Effects of lengthened formant transition duration on discrimination and neural representation of synthetic CV syllables by normal and learning-disabled children

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(Received 2 November 1998; revised 17 May 1999; accepted 8 June 1999)

In order to investigate the precise acoustic features of stop consonants that pose perceptual difficulties for some children with learning problems, discrimination thresholds along two separate synthetic /da-ga/ continua were compared in a group of children with learning problems (LP) and a group of normal children. The continua differed only in the duration of the formant transitions. Results showed that simply lengthening the formant transition duration from 40 to 80 ms did not result in improved discrimination thresholds for the LP group relative to the normal group. Consistent with previous findings, an electrophysiologic response that is known to reflect the brain's representation of a change from one auditory stimulus to another—the mismatch negativity (MMN)—indicated diminished responses in the LP group relative to the normal group to /da/ versus /ga/ when the transition duration was 40 ms. In the lengthened transition duration condition the MMN responses from the LP group were more similar to those from the normal group, and were enhanced relative to the short transition duration condition. These data suggest that extending the duration of the critical portion of the acoustic stimulus can result in enhanced encoding at a preattentive neural level; however, this stimulus manipulation on its own is not a sufficient acoustic enhancement to facilitate increased perceptual discrimination of this place-of-articulation contrast. © *1999 Acoustical Society of America.* [S0001-4966(99)00210-6]

PACS numbers: 43.71.Pc, 43.71.Ft [JMH]

INTRODUCTION

Numerous studies have established that a subset of children with diagnosed language and/or learning problems exhibit deficits perceiving certain acoustically similar speech sounds (e.g., Tallal and Piercy, 1974, 1975; Brandt and Rosen, 1980; Godfrey *et al.*, 1981; Tallal and Stark, 1981; Werker and Tees, 1987; Reed, 1989; Elliott *et al.*, 1989; Leonard and McGregor, 1992; Sussman, 1993; Stark and Heinz, 1996a, b; Kraus *et al.*, 1996; Mody *et al.*, 1997, and others). However, the precise nature of the underlying perceptual deficit and its effect on language development and academic achievement has yet to be fully explained. As part of a comprehensive study of speech sound discrimination abilities, academic achievement, and neurophysiologic responses to speech stimuli in normal and learning-disabled school-aged children, we were interested in investigating the specific acoustic-phonetic features that provoke perceptual difficulty in the disabled population. While the sound structure of naturally spoken language is sufficiently rich in acoustic and contextual cues to tolerate some degree of imprecision in perceptual acuity, measures of fine-grained speech sound perception are potentially very useful for the identification and monitoring of children whose learning problems may have an auditory-phonetic basis. Accordingly, the present paper presents a systematic examination of fine-grained discrimination of one aspect of stop-vowel syllables that has been proposed as a perceptually vulnerable feature, namely the characteristically brief formant transition duration in the initial portion of the vowel following the stop release.

An important aspect of this study is the use of a combined behavioral and neurophysiologic approach (see also Kraus *et al.*, 1993, 1996, in press). With this multidisciplinary technique, we hoped to gain insight into both stimulus representation at a preattentive neural level and perception of these speech signals in a task requiring focused attention to the stimuli. Furthermore, in both the neurophysiologic and behavioral testing paradigms, we used a task that tested the subject's ability to detect small differences between synthetic speech stimuli that varied along a single acoustic dimension. The use of this type of fine-grained discrimination task with ''stripped down'' synthetic speech stimuli allowed us to test speech sound perception under conditions that stress the system beyond what is required in natural spoken language processing. This testing procedure was deemed appropriate for investigating the auditory-perceptual deficits of school-aged children with learning problems based on the assumption that, rather than having difficulty perceiving naturally produced speech under favorable listening conditions, these subjects have difficulty under less-than-optimal listening conditions. For example, perceptual difficulties may become apparent in noisy listening environments, or when fine categorical distinctions at the segment level are important, such as when learning the sound–letter associations required for reading.

The literature on speech sound perception in impaired children is vast and somewhat diffuse in terms of subject, task, and stimulus factors. Nevertheless, several general findings have emerged, which we attempt to summarize here. With respect to subject population, various studies have examined children diagnosed as specific language impaired (SLI), reading impaired (dyslexics), or learning impaired. For example, several studies found speech perception deficits in children with ''developmental aphasia,'' or SLI (e.g., Tallal and Piercy, 1974, 1975; Frumkin and Rapin, 1980; Tallal and Stark, 1981; Stark and Heinz, 1996a, b; Elliott and Hammer, 1988; Elliott *et al.*, 1989; Sussman, 1993, and others). Similar deficits have also been documented in reading-disabled children (e.g., Tallal, 1980; Godfrey *et al.*, 1981; Brandt and Rosen, 1980; Werker and Tees, 1987; De Weirdt, 1988; Reed, 1989; Mody *et al.*, 1997, and many others). Finally, Kraus *et al.* (1996) recently reported deficits in the biological representation of speech sounds in children diagnosed with a learning disability, attention deficit disorder, or both. While these subject population groups have apparently disparate diagnostic labels, it is clear that individuals within these groups exhibit similar speech perception deficits, suggesting that these deficits are somehow correlated, or coexist with impaired language development, reading, and general academic achievement.

A variety of task-related variables have been employed in studies of speech perception abilities in impaired children; however, most tasks fall into one of two basic types. The first type of task requires subjects to respond to stimulus pairs, or longer strings of stimuli, in which each member represents a good exemplar of a particular speech sound category (e.g., Tallal and Piercy, 1974, 1975; Tallal, 1980; Frumkin and Rapin, 1980; Tallal and Stark, 1981; Stark and Heinz, 1996b; Mody *et al.*, 1997). In these tasks, subjects are typically required to identify a given stimulus as a member of one of two categories, to discriminate between the two stimuli, or to judge the order of presentation of the two stimuli. Since subjects hear only good category exemplars, these tasks tap into the subjects' abilities to make judgments that rely on perception of cross-category differences. This type of task using stimulus pairs that are minimally different has revealed identification, discrimination, and temporal order judgment impairments in clinical populations relative to normal populations.

