

# The Role of Early Language Experience in the Development of Speech Perception and Language Processing Abilities in Children with Hearing Loss

Susan Nittrouer, Ph.D., and Lisa Thuente Burton, B.A.

*Early experience with a native language serves to shape the perceptual strategies used to derive phonetic structure from the speech signal. In turn, the ability to derive phonetic structure facilitates language processing by allowing long sequences of linguistic material to be stored in working memory. Consequently, deficits in early language experience can lead to problems in the related skills of speech perception and language processing. The goal of this study was to test the prediction that children with hearing loss would demonstrate problems with speech perception and language processing consistent with what we would expect from children who had deficits in early language experience. Children ages 8 to 10 years with hearing loss were tested on four types of tasks (speech perception, phonetic awareness, recall of word strings, and comprehension of sentences with complex syntax), and results were compared to those of a group of children with normal hearing. All children with hearing loss showed evidence of restricted access to acoustic information in the speech signal and about half of them demonstrated the predicted problems with the experimental tasks. Contrary to predictions, however, the performance of roughly half the children was comparable to that of the children with normal hearing. Examination of independent variables revealed differences between the two groups of children with hearing loss only in preschool educational environments. Our conclusion is that experiential deficits associated with hearing loss can delay the development of mature speech perception and language processing abilities, but that these deleterious effects can be greatly ameliorated by appropriate and intensive early intervention.*

## Introduction

A major goal of auditory/oral education for children with hearing loss is to help these children learn to understand the speech of others. Traditionally,

---

*Susan Nittrouer, Ph.D., is Director of Exemplary Services at the Center for Persons with Disabilities at Utah State University, Logan, UT. Lisa Thuente Burton, B.A., is a teacher of the deaf at the Omaha Hearing School in Omaha, NE.*

research on the speech perception of individuals with hearing loss has focused on issues surrounding the relation between specific bits of the acoustic speech signal (usually termed "cues") and linguistic elements (features, phonemes, or words, depending on the study): for example, what cues are and are not available to listeners with hearing loss; how limits on availability affect the abilities of individuals with hearing loss to retrieve linguistic elements; and how sensory aids help to make more cues available (for a review, see Pickett, 1999). This approach to studying the speech perception of individuals with hearing loss stems directly from the focus of research on speech perception by individuals with normal hearing for the past half-century, which has broadly been to map relations between specific acoustic cues and linguistic elements.

In 1981, however, Remez, Rubin, Pisoni, and Carrell published a report showing that adults with normal hearing can recognize linguistic structure in signals that completely lack traditional speech cues. They accomplished this task by substituting frequency-modulated sinusoids for the center frequencies of the first three formants of a sentence. These signals lacked the harmonic structure and broad-band formants of natural speech, as well as any of the short-time spectral properties usually associated with obstruent and fricative production. This study of Remez and colleagues (1981) sparked subsequent investigations designed to examine how much and in what ways the speech signal can be degraded and still allow listeners to recognize its linguistic structure. Research continued using the sinewave replicas introduced by Remez and colleagues (e.g., Best, Studdert-Kennedy, Manuel, & Rubin-Spitz, 1989; Remez & Rubin, 1984, 1990; Remez, Rubin, Nygaard, & Howell, 1987), and expanded to use other methods of signal processing. In particular, Shannon and colleagues (1995) developed a method of dividing the signal into a number of frequency bands, and then modulating the amplitude of the noise within each band to match the amplitude of what the speech signal had been within that band (e.g., Dorman, Loizou, Kemp, & Kirk, 2000; Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000; Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). The collective finding of all these studies is that listeners can derive linguistic (specifically, phonetic) structure from these signals, even though the acoustic attributes long held to be critical for phonetic perception are absent.

At the same time an abundance of evidence has demonstrated that under certain conditions listeners fail to use acoustic information readily available to them. The most obvious example of this phenomenon is the well-replicated finding that listeners do not always use attributes of the acoustic speech signal when listening to a language that is not their native language (e.g., Crowther & Mann, 1992, 1994; Flege, 1989; Gottfried, 1984). For example, Miyawaki, et al. (1975) showed that native Japanese speakers were able to discriminate /ɹa/ versus /la/ only at levels barely above chance, even though they discriminated the cue that distinguishes this contrast (F3 transition) as well as native English speakers when it was presented in

isolation. A within-language example of this phenomenon is that listeners fail to use acoustic information to phonetic perception if it is not normally available. For example, adult English speakers have reliably been shown to use formant transitions in making decisions about the place of fricative production when those fricatives occur at the beginnings of syllables (e.g., Mann & Repp, 1980; Nittrouer, 1992; Nittrouer & Studdert-Kennedy, 1987; Whalen, 1981), but fail to use formant transitions in making decisions about place of fricative production for those that occur at the ends of syllables (Mann & Soli, 1991; Nittrouer, Miller, Crowther, & Manhart, 2000). Nittrouer and colleagues (2000) suggested that the reason for this perceptual asymmetry is that there is an asymmetry in the duration and extent of formant transitions associated with fricative production: Transitions are longer and more extensive for syllable-initial than for syllable-final fricatives. Of particular interest, Mann and Soli (1991) and Nittrouer and colleagues (2000) showed that even when fricative-vowel syllables are presented backwards, so that the syllable-final formant transitions are exactly as extensive as they are when they are syllable-initial, adults still fail to pay attention to this acoustic property in their decisions of syllable-final fricative identity. Apparently adults have specifically learned not to look to these transitions for information about the place of syllable-final fricatives, and so don't ever do so.

The conclusion that may be reached from the findings of all these studies is that speech perception involves much more than extracting an acoustic cue (or extracting and summing a set of acoustic cues), and then using that to "look up" the corresponding linguistic element in a kind of mental code book. Instead, speech perception seems to require knowing what signal attributes to pay attention to, and how to integrate the information provided by multiple attributes to obtain a meaningful perceptual form. This suggestion mandates that some perceptual learning be involved. As a first step to understanding what must be learned, a model termed the Developmental Weighting Shift (DWS) has been developed. The DWS proposes that the relative amounts of attention (i.e., *weight*) assigned to the various properties of the acoustic speech signal change as a child gains experience with a native language and learns which properties are informative for each phonetic decision (Nittrouer, 1996; Nittrouer, Manning, & Meyer, 1993; Nittrouer & Miller, 1997a, 1997b). The proposed end products of this developmental shift are perceptual strategies that allow listeners to comprehend phonetic structure in the most efficient and effective way possible. In turn, the ability to apprehend this structure facilitates further language processing. We know, for example, that working memory for linguistic materials is enhanced when phonetic codes are used to store words. We also know that being able to store long sequences of words is necessary if one is going to parse sentences with complex syntax, because these sentences tend to be long (Bar-Shalom, Crain, & Shankweiler, 1993; Brady, Shankweiler, & Mann, 1983; Smith, Macaruso, Shankweiler, & Crain, 1989).

Of course, testing the hypothesis that language experience specifically

accounts for shifts in perceptual strategies for speech is tricky because it is difficult to find groups of individuals that differ only in the amount of early language experience they received, independent of differences in other factors such as sensory capabilities, general cognitive abilities, or general life experiences. However, in an attempt to test this hypothesis, Nittrouer (1996) compared the speech perception strategies and phonetic awareness<sup>1</sup> of four groups of children (8–10 years of age): children with histories of early, chronic otitis media with effusion (OME); children living in conditions of low socio-economic status (low SES); children experiencing both of these conditions; and children experiencing neither condition. Children with early, chronic OME generally have periods of raised auditory thresholds that can serve to diminish access to language input (U.S. Department of Health and Human Services, 1994). Children living in conditions of low SES experience less parental language input, and what they do experience differs in kind from that of children in middle-class homes (Hess & Shipman, 1965; Honig, 1982; Laosa, 1980; Schachter, 1979; Schachter & Strage, 1982; Walker, Greenwood, Hart, & Carta, 1994). As a result, children experiencing these conditions (those of early, chronic OME and low SES) provided as clean an examination of the effects of early language experience, and deficits in that experience, as is possible. Using children from both of these populations, the reasoning went, provided some safeguard against reaching the conclusion erroneously that differences found on dependent measures between one of the experimental groups and the control group were attributable to differences in early language experience, because the only way in which the experimental groups were similar was in their constrained early language experience. That is, children who had frequent bouts of OME, but who were nevertheless from mid-SES homes, had similar general experiences to children in the control group. Children from low-SES homes who had not suffered frequent OME may have had less general experience than children in the control group, but their auditory thresholds were presumably always normal.

The speech perception task used with the children in these four groups consisted of fricative-vowel stimuli in which both the spectral content of the fricative noise and the formant transitions were manipulated. Nine synthetic fricative noises were used that varied along a continuum from one appropriate for an /ʃ/ ('sh') to one appropriate for an /s/. Formant transitions were appropriate for either a syllable-initial /ʃ/ or /s/. Earlier work with children between the ages of 3 and 7 years, and with adults, had shown that there is a developmental shift in the relative amounts of attention, or weight, given to

---

<sup>1</sup>The specific term 'phonetic' awareness is used here rather than the more general term 'phonological' awareness to highlight the fact that it is probably specifically the ability to access linguistic structure at the level of the phoneme-sized phonetic segment that facilitates the development of other language-processing abilities, rather than more general abilities in accessing linguistic structure at the levels of, for example, the syllable or onset and rime.

each of the two properties manipulated such that progressively less is given to formant transitions and more is given to fricative noises (Nittrouer, 1992; Nittrouer & Studdert-Kennedy, 1987). In Nittrouer (1996), children in the three experimental groups demonstrated labeling functions more akin to those of the younger children in the earlier studies than to those of the children in the control group. Specifically, children with histories of early, chronic OME, living in conditions of low SES, or experiencing both conditions, weighted formant transitions more and fricative-noise spectra less than the children in the control group did. Results of two tests of phonetic awareness also showed group differences: Children in any one of the three experimental groups were poorer at manipulating phonetic structure in words than were children in the control group. Thus, this study provided some support for the related notions that one function of early language experience is to help children learn the most appropriate perceptual strategies for their native language and that language-specific perceptual strategies allow listeners to access phonetic structure.

