic training, only children with delayed brainstem onset latencies showed improvements in quiet-to-noise correlations of cortical responses. Correlations for LPs with normal brainstem onset latencies did not change (see Table 1). These findings indicate an increased neural resistance to noise following training for LPs with abnormal auditory brainstem processing.

An LP control group that did not receive training ($n = 8$) was also tested and re-tested on these speech discrimination and cortical potential measures over the same time period as the trained children. This group showed no changes between testing sessions on any of these tests (see Table 1). Out of this data set, four control children had delayed ABR onset latencies to /da/. Unfortunately, any statistics performed on a group this small would be unreliable. However, close inspection of the data revealed no qualitative differences between children with normal and delayed ABR latencies in this control group. While these preliminary results are encouraging, further testing of both trained and untrained LP children is warranted.

Overall, these findings show that onset synchrony of auditory brainstem neurons differs between normal children and some children with learning impairments. In addition, children with delayed onset responses to a speech stimulus also have delays in the brainstem FFR. The effect of these brainstem neural timing deficits on speech perception in quiet is not evident. However, in the presence of noise, the deficits seen at the level of the brainstem appear to have a deleterious effect on cortical responses to the same stimulus. Early results on a small sample indicate that acoustic-phonetic training using enhanced signals selectively improves perceptual abilities for LP children with delayed brainstem responses. Training not only improves behavioral speech perception in this group, but also affects the neurophysiologic representation of cortical responses obtained in the presence of background noise. Taken together, these data suggest that certain learning deficits may originate from a disorder in auditory neural timing at the brainstem level. Measures of auditory brainstem synchrony could be used to identify which children with learning problems will likely benefit from training programs that target deficits in the neural representation of the acoustic aspects of auditory input. In addition, because the ABR matures early [12], one can envision identifying those children at risk for acoustic-phonetic-based learning problems before they reach school age. Thus, intervention and rehabilitation could begin at an earlier age.

This work was supported by NIH NIDCD R01 DC01510.

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