In the second type of task, subjects are presented with series of stimuli that represent points along an acoustic continuum. In the traditional categorical perception paradigm, both identification and discrimination functions along synthetic speech continua are measured in order to determine the ''sharpness'' of category boundaries. Using this paradigm, several studies found that, when compared to normal children, disabled children were less consistent in identifying, and less accurate at discriminating, stimuli close to category boundaries, indicating less sharply defined phonetic categories than normal children (Brandt and Rosen, 1980; Godfrey *et al.*, 1981; Werker and Tees, 1987; De Weirdt, 1988; Reed, 1989; Sussman, 1993; Mody *et al.*, 1997).

Synthetic speech continua have also been used to determine discrimination thresholds. For this measurement of fine-grained discrimination, subjects are presented with stimuli that become increasingly similar along a particular acoustic dimension according to an adaptive procedure. The discrimination threshold, or just noticeable difference score (jnd), is determined as the point at which the subject's ability to discriminate two stimuli reaches a preset criterion, such as 70% correct. Using this kind of task, several studies have shown that disabled children require greater acoustic distances between stimuli along certain synthetic speech continua in order to tell them apart (Elliott and Hammer, 1988; Elliott *et al.*, 1989; Kraus *et al.*, 1996; Stark and Heinz, 1996a).

The third variable to be manipulated across the numerous studies on this topic is the stimulus variable. While task-by-stimulus (e.g., Sussman, 1993) and population-by-stimulus (e.g., Frumkin and Rapin, 1980) interactions have been observed, several general stimulus-related effects have been reported in the literature, which we have summarized in Table I. This list is not exhaustive; nevertheless, it provides an overview of the kinds of stimulus-related factors that various researchers have investigated. With respect to consonant contrasts, voicing and place-of-articulation appear to be highly vulnerable to perceptual disruption. For voicing contrasts, the critical acoustic dimension is temporal (voice onset time). For place-of-articulation contrasts the critical acoustic dimension is either dynamic-spectral, as in the case of stop-vowel syllables, or static-spectral, as in the case of fricatives. In contrast to voicing and place-of-articulation features, the stop-glide manner feature has not been shown to provoke perceptual difficulty, nor has a combination of place, manner, and voicing features. In the case of the stop-glide contrast, the critical acoustic dimension is temporal in nature (formant transition duration.) In the case of a combination of place, manner, and voicing features, the stimulus contrasts do not differ minimally along an acoustic dimension, but rather the combination of various features differentiates the two stimuli, thus making them acoustically and phonetically more distinct.

For vowels, perceptual difficulties have been shown to arise, particularly for contrasts between vowels that are close together in the acoustic-phonetic vowel space, that is, for vowels that are acoustically similar. A contrast between peripheral vowels that are at the edges of the acoustic-phonetic vowel space (/i-æ-a-u/) has only been shown to provoke difficulty when embedded in a tri-syllabic string (/dab_ba/). A contrast between vowels that are more similar in terms of their formant frequencies (/ɛ-æ/) was shown to be less resistant to perceptual difficulty for impaired subjects. However, the data for this vowel contrast are somewhat contradictory. While a recent study found impaired perception for the /ɛ-æ/ contrast, but not for the /a-i/ contrast, regardless of stimulus length (Stark and Heinz, 1996b), earlier studies found normal perception for the /ɛ-æ/ contrast when the stimuli were

TABLE I. Summary (nonexhaustive) of findings regarding stimulus factors and impaired speech perception in children with learning problems.

Contrast	Impaired perception?	Study
Consonants		
Voicing		
/ba-pa/	Yes	9
/da-ta/	Yes	5
Place		
/ba-da/ short FTD	Yes	1,3,4,5,6,8 9,10,11,15
/ba-da/ varying FTD	Yes	12
/da-ga/ short FTD	Yes	3,4,9,14
/sa-ʃa/	Yes	2
/das-daʃ/	Yes	10
/pʌ-tʌ/ short FTD	Yes	7
/ba-da/ long FTD	No	2
Manner		
/ba-wa/	No	14
Voicing+Place+Manner		
/ba-sa/	No	15
/da-ʃa/	No	15
Vowels		
Dissimilar		
/a-i/ long (40–240 ms)	No	13
/a-i/ short (10–40 ms)	No	13
/a-æ/ /d_b/ (250 ms)	No	5,10
/i-u/ 100 ms	No	10
/i-u/ /dab_ba/ (100 ms)	Yes	10
Similar		
/ɛ-æ/ long (250 ms)	No	1,8
/ɛ-æ/ short (40 ms)	No	5
/ɛ-æ/ /_I/ (40 ms)	Yes	2
/ɛ-æ/ long (40–240 ms)	Yes	13
/ɛ-æ/ v. short (10–40 ms)	Yes	13

FTD=Formant transition duration; 1=Tallal and Piercy, 1974; 2=Tallal and Piercy, 1975; 3=Brandt and Rosen, 1980; 4=Godfrey *et al.*, 1981; 5=Tallal and Stark, 1981; 6=Werker and Tees, 1987; 7=De Weirdt, 1988; 8=Reed, 1989; 9=Elliott *et al.*, 1989; 10=Leonard and McGregor, 1992; 11=Sussman, 1993; 12=Stark and Heinz, 1996a; 13=Stark and Heinz, 1996b; 14=Kraus *et al.*, 1996; 15=Mody *et al.*, 1997.

either long (250 ms) or short (40 ms), provided that they were presented in isolation with no immediately following phonetic material (Tallal and Piercy, 1974, 1975). It is likely that this apparent cross-study discrepancy regarding the /ɛ-æ/ contrast is due to differences in both stimulus and task details. For our purposes, however, the important point is that this contrast has been known to provoke perceptual difficulty, whereas contrasts between highly dissimilar vowels have generally been shown to be resistant to perceptual breakdown.

In the present study, we focused on a population of school-aged children with learning problems, a task that measured discrimination thresholds along synthetic speech continua, and stimuli that allowed us to investigate some of the precise acoustic-phonetic characteristics of stop consonant place-of-articulation contrasts that provoke perceptual difficulty. Concurrent with the behavioral speech perception measurement, we investigated the neurophysiologic encoding of these stimulus contrasts. The specific questions that we addressed in this study were: (1) Does lengthening the consonant–vowel formant transition duration in a synthetic /da-ga/ continuum result in improved discrimination thresholds for children known to have elevated thresholds along this place-of-articulation continuum? (2) How are behaviorally determined discrimination abilities in normal and impaired subject groups reflected in an electrophysiologic response that is known to reflect the brain's preattentive representation of a change from one auditory stimulus to another? The answer to the first question should contribute directly to our understanding of the precise acoustic-phonetic features that provoke perceptual difficulties. The answer to the second question should contribute to our understanding of the nature of the underlying deficit as stemming from faulty stimulus encoding at a neural level, deficient representation at an acoustic-phonetic level, or a combination of both these factors. Taken together, the responses to these two questions should provide information that is relevant to the design of auditory training procedures for children with speech perception deficits.