The current study was originally designed to evaluate the performance of children with hearing loss on these same speech perception and phonetic awareness tasks in order to test the hypothesis that at least some part of the language problem of children with hearing loss can be modeled as arising from experiential deficits, rather than from sensory deficits. If these children demonstrated similar results to the children in the OME and low-SES groups of Nittrouer (1996) on the speech perception task, some evidence would be had for viewing hearing loss as an obstacle to language experience, as well as a sensory deficit. On the other hand, if the results of this study simply showed that these children did not weight either acoustic property (fricative noises or formant transitions) very much at all, then we would have to conclude that the speech perception difficulties of individuals with hearing loss are completely explained by the sensory deficit. The tasks of phonetic awareness were included to examine the relation between speech perception and phonetic awareness in children with hearing loss.

In the design of this current study, however, several changes in procedures were made. First, a broader range of tasks were included than were used in Nittrouer (1996). Two sets of stimuli were used in addition to the fricative-vowel syllables to examine children's weighting of different kinds of acoustic properties in speech perception. Also children's abilities to recall word strings and to comprehend sentences with complex syntax were evaluated in order to test the hypothesis that having access to phonetic structure improves one's ability to store words in working memory, and so to parse long sentences with complex syntax (e.g., Bar-Shalom et al., 1993; Nittrouer & Miller, 1999). These additional tasks had all been used in a study examining differences in speech perception and language processing for children with normal and poor phonological processing abilities (Nittrouer, 1999). Finally we wound up separating data for the children with hearing loss into two groups because these children were demonstrating two very distinct patterns of responding.

The response pattern exhibited by a child with hearing loss appeared to be explained in large part by whether that child was in a mainstreamed academic setting or in a self-contained classroom, and that distinction, in turn, seemed related to what kind of preschool intervention the child had. Although this division of children with hearing loss into two groups was not originally planned, the finding that results neatly aligned themselves in this way sharpened our experimental knife, allowing us to make finer-grained statements about the separate effects of sensory and linguistic deprivation on language development.

## Method

### *Participants*

Seventeen children with hearing loss between the ages of 8 and 10 years who had never been in educational programs using sign language participated in this study. Data from a group of children (8–10 years) with normal hearing collected as part of another study (Nittrouer, 1999) were also used. The materials for this study were the same as for that earlier study.

When this study was originally designed it was not proposed to divide the children with hearing loss into groups differentiated by whether or not they were in mainstreamed academic settings. Instead, the objective was to compare children with hearing loss to children with normal hearing to see how hearing loss (and its consequent disruption in language experience) might affect children's performance on the tasks used here, which are believed to tap into skills basic to language processing. It was only after all the data was collected and data analysis had begun that it became apparent that the children with hearing loss were showing two distinct patterns of performance, and those patterns correlated with whether children were in mainstream settings or in a self-contained classroom for children with hearing loss.

Comparing the performance of children in mainstream and nonmainstream settings was particularly informative in this case because all the children participating had been mainstreamed for at least 1 year before the time of testing. At the time that all these children entered elementary school there was no opportunity to be in a self-contained classroom for children with hearing loss using an auditory/oral approach. Just a year before data collection began for this project, however, a private, philanthropic foundation began to provide funding for a self-contained classroom in Omaha for elementary-aged school children who were deemed to be unable to learn in regular classrooms. This class was affiliated with a local, private auditory/oral school for children with hearing loss. With the initiation of the self-contained classroom, separate discussions among school personnel took place concerning every child in this study (less than a year before testing occurred) about whether that child should continue in a regular school setting, or be placed in the newly formed classroom for children with hearing loss. Unlike most cities in the United

States, which have one large school district, the metropolitan Omaha area is divided into several separate school districts. Consequently, a different set of school personnel participated in the decision-making for each child, and different evaluative tools were used. We do not know the criteria used to make the judgment in each case that a child was performing poorly enough in the mainstream that a placement in the self-contained class was warranted, and we do not have scores from that time for all children on any one diagnostic test. Nonetheless, every child in the self-contained classroom had been judged to be failing in the mainstream.

Table I shows mean values for some descriptive statistics. All children were fitted with their first hearing aids shortly after being identified, and so the age at which hearing aid use began is not given as a separate statistic. The number of hours the children wore their hearing aids each day was obtained from a parental questionnaire. General speech recognition abilities were measured using List 1 of the *Phonetically Balanced Kindergarten Test* (PBK) Word Lists (Haskins, 1949). General speech production abilities were evaluated using the Sounds-in-Words subtest of the *Goldman-Fristoe Test of Articulation* (GFTA) (Goldman & Fristoe, 1986). Socioeconomic status (SES) was rated using a two-factor index of social ranking on which scores between 1 and 8 are

**Table I.** Descriptive statistics for children with hearing loss judged to be successful or unsuccessful in the mainstream, as well as for children in the control group. Means are provided with standard deviations given in parentheses.

	Control n=93	Mainstream n=9	Nonmainstream n=8
Better-ear PTA (dB)	—	58 (24)	49 (20)
Age of identification (months)	—	37 (29)	31 (29)
Hours of daily hearing aid use	—	12 (2)	13 (4)
PBK # correct (50 maximum possible)	—	43 (6)	36 (13)
GFTA percentiles	96 (11)	51 (33)	42 (48)
Socioeconomic status (64-point scale)	27 (15)	29 (15)	17 (10)
Block design (WISC) scaled scores	11 (3)	10 (4)	8 (4)
PPVT-III standard scores	105 (13)	96 (14)	75 (14)
Reading (WRAT-R) standard score	108 (12)	100 (12)	63 (7)

assigned for the occupation and highest educational level of the primary income earner in the family, and those scores are multiplied together (Nittrouer, 1996). The Block Design of the *Wechsler Intelligence Scale for Children-III* (WISC-III) (Wechsler, 1991) was used to estimate nonverbal reasoning abilities. The *Peabody Picture Vocabulary Test-III* (PPVT-III) (Dunn & Dunn, 1997) was used to evaluate receptive vocabulary. Finally, the Reading subtest of the *Wide Range Achievement Test-Revised* (WRAT-R) (Jastak & Wilkinson, 1984) was used to evaluate reading abilities.

Children in the mainstream and nonmainstream groups did not differ by more than a standard deviation in severity of hearing loss as measured by better-ear pure-tone averages (PTAs), in age of identification, in general speech recognition abilities, or in general speech production abilities. Children in the two groups differed by just one standard deviation on the SES scale. The largest differences of more than a standard deviation were seen between groups on the two language-related, descriptive measures: PPVT-III and WRAT-R. None of the children had any major special needs, other than hearing loss, but one child in the nonmainstream group had mild symptoms (that is, not enough to warrant diagnoses) of other physical and learning problems.

The cause of the hearing loss was not known for most of the children. The only exceptions were that 1 child in the mainstream group had meningitis at 2 years of age, another child in the mainstream group was diagnosed with a genetically related hearing loss, and 1 child in the nonmainstream group was diagnosed as having hearing loss due to the administration of an ototoxic drug during infancy.

Regarding preschool education, 6 of the 9 children in the mainstream group had attended a private school exclusively for children with hearing loss; 2 of the other children in the mainstream group went to regular (i.e., not for children with hearing loss or any other special need), private preschools with religious affiliations; and one child remained at home during the preschool years. Five of the 8 children in the nonmainstream group attended public preschool programs that serve children with various special needs; the 1 child with mild symptoms of possible physical and learning problems attended a private school exclusively for children with hearing loss; 1 child had varied preschool experiences (remaining at home, a regular daycare setting, a private school for children with hearing loss) with no setting outside of the home attended regularly or lasting more than a few months; and 1 child attended a regular public preschool in Great Britain. Regarding elementary school, 5 of the 6 children in the mainstream group whose preschool experience had been in a private school for children with hearing loss were in mainstream settings for kindergarten and the early elementary grades (through the time of testing for this study). The 6th child, whose preschool experience had been in a private school for children with hearing loss, attended a regular private school with a religious affiliation for kindergarten and the early ele-



mentary grades. The 2 children in the mainstream group who had attended regular private preschools with religious affiliations remained in those schools for kindergarten and the early elementary grades. The 1 child in the mainstream group who was at home until school age was homeschooled for kindergarten and the early elementary grades. The 1 child in the nonmainstream group who had regularly attended a private school for children with hearing loss for preschool remained in that setting for kindergarten, and then attended public schools until the year of this testing. All other children in the nonmainstream group attended public schools for kindergarten and the early elementary grades up to the year that testing was conducted. All children in the nonmainstream group were in a self-contained class for children with hearing loss at the time of testing. All children wore hearing aids, except for 2 children in the mainstream group who had cochlear implants. These children received their implants at ages 3 years, 5 months, and 3 years, 11 months.

The 93 children in the control group all passed a hearing screening of the frequencies 0.5, 1.0, 2.0, 4.0, and 6.0 kHz presented at 25 dB HL (American National Standards Institute, 1989), and had normal tympanograms at the time of testing. All these children scored better than a standard score of 85 on the Reading subtest of the WRAT-R. Mean scores for both groups of children with hearing loss were much lower (more than a standard deviation) than the mean score for the control group on the GFTA. Neither group of children with hearing loss differed by more than a standard deviation from the control group on mean SES rating or mean score on the Block Design of the WISC-III. The nonmainstream group only differed by more than a standard deviation from the control group on the measures of receptive vocabulary and reading.

#### *Equipment and Materials*

Equipment and materials used with children in the control group are described in Nittrouer (1999). To the extent possible, the same equipment and materials were used with the two groups of children with hearing loss as were used in that earlier study. However, modifications were made to accommodate their hearing loss. In particular, many of the tasks that had been presented only auditorily to the children in the control group were presented by videotape to the children with hearing loss.

The two groups of children with hearing loss were tested in a quiet room with good lighting. The child sat at a table across from the experimenter, with a 48-inch Sony® video monitor just to the side of the experimenter. Stimuli in the two speech perception tasks were presented via a computer, with a Data Translation 2801A digital-to-analog converter, a Frequency Devices 901F analog filter, a Shure amplifier, and finally a speaker. The PBK-50 words were presented via a Nakamichi® MR-2 audiocassette player, with the output going to the same speaker as that used for the speech perception tasks.

Stimuli for the phonetic awareness tasks, the working memory task, and the sentence comprehension task were presented via the Sony® video monitor. For all tasks, signal level was adjusted so that peak intensity was 72 dB SPL where the child was sitting. Children listened through their own hearing aids or cochlear implants. The experimenter checked hearing aids before testing with each child to ensure that they were working.

For the speech perception tasks, pictures 8 × 5 inches were used. For the working memory task, pictures 3 × 3 inches were used. For the sentence comprehension task, small toys and objects were used.

### *Stimuli and Procedures*

#### *Speech Perception*

Three sets of stimuli were used, each involving a different contrast: syllable-initial /s/ versus /ʃ/, /da/ versus /ta/, and /seɪ/ versus /steɪ/ (*say* versus *stay*). By using three different sets of stimuli, we were able to examine the abilities of these children to make use of different kinds of acoustic properties in their phonetic decisions. All three sets tested children's abilities to use formant transitions. In addition, the /s/ versus /ʃ/ contrast tested children's abilities to make use of spectral differences in fairly long, steady-state noises. The /da/ versus /ta/ contrast tested children's abilities to make use of spectral differences in brief noise bursts. The /seɪ/ versus /steɪ/ contrast tested children's abilities to make use of silent gaps between word-internal acoustic segments. All stimuli were generated at a 10-kHz sampling rate, and presented with low-pass filtering below 4.8 kHz.

*Syllable-initial /s/ versus /ʃ/.* These stimuli consisted of synthetic fricative noises and natural vocalic portions. The noises were single pole noises, 150 ms in duration. The center frequencies of these noises varied from 2.2 kHz to 3.8 kHz in 200-Hz steps. The vocalic portions were taken from natural tokens of a male speaker saying /sa/, /ʃa/, /su/, and /ʃu/. Five tokens of each syllable were used to provide variability across acoustic properties irrelevant to the purpose of the experiment (e.g., intonational contour), but are grouped together for the purposes of discussion here. Thus, there were two vowels, each with two kinds of formant transitions: those appropriate for a preceding /s/ and those appropriate for a preceding /ʃ/. Each noise was paired with each of the vocalic portions, making 36 syllable types in all: nine noises × two vowels × two kinds of formant transitions. Because /a/ and /u/ stimuli were presented separately during testing, each task with these stimuli consisted of 18 kinds of stimuli.

*/da/ versus /ta/.* These stimuli were constructed with natural burst noises and synthetic vocalic portions. Ten milliseconds of burst noise was excised from natural tokens of a male speaker saying /da/ and /ta/, and used in the construction of these stimuli. Because /d/ and /t/ share the same place of

closure, the spectra of these noises did not differ greatly: The /t/ noise simply had a bit more high-frequency energy than the /d/ noise. The nine vocalic portions were 270 ms long. The first formant (F1) transition took place over the first 40 ms, and changed during that time from 200 Hz to its steady-state frequency of 650 Hz. The second and third formants (F2 and F3) changed over the first 70 ms of the vocalic portions. F2 started at 1,800 Hz and fell to its steady-state frequency of 1,130 Hz. F3 started at 3,000 Hz and fell to its steady-state frequency of 2,500 Hz. F4 and F5 were held constant at their default frequencies of 3,250 Hz and 3,700 Hz, respectively. The fundamental frequency (f<sub>0</sub>) was constant at 120 Hz for the first 70 ms and then fell linearly through the rest of the vocalic portion to an ending frequency of 100 Hz. The onset of voicing was cut back in 5-ms steps from 0 ms to 40 ms. There was no source provided to F1 before the onset of voicing. Aspiration noise was the source to the formants higher than F1 before the onset of voicing. Each burst noise was combined with each vocalic portion, making 18 stimuli.

*/seɪ/ versus /steɪ/*. In these stimuli a natural /s/ noise 120 ms long was followed by one of two synthetic vocalic portions. Both portions were 300 ms long, with f<sub>0</sub> falling throughout from 120 Hz to 100 Hz. F3 fell over the first 40 ms from 3,196 Hz to 2,694 Hz, where it remained for the next 120 ms. It then rose to 2,929 Hz over 90 ms, where it remained for the final 50 ms. F2 remained constant at 1,840 Hz over the first 160 ms, and then rose to 2,240 Hz over the next 90 ms, where it remained for the final 50 ms. F1 started at either 230 Hz (most /steɪ/-like) or 430 Hz (most /seɪ/-like). In both cases, F1 rose to 611 Hz over the first 40 ms. It remained there for 120 ms and then fell to 304 Hz over 90 ms, where it stayed for the final 50 ms. Thus, there were two vocalic portions, each paired with the /s/ noise. Silent gaps varying in length from 0 ms to 55 ms, in 5-ms steps, were placed between the /s/ noise and the vocalic portions. Consequently, there were 24 stimuli in all: two F1 onsets × 12 gap durations.

For each speech perception task, stimuli were presented auditorily one at a time, and children had to assign one of two response labels to each. They indicated their choice by pointing to one of two pictures, and saying the "name" of that picture. The experimenter entered their responses into the computer. Two kinds of training were provided: first, training with digitized natural stimuli and then training with the best exemplars of each contrast. For /ʃɑ/ versus /sɑ/, for example, the best exemplars were the stimulus with the 2.2 kHz noise paired with vocalic portions that had /ʃ/ transitions and the stimulus with the 3.8 kHz noise paired with vocalic portions that had /s/ transitions. For both kinds of training, stimuli were presented five times each in random order. The child had to respond correctly to nine out of the ten stimuli to proceed to the next training phase or to the testing phase. During testing, stimuli were presented in blocks consisting of however many stimuli there were in the set. Ten blocks in all were presented. Children had to respond correctly to 80% of the presentations of the best exemplars during testing, when these stimuli were mixed with the other, more acoustically

ambiguous stimuli, to have their data included in the final analysis. Typically these requirements are implemented as a way of ensuring that data are included only from children who maintained general attention to the task. However, for these children with hearing loss it served largely to ensure that data were included only from children whose auditory sensitivities allowed them access to the relevant signal properties.

Probit functions were fit to the resulting data. These functions are effectively z-transformations, only with 5 added to each z-score so that no value is negative. From this distribution, a mean (i.e., the point on the function where the probability of either response is the same) and a slope is derived. The mean is generally termed the 'phoneme boundary,' as it is the point at which the majority of responses change from one category to the other. The separation between functions is defined at these phoneme boundaries.

### *Phonetic Awareness*

Three tasks of phonetic awareness were used. All were used by Nittrouer (1999), and specific items on each task can be found there. For these children with hearing loss, these tasks were presented via videotape. The first task had 24 items, and was the easiest. With this task, termed the "initial-consonant-the-same" (ICTS) task, children must decide which word, out of three, begins with the same initial consonant as a target word.

The other two tasks examined skills that would be expected to be learned later than that required for the ICTS task. The phoneme deletion task had 32 items, and required that the child provide the word that would result if a specified segment was removed from a nonsense item. This task was considered more difficult than the ICTS task, because the child not only had to access the phonetic structure of an item but remove one segment as well. The Pig-Latin task was considered the most difficult because the child had to remove a segment from one part of the item, and synthesize a new syllable with that segment. An aspect of this task that differed from traditional Pig Latin was that children were instructed to move only the first segment of consonant clusters, rather than the entire cluster. There were 48 items in this task. All children were asked if they had any experience with Pig Latin, and none of these children reported ever having done it. Thus, all children came to the task with no prior experience.

For all three tasks, training was provided in which the child received feedback about the response given. Once testing started, no feedback was provided. In all three phonetic awareness tasks, the number of items correct was the dependent measure.

### *Working Memory for Linguistic Materials*

Lists consisting of these same words have been used in earlier studies (Nittrouer, 1999; Nittrouer & Miller, 1999). In this study, five-word lists were

used that consisted of rhyming and nonrhyming consonant-vowel-consonant nouns. Ten lists of each kind (rhyming or nonrhyming) were presented during testing. The rhyming lists consisted of the words *hat, cat, mat, rat,* and *bat* and the nonrhyming lists consisted of the words *dog, coat, ham, rake,* and *ball*. Separate videotapes of the rhyming and nonrhyming lists were made using a male speaker. Each tape consisted of five practice lists, and ten test lists. The randomization of the words within a list differed across lists. Words were produced at the rate of one per second. A third tape was made that simply consisted of three blocks of the ten words used, spoken in random order. That tape was presented first, simply to ensure that each child could correctly perceive all words with a combination of auditory and lipread information. The child was shown all ten pictures to be used in testing and asked to pick the one representing each word as it was said. If a child made more than three errors the test tapes were not presented. The order of presentation of the rhyming and nonrhyming tapes was randomized across participants.

A child listened to a list, and then rearranged the pictures to replicate the order heard. The experimenter wrote down the order of the pictures as the child rearranged them. These lists were then compared to a master list of the actual order of presentation. The mean number of errors across each list position for each kind of list was used in further analysis.

### *Comprehension of Complex Syntax*

Five sets of sentences consisting of five sentences each were used. These sentences were used by Nittrouer (1999), and the lists of sentences can be found there. For testing with the children with hearing loss, the sentences were produced on videotape by a female speaker. All five sentences in each set could be enacted using the same set of small toys. Four of the five sentences in each set were constructed with relative clauses. In these sentences, the interaction of two animate nouns is described, as well as another action involving an inanimate object. All sentences represented possible events. The four kinds of clause structures, with examples of each, are listed below. These sentence types are classified by a two-letter code (*S* for *subject*; *O* for *object*), and these codes indicate the roles (in the main and relative clauses, respectively) of the noun occupying the *empty* position in the relative clause. For example, in the OS sentence below *the bear* is the noun for the empty position in the relative clause. The *O* indicates the role of *the bear* in the main clause; the *S* indicates the role of *the bear* in the relative clause. The noun phrase whose roles are described by the two-letter code is italicized in the examples below.

- SS: *The bear* who wore a hat chased the dog.
- SO: *The dog* that the bear chased wore a hat.
- OS: The dog chased *the bear* who wore a hat.
- OO: The bear chased *the dog* that a hat was on.

The fifth sentence in each set consisted of conjoined clauses. For the set above, the fifth sentence was 'The dog chased the bear and wore a hat.'