Formant transition duration in stop-vowel syllables has been the subject of several previous studies. Tallal and Piercy (1974, 1975) claimed that children with developmental aphasia had impaired perceptual abilities relative to normal children for /ba-da/ syllables with short (43 ms) formant transition durations, but not for /ba-da/ syllables with long (95 ms) formant transition durations. They interpreted this finding as indicating that lengthened transition durations resulted in improved perception due to the increased processing time allowed by the longer stimulus duration. This view of the underlying perceptual impairment as resulting from a basic deficit in the processing of rapidly changing signals led to the development of a training program which exposes impaired children to speech that has been modified so that the fast transitional elements are lengthened and amplified (Tallal *et al.*, 1996; Merzenich *et al.*, 1996).

In a critical assessment of this approach to the problem, Mody *et al.* (1997) claimed that the apparent improved perception of /ba-da/ stimuli with lengthened formant transition durations may instead be due to increased phonetic distance across the place-of-articulation contrast, which results from the glidelike quality of the stimuli with lengthened formant transitions (see also Reidel and Studdert-Kennedy, 1985). Thus, in their view, perception of this place-of-articulation contrast is affected far more by the phonetic nature of the contrast than by the processing time allowed for by the stimulus duration. Central to their view is the finding that nonspeech sine wave analogs of the second and third formants in the /ba-da/ contrast did not provoke perceptual difficulties. In other words, these acoustic elements were vulnerable to perceptual disruption only when they formed part of a speech contrast.

Our broad research agenda is aimed specifically at investigating the neural encoding and perception of speech signals. Thus, we do not directly address the question of whether the perceptual deficits exhibited by impaired children are general auditory or speech specific in nature. Rather, by focusing on the effect of lengthening the formant transition duration in a /da-ga/ continuum, we hoped to add to the empirical data addressing the nature of the underlying perceptual deficit as it pertains to speech perception in particular.

I. METHOD

A. Subjects

A group of 104 school-aged children served as subjects: 72 were classified as normal, and 32 were classified as having learning problems. The normal children had no history of learning or attention problems (based on a detailed parent questionnaire) and scored within normal limits (including no discrepancy between ability and achievement) on all tests in a psychoeducational test battery that was administered as part of our complete testing protocol. We therefore refer to this group as the WNL (within normal limits) group. (The psychoeducational test battery included portions of the Woodcock-Johnson Psycho-educational Battery, Woodcock-Johnson Psycho-educational Battery-Revised, and the Wide Range Achievement Test, 3rd ed.). The children with learning problems had been formally clinically diagnosed (prior to entry into the study) as having a learning disability ($n=11$), attention deficit disorder ($n=14$), or both ($n=7$). Furthermore, these impaired subjects had significantly lower scores than the normal subjects on all tests in the psychoeducational test battery. We therefore refer to this group as the LP (learning problems) group. All children had normal intelligence (Brief Cognitive Score$>$85) and normal hearing. (The Brief Cognitive Score is a measure of overall mental aptitude. Normal hearing was defined as thresholds better than 20 dB HL for 500–8000 Hz.)

It is important to note that that the psychoeducational test battery administered as part of our testing protocol served as a study-internal verification of subject group assignment. In order for a subject to be assigned to the LP group, she or he had to have a formal (professional) diagnosis, as well as below normal scores on our test battery. Similarly, in order for a subject to be assigned to the WNL group, she or he had to have no clinical diagnosis and normal scores on our test battery.

The experimental design specifically included children from various clinical diagnostic categories. The rationale behind these broadly defined inclusion criteria stems from our larger scale studies which have revealed that biologic and perceptual deficits cut across diagnostic categories such as learning disability, attention deficit disorder, and dyslexia. Our previous report on 91 children with various diagnostic categories (learning disability, attention deficit disorder, or both) indicated that 35%–40% of children in each of these categories have fine-grained auditory perceptual deficits (Kraus *et al.*, 1996). Ongoing accumulated data on 161 LP children uphold the observation that these deficits cut across diagnostic categories and are not correlated with any specific diagnostic group. Thus, a child with an auditory perceptual deficit and a diagnosis of learning disabled may have more in common (perceptually) with a child with similar perceptual deficits with another diagnostic category, such as attention deficit disorder, than with another learning-disabled child who does not exhibit an auditory perceptual deficit.

The children ranged in age from 6 to 16 years. As reviewed elsewhere (Kraus *et al.*, in press), there is no documented effect of age on either the psychophysical or neurophysiologic measures used in this study. Moreover, IQ does not vary with these psychophysical measures at any age.

B. Stimuli

Two /da-ga/ place-of-articulation continua were created using the Klatt cascade-parallel formant synthesizer (Klatt, 1980). All stimuli in both continua consisted of a formant transition period followed by a 60 ms steady-state period. There was no release burst. For all stimuli in both continua, the first and second formant onset frequencies were 220 and 1700 Hz, respectively. The third formant onset frequency varied from 2580 (/da/) to 2180 Hz (/ga/) in 40 steps of 10 Hz each. In the first continuum (daga40), these three formants reached the vowel steady-state frequencies of 720, 1240, and 2500 Hz over a period of 40 ms, giving a total stimulus duration of 100 ms. In the second continuum (daga80), this formant transition duration was lengthened to 80 ms, giving a total stimulus duration of 140 ms. For stimuli in both continua, the fourth and fifth formants were held constant across the entire stimulus duration at 3600 and 4500 Hz, respectively. Bandwidths were set as follows: $F1=60\,\text{Hz}$, $F2=90\,\text{Hz}$, $F3=150\,\text{Hz}$, $F4=200\,\text{Hz}$, and $F5=200\,\text{Hz}$. Each stimulus started with $F0$ set at 100 Hz. The fundamental frequency rose linearly to 125 Hz over the first 35% of the stimulus duration, and then fell linearly to 80 Hz over the remainder of the stimulus duration.