Before testing, children were provided with a demonstration of what was expected of them. This demonstration consisted of one set of sentences, of the types described above, acted out by the experimenter after the sentence was heard. Next, the child was provided with four practice sentences: three with no relative or conjoined clauses, and one with conjoined clauses. The test materials were not presented if a child acted out one of these practice sentences incorrectly. The five sets of sentences were presented next. The experimenter scored whether the child had acted out the sentence correctly or not. The total number of errors to each kind of sentence was used for further analysis.

## Results

### *Speech Perception*

*Syllable-initial /s/ versus /ʃ/.* Data was excluded from analysis for 3 children in the mainstream group and for 4 children in the nonmainstream group. Two of the 3 children in the mainstream group whose data was excluded were able to do the training trials for this task, but then fell below the requisite number of correct responses for the best exemplars during testing. The third child, one of the children with a cochlear implant, was not able to label the natural tokens at the required level of accuracy during the first training trial. (The other child in the study with a cochlear implant was able to meet the criteria to have her data included in the analysis.) Three of the four children in the nonmainstream group whose data were excluded were not able to recognize correctly even natural tokens of these syllables during the first training trial. One child in the nonmainstream group was able to do the training trials for this task, but did not meet the criterion for correct responses to best exemplars during testing. No child was able to meet criteria during training with natural tokens, but unable to do so with the best exemplars of the test stimuli. Consequently, we conclude that the use of synthetic noises did not interfere with children's abilities to label these stimuli.

The mean PTA for the children who did not meet criteria to have their data included was 57 dB HL (SD = 19 dB), while the mean PTA for the children who did meet criteria was 46 dB HL (SD = 18 dB). So, there was a tendency for children with poorer hearing sensitivity to have difficulty with these stimuli, but hearing did not completely account for children's abilities to do the task: There is certainly an overlap in PTAs between the two groups. To the extent that hearing loss can explain differences in success with this task, we would expect the greatest difficulty to be had with the fricative noises themselves. Therefore, children who were unable to pass a training trial for this task or who failed to label 80% of best exemplars correctly during testing were asked to label the 2.2 kHz and 3.8 kHz noises, presented without a following vocalic portion, ten times each in random order. Four of the seven

children who did not meet the criteria to have their data included were able to label these noises with perfect accuracy. One child labeled them with 90% correct performance, the child with a cochlear implant labeled them with 80% correct performance, and the poorest performer had only 60% correct on this task. Thus we find further evidence that problems with this task were not explained completely by difficulty hearing the relevant acoustic properties.

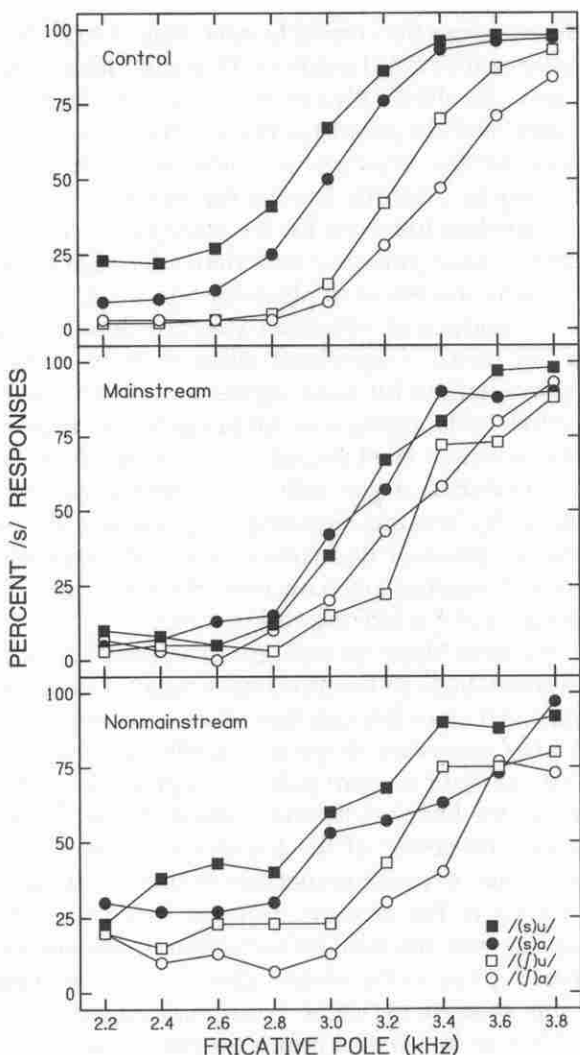
Figure 1 shows labeling functions for the three groups for this set of stimuli. Table II displays mean phoneme boundaries for each syllable type, and shows that the general placement of phoneme boundaries was similar across groups. In fact, an analysis of variance (ANOVA) done on these phoneme boundaries did not reveal a significant effect of group.<sup>2</sup> Thus the general nature of the representations for these segments was not affected by hearing loss. That is, children with hearing loss did not generally require higher spectral content in the noises to label stimuli as /s/, rather than as /ʃ/. Neither did they place boundaries at generally lower frequencies (of the fricative noise) due to difficulty hearing high-frequency sounds. Instead it appears that to the extent that phonetic decisions were based on fricative noise spectra, the children with hearing loss associated the same kinds of noises with each fricative category as the hearing children did.

Table III displays mean slope for each group across the four syllable types, as well as mean separations in functions (measured at the phoneme boundaries) depending on whether formant transitions were appropriate for /s/ or /ʃ/, for /a/ and /u/ separately. Slope is generally taken to be an estimate of the perceptual attention (or weight) paid to the property represented on the abscissa: the steeper the function, the more attention paid to that property. In this case, the center frequency of the fricative noise is represented on the abscissa. The separation in functions is taken to be an estimate of the perceptual weight assigned to the acoustic property that varied dichotomously across stimuli: in this case, the formant transitions. Comparing each group of children with hearing loss to the control group, we see that children in the mainstream group showed the same perceptual attention to the fricative noise as the children in the control group (slopes are similar), but paid less attention to the formant transitions (functions are less separated). Children in the nonmainstream group showed the opposite trend: less perceptual attention to the fricative noise, but similar attention to the formant transitions (functions are shallower but similarly separated, as those of the control group).

In fact, these observations are supported by ANOVAs done on these measures. For mean slope, the overall effect of group was significant,  $F(2,100) = 5.92$ ,  $p = 0.004$ . Post hoc t-tests conducted using separate variances (and appropriately adjusted degrees of freedom) showed significant differences for the control versus nonmainstream groups,  $t(5) = 7.98$ ,  $p < 0.001$ , and for the mainstream versus nonmainstream groups,  $t(7) = 3.28$ ,  $p = 0.013$ . For

---

<sup>2</sup>Throughout this manuscript, exact results will be given for statistical tests only if  $p$  values are less than 0.10.



**Figure 1.** Mean labeling functions for the fricative-vowel stimuli. Center frequency of the fricative noise is shown on the x-axis, and whether formant transitions are appropriate for /f/ or /s/ is indicated by the symbol in parentheses in the legend. Numbers of children in each group with data included were as follows: control = 93; mainstream = 6; nonmainstream = 4.

the /()a/-/s)a/ difference, the overall effect of group was significant,  $F(2,100) = 3.45$ ,  $p = 0.035$ . The post hoc t-tests using separate variances were close to significant levels for the control versus mainstream groups,  $t(5) = 2.11$ ,  $p = 0.085$ , and for the mainstream versus nonmainstream groups,  $t(5) = -2.01$ ,  $p = 0.081$ . When the pooled variance was used, the comparison of the control versus mainstream groups reached significant levels,  $t(100) =$



**Table II.** Mean phoneme boundaries (in Hz) for /s/-vowel versus /ʃ/-vowel perception experiment. Standard deviations are given in parentheses.

	Control n=93	Mainstream n=6	Nonmainstream n=4
/ʃa/	3,349 (232)	3,295 (264)	3,513 (336)
/sa/	2,943 (189)	3,092 (175)	2,975 (124)
/ʃu/	3,274 (159)	3,353 (182)	3,251 (190)
/su/	2,706 (375)	3,068 (66)	2,778 (115)

**Table III.** Relevant means for labeling of /ʃ/-vowel and /s/-vowel stimuli. Mean slope, across the four vocalic portions, is given in change in probit units per kHz of change in fricative-noise spectrum. Separations in functions, depending on formant transitions (i.e., /ʃV-/sV/), is given in kHz of fricative noise. Standard deviations are given in parentheses.

	Control n=93	Mainstream n=6	Nonmainstream n=4
Mean slope	3.37 (1.15)	2.96 (1.02)	1.41 (0.45)
/ʃa-/s a/	506 (273)	204 (344)	538 (219)
/ʃu-/s u/	568 (431)	284 (136)	474 (118)

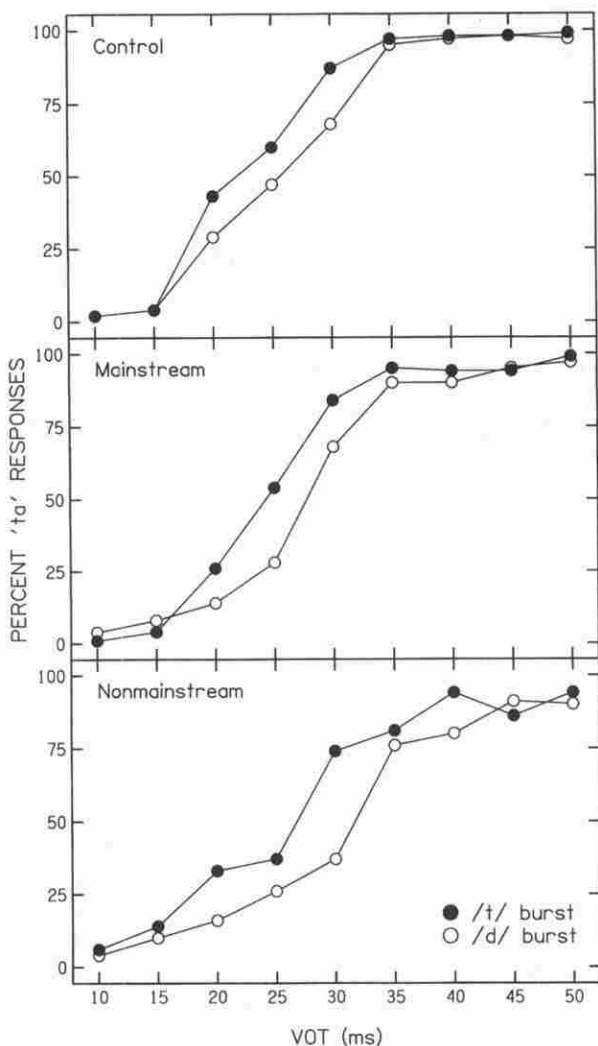
2.60,  $p = 0.011$ . For the /ʃu-/s u/ difference, the overall effect of group was not significant, possibly because the standard deviation for the control group was roughly four times as large as for either group of children with hearing loss. However, when either the *Welch* or the *Brown-Forsythe* test was used, neither of which assumes homogeneity of variance, the main effect of group was significant: for the *Welch* test,  $F(2,19) = 7.40$ ,  $p = 0.013$ ; for the *Brown-Forsythe* test,  $F(2,19) = 9.74$ ,  $p = 0.001$ . If we accept the results of these latter tests, and so perform the post hoc *t*-tests with separate variances, we find statistical significance for the comparison of the control versus mainstream groups,  $t(13) = 3.98$ ,  $p = 0.002$ , and a result close to significant for the comparison of the mainstream versus nonmainstream groups,  $t(7) = -2.33$ ,  $p = 0.052$ .