Short syllable durations (100 and 140 ms for daga40 and daga80, respectively) were chosen in order to facilitate the use of identical stimuli in the behavioral and electrophysiologic tests. The use of short stimuli in the electrophysiologic test optimized the recording session by increasing the number of responses it was possible to record in a given time period. Pilot behavioral testing confirmed that these stimuli were appropriate for use with the target subject population. Additionally, a very small step size was chosen for this $F3$ onset frequency continuum in order to maximize the chance that significant perceptual differences along this continuum between the WNL and LP subject groups would be revealed.

As a task control condition, a stop-glide continuum going from /ba/ to /wa/ was also created. It was expected that discrimination along this continuum would be relatively easy for impaired subjects (Kraus *et al.*, 1996), and therefore that equivalent performance in this condition across subject groups would establish that any group differences on the /da-ga/ continua were not due to general task-related difficulties. Stimuli in this continuum consisted of a formant transition period followed by a steady-state period, with no release burst. For all stimuli, the first and second formant onset frequencies were set at 234 and 616 Hz, respectively. These two formants then rose linearly to reach their steady state values of 769 and 1232 Hz, respectively. The duration of this formant transition period varied from 10 (the /ba/ end of the continuum) to 40 ms (the /wa/ end of the continuum) in 30 steps of 1 ms each. For all stimuli in this continuum the total stimulus duration was 100 ms. The third, fourth, and fifth formants were held constant across the entire stimulus duration at 2862, 3600, and 4500 Hz, respectively. Bandwidths were set as follows: $F1=60\,\mathrm{Hz}$, $F2=90\,\mathrm{Hz}$, $F3=150\,\mathrm{Hz}$, $F4=200\,\mathrm{Hz}$, and $F5=200\,\mathrm{Hz}$. Each stimulus started with $F0$ set at 100 Hz. The fundamental frequency rose linearly to 120 Hz over the first 11 ms of the stimulus, and then fell linearly to 80 Hz over the remainder of the stimulus duration.

C. Procedure

1. Behavioral discrimination thresholds

All subjects participated in both behavioral and neurophysiologic tests of their ability to discriminate stimuli along the two /da-ga/ continua (test conditions) and the /ba-wa/ continuum (control condition). Behavioral discrimination thresholds were determined using an adaptive tracking algorithm (Parameter Estimation by Sequential Tracking) with a four-interval AX discrimination task (4IAX). On each trial in this task, the subject was presented with two pairs of stimuli from a given continuum. In one pair, the two stimuli were identical; in the other pair, the stimuli were different. The subject responded by indicating on a two-button response box which pair was different. Feedback was provided for each response. One end of the stimulus continuum was designated the ‘‘anchor’’ end, and the ‘‘same pair’’ was always two presentations of this anchor stimulus. In the ‘‘different pair’’ the anchor stimulus and another stimulus from the continuum were presented. The PEST algorithm is designed so that the stimuli in the ‘‘different pair’’ get increasingly harder to discriminate (i.e., closer together on the continuum), and the subject’s just-noticeable-difference score (jnd) is determined by the distance between stimuli in the ‘‘different pair’’ that is required to achieve a performance level of 69% correct (Carrell *et al.*, 1999). In order to ensure an accurate jnd score, at least two measurements were taken. If the two scores differed widely, then a third measurement was taken. The final jnd score was then calculated as the average of the two best scores.

In the present study, both the daga40 and daga80 continua consisted of stimuli whose $F3$ onset frequency varied from 2580 to 2180 Hz in 40 steps of 10 Hz. Thus, assuming the subject could reliably discriminate between the anchor stimulus (stimulus 1) and the stimulus at the other extreme of the continuum (stimulus 41), the range of possible jnd scores in these test conditions was 1–40, with each step representing an $F3$ onset difference of 10 Hz. In both cases, stimulus 1 ($F3$ onset$=2580\,\mathrm{Hz}$) was designated as the anchor stimulus. Thus, for example, a jnd of 5 indicated that the subject could discriminate stimulus 1 from stimulus 5 with 69% accuracy, that is, the subject needed an $F3$ onset frequency difference of 40 Hz ($F3=2580\,\mathrm{Hz}$ versus $F3=2540\,\mathrm{Hz}$) in order to tell the stimuli apart 69% of the time.

In the control condition (bawa), the transition duration varied from 10 to 40 ms in 30 steps of 1 ms each. Thus, the range of possible jnd scores was 1–30 with each step representing a transition duration difference of 1 ms. In this condition, the stimulus with the 40-ms transition duration was designated as the anchor stimulus. A jnd of 7, for example, indicated that the subject could discriminate stimuli with transition durations of 40 and 33 ms with 69% accuracy.

The total test time required for obtaining an average jnd score for each stimulus continuum was approximately 30 min per subject. This included time for instructions to the subject and breaks between individual measurements during which subjects selected ‘‘prizes’’ such as candy, stickers, pencils, etc.

2. Neurophysiology

In order to probe the representation of the daga40 and daga80 stimulus contrasts at a preattentive neural level, mismatch negativity (MMN) responses were recorded from all subjects to stimulus pairs from each of the two place of articulation continua, as well as from the stop-glide continuum. The mismatch negativity is a passively elicited cortical evoked potential that is known to reflect the brain’s response to an acoustic change (Näätänen, 1995). It is elicited with an ‘‘oddball’’ stimulus delivery paradigm, in which a ‘‘deviant’’ stimulus is presented embedded in a string of ‘‘standard’’ stimuli. The MMN is seen as a negative deflection around approximately 200 ms after stimulus presentation. It is most clearly noticeable in the difference between the wave in response to the stimulus when presented in a string of identical stimuli and the wave in response to the same stimulus when presented as a deviant stimulus in a string of contrasting standard stimuli. During recording, the subject is engaged in an unrelated task such as watching a video. Thus, it provides a neurophysiologic index of the brain’s representation of an acoustic contrast at a preattentive neural level. For extensive discussion of MMN characteristics, generators, and research applications, see Näätänen *et al.* (1978) and Näätänen and Kraus (1995).

Stimulus pairs for the present study were selected based on pilot behavioral testing which indicated that an $F3$ onset difference of 80 Hz between the standard and deviant stimuli would constitute a MMN recording between stimuli near the behavioral discrimination threshold along a /da-ga/ continuum for normal adult listeners. Accordingly, for both the daga40 and the daga80 continua, the /da/ endpoint stimulus ($F3$ onset$=2580\,\mathrm{Hz}$) and the stimulus eight steps away on the continuum ($F3$ onset$=2500\,\mathrm{Hz}$) were selected as the deviant and standard stimuli, respectively. The same selection criterion was applied to the control (bawa) condition. In this case, the standard and deviant stimuli had transition durations of 35 and 40 ms, respectively.

A detailed description of procedures used to record the MMN in school-aged children is described elsewhere (Kraus *et al.*, 1993, 1996), therefore here we provide only an abbreviated description of the recording procedures. Subjects were seated in a comfortable reclining chair in a sound-treated booth. During data collection they watched a video of their own choosing. Stimuli were presented to the subject’s right ear at approximately 75 dB SPL through an insert earphone. Subjects listened to the movie soundtrack through the left ear (free field, no earphones). In both the daga40 and the daga80 conditions the stimulus onset asynchrony was 590 ms; in the bawa condition the stimulus onset asynchrony was 710 ms. In all conditions, deviant stimuli were randomly interspersed

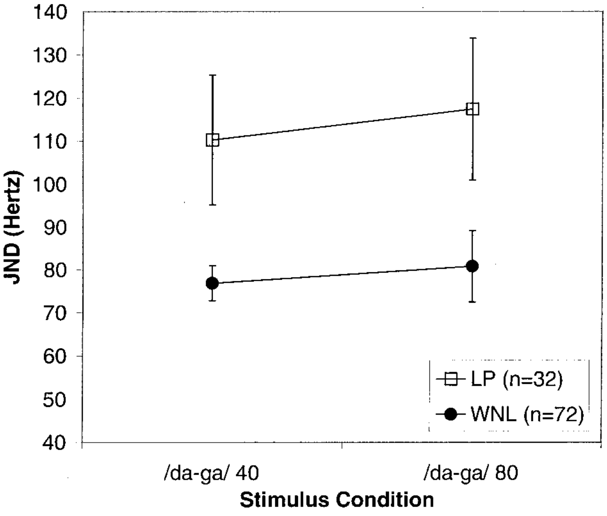

FIG. 1. Discrimination thresholds for the normal children (WNL) and children with learning problems (LP) along the daga40 (short transition) and daga80 (long transition) stimulus continua.

between standard stimuli with a minimum of three standard stimuli between deviants. Frequency of occurrence of the deviant stimulus was 10%. In each recording session, responses to approximately 200–250 deviant stimuli were recorded. In addition to the oddball presentation paradigm, responses were recorded to approximately 1000 presentations of the deviant stimulus presented alone. The wave of interest is the average ''deviant'' wave minus the average ''alone'' wave. That is, we were interested in the comparison between the response to the deviant stimulus when presented embedded in stream of standard stimuli versus the response to the same stimulus when presented alone. Neurophysiologic representation of the difference between the standard and the deviant stimulus is manifested in this difference wave as a negativity around approximately 200 ms after stimulus presentation. Data were recorded from nine active scalp electrode sites in accordance with the 10–20 recording system (American Electroencephalographic Society, 1991). Previous studies have shown the MMN to be robust at the *Fz* (frontal, midline) location, therefore in this paper we present only recordings from that site. [For additional information regarding MMN data analysis techniques, see McGee *et al.* (1997).]

II. RESULTS

A. Behavioral discrimination thresholds

Figure 1 shows the discrimination thresholds for the normal children (WNL) and children with learning problems (LP) along the daga40 (short transition) and daga80 (long transition) stimulus continua. In both conditions, the normal children required an $F3$ onset frequency difference of approximately 75–80 Hz in order to discriminate the stimuli with 69% accuracy. The children with learning problems required an $F3$ onset frequency difference of approximately 110–117 Hz in order to perform at this same level. For both groups, there was no difference in their discrimination thresholds along the daga40 and daga80 continua. A two-factor repeated measures ANOVA with Group (WNL vs. LP) and Stimulus (daga40 vs. daga80) as factors showed a significant main effect of Group $[F(1,176)=7.56,\ p<0.05]$. The main effect of Stimulus was not significant, nor was the Group by Stimulus interaction. In other words, in both conditions the LP subjects had elevated discrimination thresholds relative to the WNL subjects; and, for both groups, the lengthened transition duration had no effect on discrimination threshold.

In the /ba-wa/ task control condition, both subject groups had jnd's of approximately 7, indicating that they needed transition duration differences of approximately 7 ms in order to tell the stimuli apart. Importantly, there was no difference in performance in this condition across the two groups. This equivalent performance established that the group difference observed in the daga40 and daga80 conditions was not due to a general task-related difficulty on the part of the impaired subjects. Rather, the elevated discrimination thresholds in the /da-ga/ conditions were stimulus-related (see also Kraus *et al.*, 1996).

B. Neurophysiology

Figure 2 shows grand averaged waveforms from the normal children (WNL, $n=72$) and children with learning problems (LP, $n=32$) to the daga40 and daga80 stimulus pairs selected for the MMN recordings. Recall that these stimuli were selected such that their $F3$ onset frequencies differ by 80 Hz, and the waves shown in the figure come from the *Fz* (frontal, midline) recording site. In each quadrant of the figure the upper two waveforms show the electrophysiologic response to the deviant stimulus ($F3$ onset frequency=2580 Hz) when presented as a rare stimulus in a string of standard stimuli ($F3$ onset frequency=2500 Hz) and when presented alone. The lower waveform represents the difference between these two waveforms at each point in the recording window, with the horizontal line at zero. In all cases, positive is up. The boxes below the difference wave indicate the points at which the difference wave is significantly different from zero at the $p<0.01$ and $p<0.001$ levels (by one-group, two-tailed *t*-tests). The height of these boxes differentiates the two levels of significance (see labels in the lower right quadrant). These grand averaged waveforms allow us to gain initial insight into the overall response patterns across groups, and as such are useful indicators of intergroup central tendency variation.