In sum, we find that neither group of children with hearing loss attended to both acoustic properties as much as the children in the control group,

which could reasonably be due to auditory constraints. Within those constraints, however, the two groups of children with hearing loss show evidence of two different perceptual strategies. The children in the nonmainstream group weighted the formant transitions more and the fricative-noise spectra less than the children in the mainstream group. This between-groups result is notable because it mirrors earlier results that have consistently shown that children either with risk factors for language problems, such as histories of OME or low SES (Nittrouer, 1996), or with poor phonological processing abilities (Nittrouer, 1999) weight formant transitions more and fricative-noise spectra less than the children in appropriate control groups. In those earlier studies, the perceptual strategy of attending to formant transitions more and fricative-noise spectra less was associated with poor phonetic awareness and language-processing abilities.

*/da/ versus /ta/*. One child in the mainstream group and one child in the nonmainstream group were unable to label natural tokens of these stimuli correctly, and so they did not participate. Figure 2 displays labeling functions for the three groups, and seems to show that children in the control and mainstream groups had labeling functions of similar steepness, with the same separation between them. Those of the children in the nonmainstream group appear slightly flatter and more widely separated. Table IV shows mean phoneme boundaries. It seems that children in the mainstream and nonmainstream groups required slightly longer voice onset times (VOTs) to label stimuli as */ta/*, rather than */da/*, and an ANOVA supports this observation: For the main effect of group,  $F(2,105) = 6.69$ ,  $p = 0.002$ . However, this slight difference in phoneme boundaries, of less than 5 ms, should have no consequence for speech perception: VOTs for syllable-initial */d/* in English are generally less than 20 ms, and those for syllable-initial */t/* are generally greater than 70 ms (e.g., Lisker & Abramson, 1964; Nittrouer, 1993).

Table V shows mean slopes across functions for */d/* and */t/* bursts for each group, as well as mean separations between functions. These numbers support what we saw in Figure 2, that children in the mainstream group showed the same results as children in the control group, but children in the nonmainstream group had shallower and more widely separated functions, depending on whether the burst was appropriate for a */d/* or a */t/*. An ANOVA done on these derived values supports these observations. For slope, the main effect of group was significant,  $F(2,105) = 4.75$ ,  $p = 0.010$ . Post hoc *t*-tests done using separate variances found a significant difference only between children in the control and nonmainstream groups,  $t(6) = 3.15$ ,  $p = 0.017$ . However, when the pooled variance was used, the difference between the mainstream and nonmainstream groups was also significant,  $t(105) = 2.17$ ,  $p = 0.032$ . For the separation in functions, the main effect of group was again found to be significant,  $F(2,105) = 4.80$ ,  $p = 0.010$ . For this variable, significant post hoc *t*-tests were obtained only when the pooled variance was used: for control versus nonmainstream groups,  $t(105) = -3.09$ ,  $p = 0.003$ ; for mainstream versus nonmainstream groups,  $t(105) = -2.10$ ,  $p = 0.039$ .



**Figure 2.** Mean labeling functions for stimuli in the /da/ versus /ta/ task. VOT is shown on the x-axis. Responses to stimuli with the /t/ burst are shown with filled symbols, while responses to stimuli with the /d/ burst are shown with open symbols. Numbers of children in each group with data included were as follows: control = 93; mainstream = 8; nonmainstream = 7.

/seɪ/ versus /steɪ/. Seven of the eight children in the nonmainstream group were unable to meet the criterion for training with natural stimuli needed to participate in testing. Because the results of one participant would not be representative of that group as a whole, data for the nonmainstream group was not included for this task. Six of the eight children in the mainstream group were able to meet all training and testing criteria.

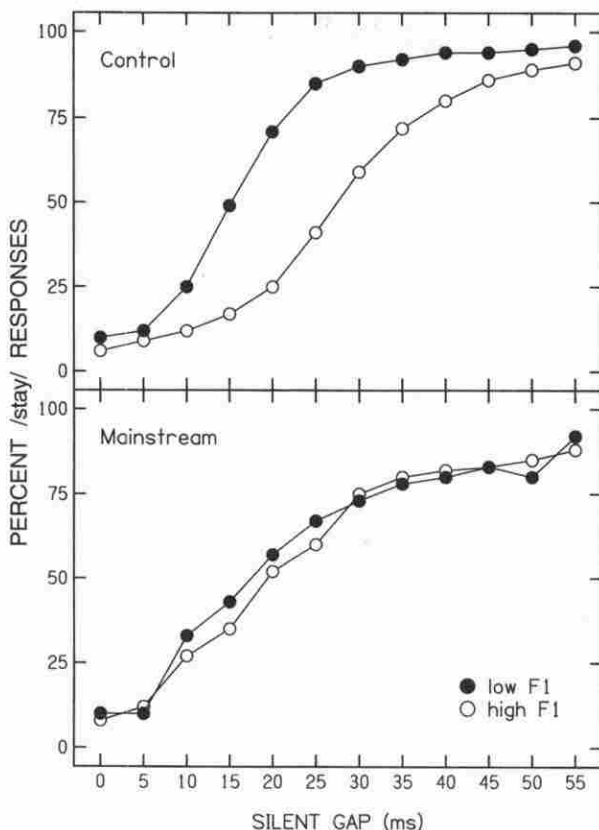
**Table IV.** Mean phoneme boundaries (in ms) for /da/ versus /ta/ stimuli. Standard deviations are given in parentheses.

	Control n=93	Mainstream n=8	Nonmainstream n=7
/da/	25.6 (3.5)	28.0 (3.9)	31.3 (0.05)
/ta/	23.1 (3.2)	25.2 (4.0)	26.3 (4.0)

**Table V.** Relevant means for labeling of /da/ versus /ta/ stimuli. Mean slope is given in change in probit units per ms of change in VOT. Separations in functions depending on formant transitions (i.e., /d/ burst- /t/ burst) is given in ms of VOT. Standard deviations are given in parentheses.

	Control n=93	Mainstream n=8	Nonmainstream n=7
Slope (across vocalic portions)	0.17 (0.05)	0.17 (0.07)	0.11 (0.05)
/d/ burst- /t/ burst	2.53 (1.99)	2.79 (1.74)	5.03 (3.23)

Figure 3 shows mean labeling functions for the control and the mainstream groups, and clearly shows that the functions of the children with hearing loss were closer together than those of the children with normal hearing. Table VI shows mean phoneme boundaries for the two groups, and Table VII shows mean slopes and separations in functions, depending on whether the F1 onset was high (appropriate for /seɪ/) or low (appropriate for /steɪ/). An ANOVA done on phoneme boundaries did not reveal a significant main effect of group, indicating that functions were located in the same general vicinity along the gap continuum for both groups. That is, the children with hearing loss did not require particularly long gaps in order to label these stimuli as *stay*. A t-test done on mean slopes did not reveal a significant group effect, and so we conclude that the children with hearing loss used these gaps in their phonetic judgments to the same extent as the children with normal hearing. Only the t-test done on the separation between phoneme boundaries, depending on F1 onset, showed a statistically significant result,  $t(97) = 2.56$ ,  $p = 0.012$ . From this result we conclude that the children in the mainstream group failed to weight the F1 onset to the same extent as the children in the control group. This result could of course be due to the children in the mainstream group not being able to recognize the difference in F1 onsets between the two kinds of stimuli, but that seems unlikely. The experiment with /da/



**Figure 3.** Mean labeling functions for stimuli in the *say* versus *stay* task. Duration of the silent gap is shown on the x-axis. Responses to stimuli with the low F1 onset (most *stay*-like) are shown with filled symbols, while responses to stimuli with the high F1 onset (most *say*-like) are shown with open symbols. Numbers of children in each group with data included were as follows: control = 93; mainstream = 6.

and /ta/ demonstrated that the children in the mainstream group used F1 transitions to the same extent as children in the control group, and those F1 transitions were similar to those in these stimuli.

#### *Phonetic Awareness*

Figure 4 shows mean percent correct responses for each group on each task of phonetic awareness. The error bars show standard deviations. None of the children in the nonmainstream group were able to get even one item correct on the Pig Latin task, and so there are no data plotted for this group on this task.

ANOVAs done on scores for each task, with post hoc t-tests, supported the

**Table VI.** Mean phoneme boundaries (in ms) for /seɪ/ versus /steɪ/ stimuli. Standard deviations are given in parentheses.

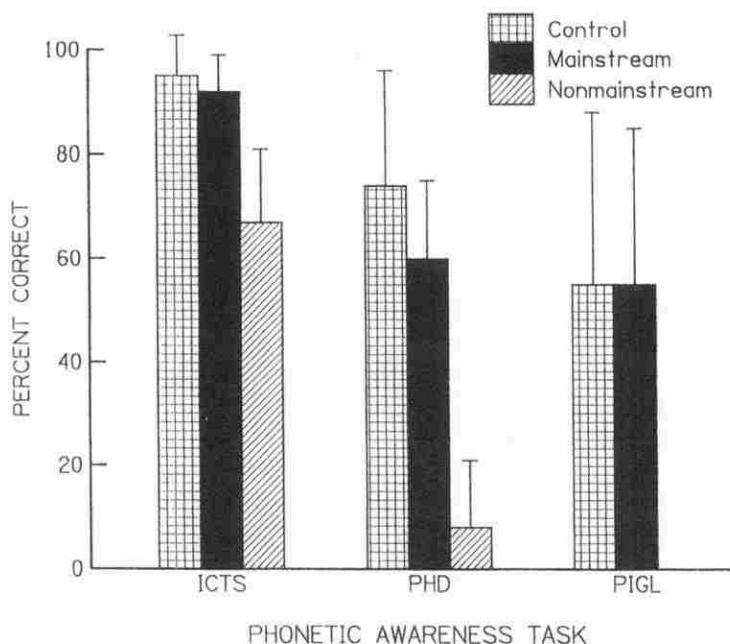
	Control <i>n</i> =93	Mainstream <i>n</i> =6
/seɪ/	27.0 (8.5)	23.7 (14.5)
/steɪ/	16.5 (6.6)	21.7 (15.0)

**Table VII.** Relevant means for labeling of /seɪ/ versus /steɪ/ stimuli. Mean slope is given in change in probit units per ms of change in gap. Separations in functions depending on formant transitions (i.e., high F1–low F1) is given in ms of gap. Standard deviations are given in parentheses.

	Control <i>n</i> =93	Mainstream <i>n</i> =8
Slope (across vocalic portions)	0.09 (0.033)	0.07 (0.021)
/seɪ/–/steɪ/	10.51 (8.00)	1.98 (5.98)

trends seen in Figure 4.<sup>3</sup> For the ICTS task, there was a significant overall effect of group,  $F(2,107) = 35.81$ ,  $p < 0.001$ . The post hoc *t*-tests using separate variances showed significant differences for the control versus nonmainstream groups,  $t(7) = 5.57$ ,  $p < 0.001$ , and for the mainstream versus nonmainstream groups,  $t(10) = 4.52$ ,  $p = 0.001$ . For the phoneme deletion task, there was a significant overall effect of group,  $F(2,107) = 35.31$ ,  $p < 0.001$ . The post hoc *t*-tests using separate variances showed significant differences for the control versus nonmainstream groups,  $t(11) = 13.01$ ,  $p < 0.001$ , and for the mainstream versus nonmainstream groups,  $t(14) = 7.68$ ,  $p < 0.001$ , just as was found for the ICTS task. However, for phoneme deletion, there was also a significant difference observed for the control versus mainstream groups,  $t(11) = 2.57$ ,  $p = 0.025$ . For the Pig Latin task, there was again a significant overall effect of group,  $F(2,107) = 11.17$ ,  $p < 0.001$ . The post hoc *t*-tests using separate variances showed significant differences for the control versus nonmainstream groups,  $t(92) = 16.10$ ,  $p < 0.001$ , and for the mainstream versus nonmainstream groups,  $t(8) = 35.36$ ,  $p < 0.001$ . There was no difference in performance for the control and mainstream groups on this task. In summary,

<sup>3</sup>Results reported here are for statistical tests performed on the percent correct data, without transformation. However, these tests were also done using arcsin transformed data, with no differences in outcomes.



**Figure 4.** Mean percent correct in each of the three phonetic awareness tasks. ICTS = Initial Consonant the Same; PHD = Phoneme Deletion; PIGL = Pig Latin. All children in all groups contributed data.

children in the control and mainstream groups performed similarly on the developmentally simplest (ICTS) and most difficult (Pig Latin) tasks, but children in the control group were somewhat more skilled than children in the mainstream group on the task of intermediate difficulty (phoneme deletion). On all tasks, children in the nonmainstream group showed poorer phonetic awareness skills than children in the other two groups.

#### *Working Memory for Linguistic Materials*

Three children in the mainstream group and 2 children in the nonmainstream group were unable to recognize correctly the words presented via the videotape. In particular, the rhyming words presented confusion for them. These children were not tested on this task.

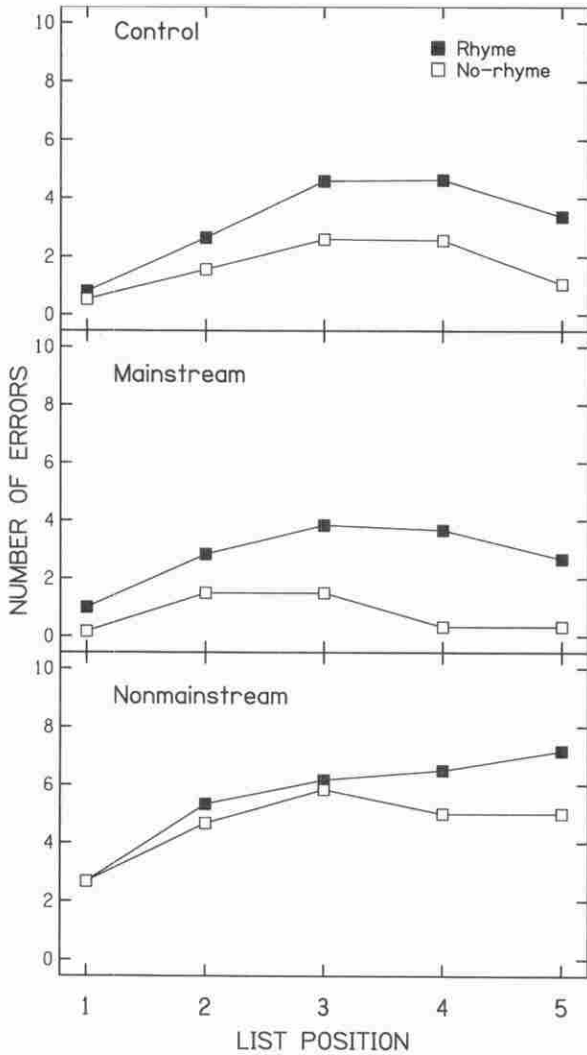
Figure 5 displays mean number of errors across the five list positions for each group, for the rhyming and nonrhyming word lists. In general, it appears as if children in the control and mainstream groups performed similarly, while children in the nonmainstream group appear to have made more errors on both kinds of lists. ANOVAs done on the numbers of errors for each kind of list separately support these impressions. For the rhyming

materials, the overall effect of group was significant,  $F(2,102) = 16.88$ ,  $p = 0.001$ . Post hoc *t*-tests done with separate variances revealed significant differences between the control versus nonmainstream groups,  $t(6) = -4.72$ ,  $p = 0.003$ , and between the mainstream and nonmainstream groups,  $t(9) = -3.64$ ,  $p = 0.005$ . For the nonrhyming materials, the overall effect of group was also significant,  $F(2,102) = 27.16$ ,  $p < 0.001$ . Post hoc *t*-tests again showed significant differences between the control versus nonmainstream groups,  $t(5) = -3.61$ ,  $p = 0.014$ , and between the mainstream and nonmainstream groups,  $t(5) = -4.68$ ,  $p = 0.004$ . For these materials, the comparison of control versus mainstream groups also demonstrated a significant result,  $t(9) = 3.74$ ,  $p = 0.004$ , indicating that children in the mainstream group made fewer errors than children in the control group. Finally, an ANOVA was done on the difference scores between the rhyming and nonrhyming lists, but this test did not show a significant result. Thus, children in the nonmainstream group made more errors than children in the control and mainstream groups, but the difference in error rates as a function of whether or not words rhymed was similar for children in all three groups. This finding is commensurate with that of Nittrouer and Miller (1999) showing that children with normal hearing who were divided into groups by whether their reading ability was normal or poor differed in overall error rates, such that poor readers made more errors than normal readers, but that there was no difference between groups in the magnitude of the rhyming effect.

### *Comprehension of Complex Syntax*

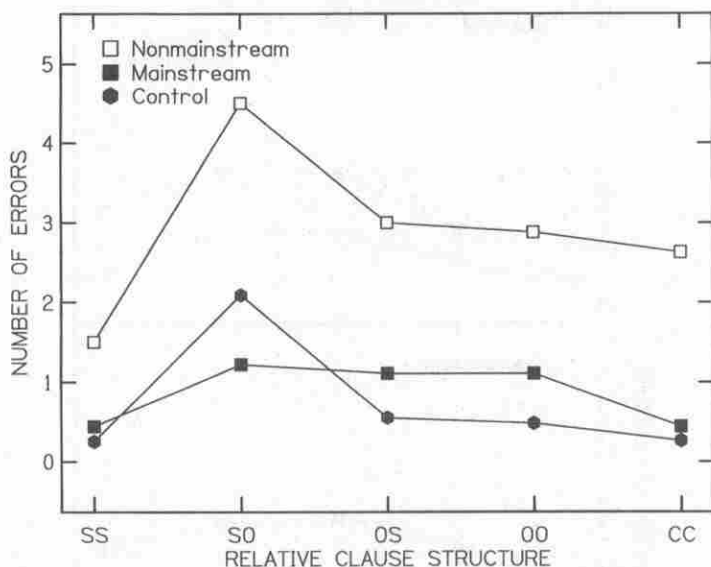
Figure 6 shows the mean number of errors for each sentence type, for each group. Clearly children in the nonmainstream group made more errors than children in the control or mainstream groups, while children in these latter two groups performed similarly. A two-way ANOVA was done on this data with group as the between-subjects factor and sentence type as the within-subjects factor. Both factors showed significant effects: group,  $F(2,107) = 49.62$ ,  $p < 0.001$ ; sentence type,  $F(4,428) = 24.61$ ,  $p < 0.001$ . The group effect is surely due to children in the nonmainstream group making more errors overall than children in the other two groups, and the sentence type effect is most likely due to children, overall, making more errors for sentences with the SO structure than for sentences with other types of relative or conjoined clauses. In addition, the Group  $\times$  Sentence Type interaction was significant,  $F(8,428) = 3.41$ ,  $p < 0.001$ . This interaction is most likely the result of children in the mainstream group failing to show the error peak for sentences with the SO structure, as children in the other two groups did. This failure to do so is unusual, as other studies using this paradigm have generally shown similar peaks in the error rates for the SO structure, for all participants (e.g., Mann, Shankweiler, & Smith, 1984; Nittrouer, 1999; Smith et al., 1989), although one study did not (Bar-Shalom et al., 1993). It is hard to say why this result occurred for children in the mainstream group. Regardless of the reason for





**Figure 5.** Mean number of errors made in the working memory task for rhyming and nonrhyming word lists. Numbers of children in each group with data included were as follows: control = 93; mainstream = 6; nonmainstream = 6.

that finding, however, the finding that children in the nonmainstream and control groups showed the same pattern of errors across sentence types, even though children in the nonmainstream group made significantly more errors, suggests that the children in the nonmainstream group did not suffer from a syntactic deficit, but rather from a deficit in phonological processing. Investigators such as Bar-Shalom et al. (1993) have suggested that problems in processing linguistic materials can frequently be traced to problems access-



**Figure 6.** Mean number of errors made in the sentence comprehension task. All children in all groups contributed data.

ing and/or using phonetic structure to store those materials in working memory. They use the findings of large numbers of comprehension errors in combination with the expected pattern of errors across sentence types as evidence for this position. By the same reasoning, the finding of similar error rates for children in the mainstream and control groups suggests that children in both these groups were able to access and use phonetic structure for further linguistic processing equally well.