In all four cases shown in Fig. 2, we see evidence of a MMN response. That is, in all cases there is a period of negativity starting at around 200 ms after stimulus onset. However, the overall magnitude of this negative deflection appears to vary across groups and stimuli. These variations in MMN responses are seen most clearly in Fig. 2 by the duration of the highly significant negative periods, that is, by the extent of the boxes along the bottom of the plots. These grand averaged waveforms show that the LP group had diminished responses relative to the normal group in the short transition duration condition (daga40). However, the impaired and normal groups had more similar responses in the long transition duration condition (daga80). Similarly, in the LP group, the lengthened transition duration stimuli resulted in an enhanced neurophysiologic response relative to the

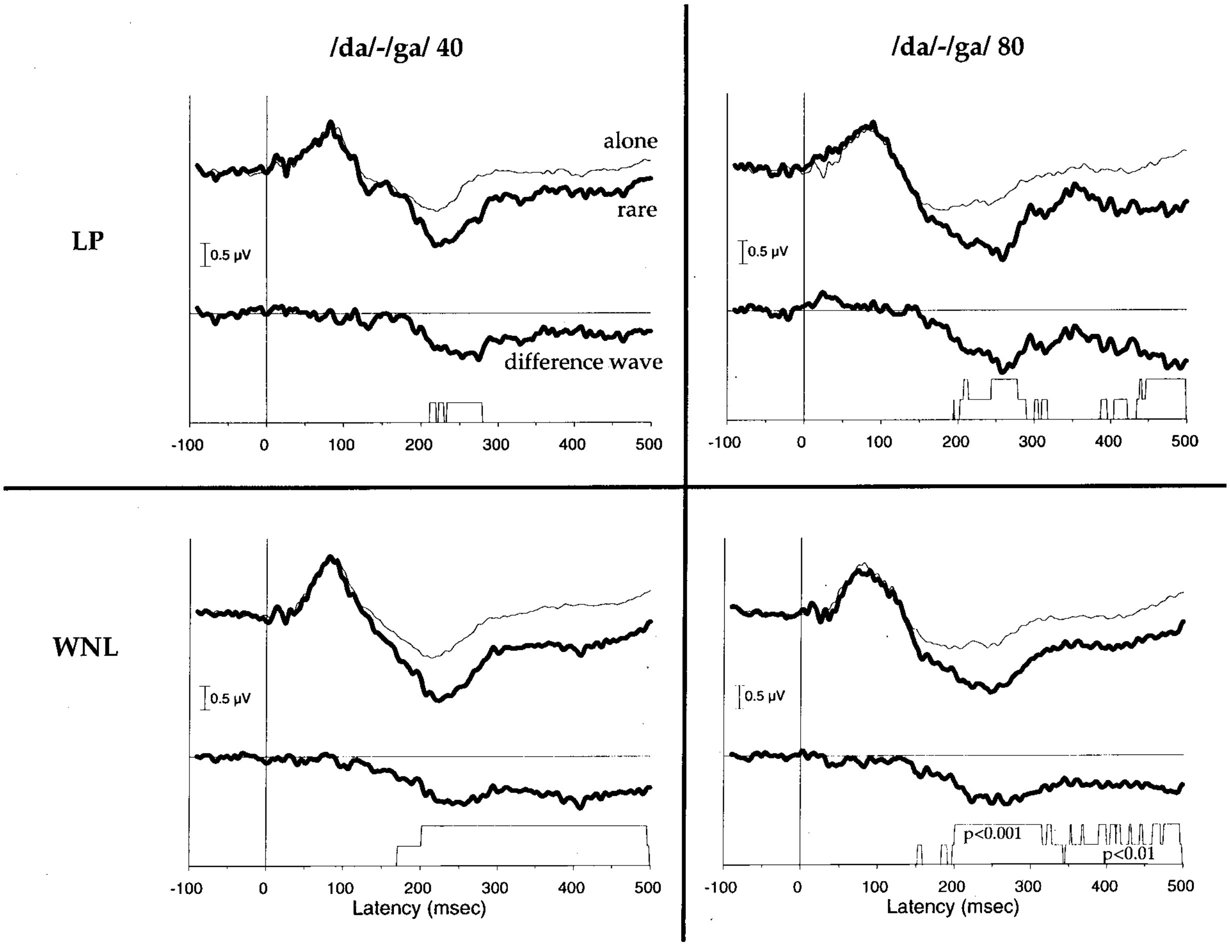

FIG. 2. Grand averaged waveforms from the normal children (WNL, $n=72$) and children with learning problems (LP, $n=32$) to the daga40 and daga80 stimulus pairs selected for the MMN recordings. Waves shown in the figure come from the *Fz* (frontal, midline) recording site. In each quadrant, the upper two waveforms show the electrophysiologic response to the deviant stimulus (*F*3 onset frequency=2580 Hz) when presented as a rare stimulus in a string of standard stimuli (*F*3 onset frequency=2500 Hz) and when presented alone. The lower waveform, represents the difference between these two waveforms at each point in the recording window, with the horizontal line at zero. In all cases positive is up. The boxes below the difference wave indicate the points at which the difference wave is significantly different from zero at the $p<0.01$ and the $p<0.001$ levels (by one-group, two-tailed *t*-tests). The height of these boxes differentiates the two levels of significance (see labels in the lower right quadrant).

short transition duration stimuli. In the normal group, the lengthened transition duration had no effect on neurophysiologic responses. Thus, the overall impression of the grand averaged waveforms is that the MMN in the daga40 condition for the group of children with learning impairments (Fig. 2, top left panel) is diminished relative to the other three cases.

In order to quantify this general impression from the grand averaged waveforms, the area of negativity was calculated for each individual subject's difference wave. This measure was calculated as the area between the difference wave and the zero line, and took into account both the duration and the amplitude of the MMN response. A large area (e.g., greater than 450 μV×ms) indicated a robust MMN response, whereas a small area (e.g., less than 100 μV×ms) indicated a diminished MMN response. Figure 3 shows the percentage of subjects from each group with large and small MMN responses (as defined above) for each stimulus condition. By focusing our analyses on the extreme ends of the MMN area distributions for the two subject groups we could observe the relative robustness of MMN response across the two subject populations. In this figure, as in the grand averaged waveforms shown in Fig. 2, we see a different pattern of results for the impaired subjects in the daga40 condition (open squares) in comparison to the pattern of responses for the other three cases. In the daga40 condition for the impaired subjects, the distribution of MMN areas was skewed towards small areas. In contrast, the distributions of MMN areas were skewed towards large areas in each of the other three cases. It is important to note that, in all four cases, the majority of individual subjects showed MMN responses with areas between 100 and 450 μV ms. However, group and stimulus differences were revealed when we examined the edges of the MMN area distributions.