### General Discussion

This study was undertaken to test the hypothesis that hearing loss early in life can be modeled to some extent as a deficit in language experience, rather than strictly as a sensory deficit. As originally designed, the goal was to see if the speech perception and related language processing abilities of children with hearing loss showed similarities to what has been observed for children with experiential deficits, but no hearing loss. The serendipitous circumstance that children with hearing loss differed in how well they were handling mainstream settings, but nonetheless had similar degrees of hearing loss, provided an opportunity to separate the contributions made by deficits in sensory capabilities and in language experience.

Regarding speech perception abilities, the results showed that the children with hearing loss, both in mainstreamed and nonmainstreamed academic settings, demonstrated the effects of having restricted access to the acoustic

properties of the signal: In each of the three speech perception tasks the children with hearing loss performed differently from the children with normal hearing. However, differences in perceptual strategies existed between the two groups of children with hearing loss, and we suggest that these differences in strategies arose from differences in early language experience and, thus, in perceptual learning. On the /s-/ʃ/ task, for example, each mainstream and nonmainstream group of children with hearing loss paid attention to only one of the two manipulated properties (fricative-noise spectrum or formant transitions) to the same extent as children in the control group, but it was a different property for each group. Because there is nothing in the audiological profiles of children in the two groups to explain such a difference, we suggest that children in each group had learned to tune their attention to different aspects of the acoustic signal. Children in the nonmainstream group did not weight fricative-noise spectra as much as children in the control group, a result that might be attributable to poor high-frequency hearing sensitivity. However, given that children in the mainstream group were able to weight the fricative-noise spectra as much as children in the control group, we may presume that the failure of children in the nonmainstream group to do so is not explained strictly by limits on their auditory capacities. Considering another example, we see that children in the mainstream group did not weight the F1 transition as much as children in the control group in their /seɪ/ versus /steɪ/ decisions. It is tempting to attribute this finding to limited auditory capacities on the part of these children. However, the same children (those in the mainstream group) showed evidence of weighting F1 transitions as much as children in the control group in their /dɑ-/ /tɑ/ decisions. Thus it seems that one way that limitations in auditory capabilities affect perception is through an influence on perceptual learning, perhaps even more than through a direct influence on the perceptual processes themselves. There is some evidence in this data to suggest that children with hearing loss learn to focus largely on one available acoustic property in making phonetic decisions, rather than appropriately dividing their attention among the several relevant attributes of the acoustic speech signal, as listeners with normal hearing do. The property that receives priority, so to speak, appears to be influenced by the early language environment: Children who attended programs dedicated to educating children with hearing loss show different perceptual processing strategies than children who attended programs not specifically dedicated to children with hearing loss. Of course, there is also evidence that in some instances children with hearing loss fail to learn to attend sufficiently to any acoustic property in making phonetic decisions: Seven of the 8 children in the nonmainstream group were unable to label accurately even natural tokens of *say* and *stay*. Again, there is nothing in the audiological profiles of these children to cause us to suspect that they had any greater auditory limitations than the children in the mainstream group that would make them unable to do so.

Another goal of the study was to see if there was evidence of a relation

between the speech perception strategies and other language processing abilities of these children with hearing loss, as has been found for other children (Nittrouer, 1996; 1999). This goal was met: Children in the mainstream group who demonstrated perceptual strategies for speech most similar to those of children in the control group showed similar performance on the tasks of phonetic awareness, working memory, and sentence comprehension to that of children in the control group. On the other hand, children in the nonmainstream group, who demonstrated different perceptual strategies for speech than those found for children in the control and mainstream groups, performed more poorly on the other experimental tasks. At the same time, the speech perception and language processing abilities of the children in the nonmainstream group resembled those of children with histories of early chronic OME, children living in conditions of low SES, and children who simply demonstrated poor phonological processing abilities.

Why were these differences in speech perception and language processing abilities observed among these children with hearing loss? Of course, this sample of 17 children is not large enough to allow us to answer this question with absolute certainty. Nonetheless, the fact that the two groups were split definitively in, and only in, the kind of preschool program they attended allows us to speculate that the answer has something to do with the quality of intervention provided during the preschool years. Most of the children in the mainstream group (6 out of 9) participated in a strong auditory/oral program during their preschool years. This program was housed in a school dedicated to facilitating the language development of children with hearing loss. All activities focused on language development. All staff members, from classroom teachers to the school secretary, worked to expand and improve the language abilities of the children at all times. Effectively, there was no time during the child's school day when language instruction was not occurring. Furthermore, the school's staff worked closely with parents to transfer goals and expectations to the home. The 3 children in the mainstream group who did not attend this auditory/oral program were either in private preschool programs with very favorable teacher-child ratios or were at home with a parent who actively worked to enhance the child's language environment.

Children in the nonmainstream group, on the other hand, largely attended preschool programs that were more general in focus, serving broader populations of children with special needs. Although access to support services was present, such as regular sessions with speech-language pathologists, the individuals providing these services were not specifically trained to work with children with hearing loss and had not done so for the majority of their careers. Presumably, activities in the classrooms were not narrowly focused on providing language experiences because language deficits were not the primary handicaps of all children in the classrooms. Consequently, individual educational plans for children in the two kinds of settings (the auditory/oral program and programs for multiple categories of special needs) may have appeared to be the same, but differences in the quantity and quality of natur-

al language experience each setting provided probably existed. As a result of these differences in early educational experience, we propose that the children who wind up forming the mainstream group in this study were provided with the necessary and sufficient experience to develop effective perceptual strategies for their native language. In particular, they learned what components of the speech signal provide the best information about phonetic structure. Furthermore, they learned that phonetic structure is there to be recovered from the signal, and then used for storing words in working memory. The use of this highly efficient strategy for storing words in working memory facilitated syntactic processing for them.

In sum, we emphasize the need for intervention with young children to focus on providing experience with complete, meaningful language in ecologically appropriate settings. The skills that children need to acquire to become competent language users and succeed in the mainstream cannot be broken down into discrete chunks and taught in isolation. Instead, we must provide children with hearing loss with abundant language experience, so that they can derive the appropriate perceptual strategies on their own, as children with normal hearing do.

The model of speech perception and subsequent language processing that is offered here differs in a fundamental way from some other suggestions of what children with hearing loss need in order to succeed with spoken language. The importance of syntactic competence to spoken language comprehension has long been acknowledged, but most often in accounts of language processing that suggest that context (including syntax) influences perception through "top-down" channels, such that "bottom-up" and "top-down" information are independent (Boothroyd & Nittrouer, 1988; Cole & Jakimik, 1978; Marslen-Wilson & Welsh, 1978). According to such accounts, the nature of the auditory signal is not altered by language experience, but syntactic competency is. Consequently, all means of enhancing syntactic knowledge should be equally valuable, including manually coded English sign systems. In fact, one could argue that acquiring syntactic knowledge through a signed English system would facilitate the development of appropriate processing skills for spoken language for individuals with hearing loss because the information provided by "top-down" syntactic knowledge is independent of the speech signal received, but nonetheless useful in language processing. The model being suggested here proposes that language experience changes the very nature of the signal being used for language processing by facilitating the development of language-specific perceptual strategies: The child with hearing loss learns what aspects of the signal to weight most strongly in order to derive a phonetically relevant form. That aspect of language learning cannot be attained with a signed language, not even a signed English system.

One challenge that may be raised to the suggestion that differences in early educational settings accounted for the difference between groups in mainstreaming success is that there is a difference of approximately one standard deviation in SES scores between the children who form the mainstream and

those who form the nonmainstream groups. Children (with normal hearing) growing up in low-SES settings have been shown to lag behind their mid-SES peers in speech and language development (Black & Sonneschein, 1993; Grant, 1990; Oller, Eilers, Steffens, Lynch, & Urbano, 1994), and specifically in phonological awareness (Raz & Bryant, 1990). Thus, the difference in SES between the two groups of children with hearing loss could explain some of the variance in their performance. However, the mean SES score of 17 for the nonmainstream group does not represent abject poverty. The mean SES score of the low-SES group in Nittrouer (1996) was 6. Furthermore, regardless of how the difference in SES scores between the two groups is viewed, this study serves to define the skills that are needed for a child with hearing loss to succeed in mainstream academic settings. A goal for professionals serving children with hearing loss should be to provide all children, regardless of SES, with the experiences they need to develop the skills demonstrated by the mainstream group in this study. Meeting this goal requires that children from low-SES environments be provided with more, not less, intensive intervention. In fact, we might ask why the children with lower SES scores ended up in multiple-category classrooms at a higher rate than children with higher SES scores. Were the parents of the children in the mainstream group more knowledgeable and/or more assertive about obtaining an appropriate preschool education for their children? It generally costs a school district more to send a child to a private school dedicated to educating children with one special need than to keep the child in a multiple-category classroom within the district. Was there some subtle bias at work concerning which children would be sent to a school exclusively for children with hearing loss? Be that as it may, the children in the nonmainstream group, who had slightly lower SES scores than the children in the mainstream group, had just that much more reason for needing the environment of a school dedicated to fostering language development. As evidence accumulates that preschool programs exclusively for children with hearing loss can enhance the skills those children will need to compete with hearing peers in regular school settings, we should work to obtain that kind of early education for all children with hearing loss, but especially for those who have the additional risk factor of low SES.

### Acknowledgements

This work was supported by the National Institute on Deafness and Other Communication Disorders (NIDCD), Grant Number P60 DC00982 to Boys Town National Research Hospital. We are grateful to Karen Rossi, director of the Omaha Hearing School, for providing us with space in which to do the testing for this study.

### References

- American National Standards Institute. (1989). *Specifications for Audiometers* (ANSI S3.6-1989). New York: ANSI.

- Bar-Shalom, E.G., Crain, S., & Shankweiler, D.P. (1993). A comparison of comprehension and production abilities of good and poor readers. *Applied Psycholinguistics*, *14*, 197-227.
- Best, C.T., Studdert-Kennedy, M., Manuel, S., & Rubin-Spitz, J. (1989). Discovering phonetic coherence in acoustic patterns. *Perception & Psychophysics*, *45*, 237-250.
- Black, M.M., & Sonnenschein, S. (1993). Early exposure to otitis media: A preliminary investigation of behavioral outcome. *Developmental and Behavioral Pediatrics*, *14*, 150-155.
- Boothroyd, A., & Nittrouer, S. (1988). Mathematical treatment of context effects in phoneme and word recognition. *Journal of the Acoustical Society of America*, *84*, 101-114.
- Brady, S., Shankweiler, D., & Mann, V. (1983). Speech perception and memory coding in relation to reading ability. *Journal of Experimental Child Psychology*, *35*, 345-367.
- Cole, R.A., & Jakimik, J. (1978). Understanding speech: How words are heard. In G. Underwood (Ed.), *Strategies of Information Processing* (pp. 67-116). New York: Academic.
- Crowther, C.S., & Mann, V.A. (1992). Native language factors affecting use of vocalic cues to final consonant voicing in English. *Journal of the Acoustical Society of America*, *92*, 711-722.
- Crowther, C.S., & Mann, V.A. (1994). Use of vocalic cues to consonant voicing and native language background: The influence of experimental design. *Perception & Psychophysics*, *55*, 513-525.
- Dorman, M.F., Loizou, P.C., Kemp, L.L., & Kirk, K.I. (2000). Word recognition by children listening to speech processed through a small number of channels: Data from normal-hearing children and children with cochlear implants. *Ear and Hearing*, *21*, 590-596.
- Dunn, L.M., & Dunn, L.M. (1997). *Peabody Picture Vocabulary Test-III*. Circle Pines, MN: American Guidance Service.
- Eisenberg, L.S., Shannon, R.V., Martinez, A.S., Wygonski, J., & Boothroyd, A. (2000). Speech recognition with reduced spectral cues as a function of age. *Journal of the Acoustical Society of America*, *107*, 2704-2710.
- Flege, J.E. (1989). Chinese subjects' perception of the word-final English /t/ - /d/ contrast: Performance before and after training. *Journal of the Acoustical Society of America*, *86*, 1684-1697.
- Goldman, R., & Fristoe, M. (1986). *Goldman Fristoe Test of Articulation*. Circle Pines, MN: American Guidance Service.
- Gottfried, T.L. (1984). Effects of consonant context on the perception of French vowels. *Journal of Phonetics*, *12*, 91-114.
- Grant, R. (1990). The special needs of homeless children: Early intervention at a Welfare Hotel. *Topics in Early Childhood Special Education*, *10*, 76-91.
- Haskins, H. (1949). A phonetically balanced test of speech discrimination for children. Unpublished master's thesis, Northwestern University, Evanston, IL.

- Hess, R.D., & Shipman, V. (1965). Early experience and the socialization of cognitive modes in children. *Child Development, 36*, 86-99.
- Honig, A.S. (1982). Language environments for young children. *Young Children, 38*, 56-67.
- Jastak, S., & Wilkinson, G.S. (1984). *The Wide Range Achievement Test-Revised*. Wilmington, DE: Jastak Associates.
- Laosa, L.M. (1980). Maternal teaching strategies in Chicano and Anglo-American families: The influence of culture and education on maternal behavior. *Child Development, 51*, 759-765.
- Lisker, L., & Abramson, A.S. (1964). A cross-language study of voicing in initial stops: Acoustical measurements. *Word, 20*, 384-422.
- Mann, V.A., & Repp, B.H. (1980). Influence of vocalic context on perception of the [ʃ]-[s] distinction. *Perception & Psychophysics, 28*, 213-228.
- Mann, V.A., Shankweiler, D., & Smith, S.T. (1984). The association between comprehension of spoken sentences and early reading ability: The role of phonetic representation. *Journal of Child Language, 11*, 627-643.
- Mann, V., & Soli, S.D. (1991). Perceptual order and the effect of vocalic context on fricative perception. *Perception & Psychophysics, 49*, 399-411.
- Marslen-Wilson, W.D., & Welsh, A. (1978). Processing interactions and lexical access during word recognition in continuous speech. *Cognitive Psychology, 10*, 29-63.
- Miyawaki, K., Strange, W., Verbrugge, R., Liberman, A.M., Jenkins, J.J., & Fujimura, O. (1975). An effect of linguistic experience: The discrimination of /ɹ/ and /r/ by native speakers of Japanese and English. *Perception & Psychophysics, 18*, 331-340.
- Nittrouer, S. (1992). Age-related differences in perceptual effects of formant transitions within syllables and across syllable boundaries. *Journal of Phonetics, 20*, 1-32.
- Nittrouer, S. (1993). The emergence of mature gestural patterns is not uniform: Evidence from an acoustic study. *Journal of Speech and Hearing Research, 36*, 959-972.
- Nittrouer, S. (1996). The relation between speech perception and phonemic awareness: Evidence from low-SES children and children with chronic OM. *Journal of Speech and Hearing Research, 39*, 1059-1070.
- Nittrouer, S. (1999). Do temporal processing deficits cause phonological processing problems? *Journal of Speech, Language, and Hearing Research, 42*, 925-942.
- Nittrouer, S., Manning, C., & Meyer, G. (1993). The perceptual weighting of acoustic cues changes with linguistic experience. *Journal of the Acoustical Society of America, 94*, S1865.
- Nittrouer, S., & Miller, M.E. (1997a). Developmental weighting shifts for noise components of fricative-vowel syllables. *Journal of the Acoustical Society of America, 102*, 572-580.
- Nittrouer, S., & Miller, M.E. (1997b). Predicting developmental shifts in perceptual weighting schemes. *Journal of the Acoustical Society of America, 101*, 2253-2266.



- Nittrouer, S., & Miller, M.E. (1999). The development of phonemic coding strategies for serial recall. *Applied Psycholinguistics*, 20, 563–588.
- Nittrouer, S., Miller, M.E., Crowther, C.S., & Manhart, M.J. (2000). The effect of segmental order on fricative labeling by children and adults. *Perception & Psychophysics*, 62, 266–284.
- Nittrouer, S., & Studdert-Kennedy, M. (1987). The role of coarticulatory effects in the perception of fricatives by children and adults. *Journal of Speech and Hearing Research*, 30, 319–329.
- Oller, D.K., Eilers, R.E., Steffens, M.L., Lynch, M.P., & Urbano, R. (1994). Speech-like vocalizations in infancy: An evaluation of potential risk factors. *Journal of Child Language*, 21, 33–58.
- Pickett, J.M. (1999). *The acoustics of speech communication: Fundamentals, speech perception theory, and technology*. Boston: Allyn and Bacon.
- Raz, I.S., & Bryant, P. (1990). Social background, phonological awareness and children's reading. *British Journal of Developmental Psychology*, 8, 209–225.
- Remez, R.E., & Rubin, P.E. (1984). Perception of intonation in sinusoidal sentences. *Perception & Psychophysics*, 35, 429–440.
- Remez, R.E., & Rubin, P.E. (1990). On the perception of speech from time-varying attributes: Contributions of amplitude variation. *Perception & Psychophysics*, 48, 313–325.
- Remez, R.E., Rubin, P.E., Nygaard, L.C., & Howell, W.A. (1987). Perceptual normalization of vowels produced by sinusoidal voices. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 40–61.
- Remez, R.E., Rubin, P.E., Pisoni, D.B., & Carrell, T.D. (1981). Speech perception without traditional speech cues. *Science*, 212, 947–950.
- Schachter, F.F. (1979). *Everyday Mother Talk to Toddlers: Early Intervention*. New York: Academic Press.
- Schachter, F.F., & Strage, A.A. (1982). Adults' Talk and Children's Language Development. In S.G. Moore & C.R. Cooper (Eds.), *The Young Child: Reviews of Research* (Vol. 3, pp. 79–96). Washington, D.C.: National Association for the Education of Young Children.
- Shannon, R.V., Zeng, F.-G., Kamath, V., Wygonski, J., & Ekelid, M. (1995). Speech recognition with primarily temporal cues. *Science*, 270, 303–304.
- Smith, S.T., Macaruso, P., Shankweiler, D., & Crain, S. (1989). Syntactic comprehension in young poor readers. *Applied Psycholinguistics*, 10, 429–454.
- U.S. Department of Health and Human Services. (1994). *Otitis media with effusion in young children* (AHCPR Publication No. 94-0622). Rockville, MD: Agency for Health Care Policy and Research.
- Walker, D., Greenwood, C., Hart, B., & Carta, J. (1994). Prediction of school outcomes based on early language production and socioeconomic factors. *Child Development*, 65, 606–621.
- Wechsler, D. (1991). *Wechsler Intelligence Scale for Children-Third Edition*. San Antonio, TX: Harcourt Brace Janovich.
- Whalen, D.H. (1981). Effects of vocalic transitions and vowel quality on the English [s]–[ʃ] boundary. *Journal of the Acoustical Society of America*, 69, 275–282.