Specifically, in the impaired subject group for the daga40 condition, 22% of the individual subjects had very small ($<100\,\mu$V×ms) MMN areas, whereas only 9% had very large MMN areas ($>450\,\mu$V×ms). In contrast, only 11% of the normal subjects had very small MMN areas ($<100\,\mu$V×ms), whereas 28% had very large MMN areas ($>450\,\mu$V×ms) in this stimulus condition. A significant chi-square statistic [chi-square $(1)=5.29$, $p=0.021$] indicated that the distribution of MMN areas for the impaired subjects was significantly different from that of the normal subjects

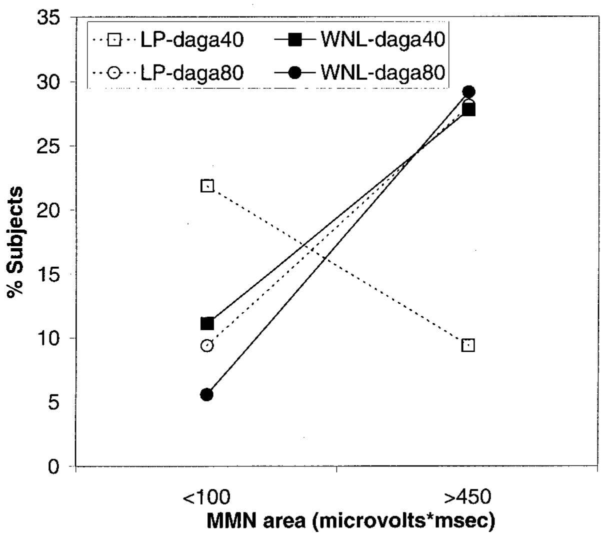

FIG. 3. Percentage of subjects from each group with very large and very small MMN areas for each stimulus condition.

for the daga40 condition. In the daga80 condition, the distribution of MMN areas was similar across the two subject groups. A relatively small percentage of both subject groups in this condition had very small MMN areas: 9% and 6% for the impaired and normal groups, respectively. A considerably larger percentage of both subject groups had large MMN areas in this condition: 28% and 29% for the impaired and normal groups, respectively. In this case, the chi-square statistic showed that the MMN area distributions were not significantly different across the two subject groups.

An examination of the MMN area distributions within each group of subjects across the two stimulus conditions showed a significant difference in MMN area distributions between the daga40 and daga80 conditions in the impaired group [chi square $(1)=6.89$, $p=0.032$], but not in the normal group. In the impaired group, a considerably larger percentage of subjects had small MMN areas than large MMN areas (22% versus 9%) for the daga40 condition, whereas, in the daga80 condition, a considerably larger percentage of subjects had large MMN areas than small MMN areas (28% versus 11%). For the normal subjects, in both conditions the distributions were skewed towards larger MMN areas. Finally, in the control condition with the /ba-wa/ contrast, both the grand averaged waveforms and the MMN area distributions showed equivalent responses in the impaired and normal subject groups.

In summary, an examination of the MMN responses from the same children who participated in the behavioral tests described above showed that responses from the group of impaired subjects in the short transition duration condition tended to be diminished relative to their responses in the long transition duration condition, as well as relative to the responses from the group of normal children in both stimulus conditions. This pattern of MMN responses was evident in the grand averaged waveforms, which provided an indication of the responses across the whole group of subjects. Additional support for this response pattern was obtained by examining the distribution of MMN area measures in individual subjects within each subject group in each stimulus condition. In this analysis, we found that small MMN areas were more frequent than large MMN areas in the impaired subject group in the daga40 condition. However, in the daga80 condition, large MMN areas were more frequent than small MMN areas for this same group of subjects. For the normal subjects, in both stimulus conditions, large MMN areas were more frequent than small MMN areas.

Given that in all cases a high proportion of subjects (approximately 61%–69%) showed intermediate MMN areas (between 100 and 450 μV ms), these neurophysiologic data need to be interpreted with caution. That is, there was a high degree of overlap across groups and stimulus conditions, indicating that MMN response magnitude on its own is not a good basis for subject or stimulus categorization. Nevertheless, these groupwise neurophysiologic data, in combination with the behavioral discrimination data, can provide meaningful initial insights into the nature of the underlying auditory-perceptual deficit that many children with learning problems contend with.

III. GENERAL DISCUSSION

Taken together, these behavioral and neurophysiologic data suggest that the source of the underlying perceptual deficit may be a combination of faulty stimulus representation at the neural level as well as deficient perception at an acoustic-phonetic level. Specifically, the group of children with diagnosed learning problems exhibited a behavioral deficit in discriminating minimally different stimuli along a /da-ga/ continuum regardless of whether the critical formant transition was relatively short or long in duration. The neurophysiologic data indicated that, in the short transition duration condition, a stimulus contrast below the impaired group's mean discrimination threshold was not well represented at a preattentive neural level in this subject group. Thus, in this case, the neurophysiologic data paralleled the behavioral data, suggesting a biological basis for the impaired behavioral perception (see also Kraus *et al.*, 1996). In the long transition duration condition, the neurophysiologic data indicated that the $F3$ contrast was more robustly represented in the impaired subject group at the neural level than the short transition duration stimuli; however, the behavioral data showed that their impaired perception of this contrast persisted despite the lengthened transition duration.

While the behavioral and physiologic responses are related in that they reflect auditory pathway representation of acoustic events, it must be remembered that these are inherently *different* responses which represent different levels of processing. That is, the neurophysiologic response is a preattentive neural representation of acoustic change, whereas the behavioral response also involves focused attention and later phonetic processing. Thus, the convergent behavioral and neurophysiologic findings in the short transition duration condition, in combination with the more divergent behavioral and neurophysiologic findings in the long transition duration condition, suggest that robust stimulus representations at both levels of processing are necessary for fine-grained discrimination of the /da-ga/ contrast. In the short transition duration condition, faulty stimulus encoding at the neural level appeared to underlie the observed elevated discrimination threshold in the LP subject group. In the long transition duration condition, regardless of the relatively robust stimulus representation at the neural level, perceptual discrimination was still impaired in this subject group, thus implicating a breakdown at higher levels of processing.

The present behavioral results replicate previous findings reported in the literature showing impaired place-of-articulation perception for disabled children relative to normal children (see Table I and references therein). Furthermore, based on these behavioral findings, it appears that simply lengthening the formant transition duration from 40 to 80 ms is not effective in enhancing discrimination between stimuli along a /da-ga/ continuum. This behavioral result seems to stand in contrast to the earlier finding of Tallal and Piercy (1975) who showed enhanced perception by children with developmental aphasia of a synthetic /ba-da/ contrast when the formant transition duration was lengthened from 43 to 95 ms. However, there are several subject-, task-, and stimulus-related factors that differentiate the two studies. The impaired subjects in the present study had diagnoses of learning disability, attention deficit disorder, or both, whereas in the Tallal and Piercy study the subjects were diagnosed as developmental aphasics. In the present study, our task determined discrimination thresholds along a /da-ga/ continuum. In contrast, Tallal and Piercy (1975) examined the identification, serial ordering, discrimination, and serial recall of /ba/ and /da/ stimuli that represented good exemplars of the /b/ and /d/ categories. Finally, in the present study, the duration of the steady-state portion of the stimuli remained constant across the daga40 and daga80 conditions; whereas in the Tallal and Piercy study the duration of the steady-state portion was shorter in the long formant transition condition than in the short formant transition condition. In proportional terms, the transition durations of the stimuli in the present study occupied 40% and 57% of the daga40 and daga80 stimuli, respectively. In the Tallal and Piercy stimuli, the transition durations occupied 17% and 38% of the short and long transition duration stimuli, respectively. These subject, task, and stimulus differences between the two studies may well account for the different results.

Nevertheless, the present finding of no perceptual discrimination enhancement with lengthened formant transition duration suggests that a revision of the general interpretation offered in the earlier studies by Tallal and colleagues is called for. Specifically, Tallal and Piercy (1975) concluded that ‘‘... it is the brevity not the transitional character of this component of synthesized consonants which results in the impaired perception...’’ (p. 73). This conclusion was based on their finding of impaired perception of synthetic /ba/ and /da/ with brief formant transition durations and /ɛɪ/ and /æɪ/ with brief initial vowels, but intact perception of these same CV syllables with extended formant transition durations and long steady-state /ɛ/ and /æ/. However, the present study (with subjects with very similar perceptual deficits to the Tallal and Piercy subjects) suggests that this earlier finding fails to generalize to other stimuli (from /ba-da/ to /da-ga/), and also fails to transfer to a novel task (from endpoint identification to discrimination along a continuum). Thus, there appear to be stimulus- and task-specific (and perhaps also subject-specific) factors that interact with signal manipulations that attempt to enhance perception of synthetic speech sounds. The origin of these interactions remains to be identified. However, by examining the neurophysiologic encoding of the /da-ga/ contrast for both short and long formant transition duration stimuli, the present neurophysiologic data provided some insight into the relationship between the preattentive representation of this contrast at the neural level and its perceptual discrimination in a task requiring focused attention to the stimuli.

The present data raise the following, critical question: What bearing do these findings have on the design of remediation programs for children who exhibit speech perception deficits? In response to this question we offer the following speculations based largely on previous findings reported in the literature. Major generator sources for the MMN (obtained from animal models and modeled from scalp-recorded data in humans) include the extralemniscal auditory thalamocortical pathway (reviewed in Alho, 1995; Kraus *et al.*, 1994). Because the MMN has nonprimary, extralemniscal auditory CNS origins (Kraus *et al.*, 1994; Scherg and Picton, 1990) and these pathways inherently exhibit plasticity (Edelin and Weinberger, 1991; Kraus and Disterhoft, 1982), it is amenable to training. Moreover, during speech sound training, learning-associated neurophysiologic changes can be evident before learning is manifested behaviorally (Tremblay *et al.*, 1998). Consequently, the better neurophysiologic representation of the longer duration stimuli may underlie the success of training strategies which employ stimuli with lengthened formant transition stimuli (e.g., Tallal *et al.*, 1996; Merzenich *et al.*, 1996). Brief duration stimuli, which are poorly represented physiologically by the auditory CNS, may be difficult for children to access for training purposes. However, given that the present data showed that lengthening the critical formant transition duration on its own did not result in improved discrimination thresholds along the /da-ga/ continua, it is also likely that any effective training procedure will also need to include direct means of enhancing perception at a phonetic level.

The conclusions and interpretations of the present study are necessarily tentative due to various practical limitations that are imposed on any study of this scale with this subject population. One such constraint is the range of testing paradigms that can be included in the experimental protocol. Ideally, the behavioral data set would have included both discrimination and labeling functions from each individual subject for each stimulus condition. However, in order to avoid excessively long, tedious, and numerous testing sessions with the children in the study, performance on only one kind of task was included in the protocol. The discrimination task was selected because it directly reflects the subject's ability to perceive fine-grained acoustic contrasts, and therefore more closely parallels the task requirements of the oddball paradigm used to elicit the MMN than a labeling task. Clearly, the availability of corresponding labeling data would have made it possible to examine in greater detail the relationship between the present data and the Tallal and Piercy (1975) data.

A second limitation of the present data set is related to the auditory nature of the long transition duration stimuli. As a direct consequence of the lengthened transition durations for all of the first three formants, these stimuli lose their stoplike quality and sound somewhat glidelike. The construction of the stimuli for the present study was inspired by the Tallal and Piercy stimuli (which also had lengthened $F1$, $F2$, and $F3$); however, it is important to note that other studies have maintained the stoplike quality of this type of CV stimulus by lengthening only the higher formants while maintaining relatively short first formant transitions (Keating and Blumstein, 1978; Sussman and Carney, 1989). The effect of this manner-class shift between the short and long transition stimuli therefore remains an issue for future research.

As a final word, we would like to stress that a critical feature of the present study was the combined behavioral-neurophysiologic approach. The combination of the two sources of data provided insight into the underlying perceptual processes that neither technique could have provided alone. Furthermore, in combination with other studies of auditory-perceptual plasticity, we believe that we will be able to identify critical elements of training procedures that can eventually be incorporated into efficient, effective, and scientifically grounded intervention programs for children with speech perception deficits.

ACKNOWLEDGMENTS

This work was supported by NIH-NIDCD (Grant Nos. DC 01510 and DC 03762) and by the Foundation for Hearing and Speech Rehabilitation. We gratefully acknowledge the data collection and processing assistance of Audrey Cameron, Beth Perez, and Brad Wible. We also thank two anonymous reviewers for insightful and helpful suggestions for improving the manuscript.

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