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Bases of reading impairment in speech perception: A deficit in rate of auditory processing or in phonological coding?

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BASES OF READING IMPAIRMENT IN SPEECH PERCEPTION: A DEFICIT IN RATE OF AUDITORY PROCESSING OR IN PHONOLOGICAL CODING?

by

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A dissertation submitted to the Graduate Faculty in Speech and Hearing Sciences in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York.

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Abstract

BASES OF READING IMPAIRMENT IN SPEECH PERCEPTION:
A DEFICIT IN RATE OF AUDITORY PROCESSING OR IN
PHONOLOGICAL CODING?

by

Maria Mody

Adviser: Michael Studdert-Kennedy, Ph.D.

Previous research has suggested that lack of phonological awareness in reading impaired children may arise from a more basic deficit in speech perception. The current study investigated two possible sources for such a deficit. First, poor readers may suffer from a generally impaired rate of auditory processing, indexed, for example, by their apparent difficulties in processing the rapid spectral changes typical of formant transitions at the onset of stop-consonant vowel syllables, as in /bɑ/ and /dɑ/. Alternatively, poor readers may suffer from a deficit in phonological coding: their auditory perception may be normal, but they have difficulty deriving phonological segments from the auditory stream. Forty second-grade good and poor readers (n=20 in each group), mean age 8.0 years, matched on verbal and performance I.Q., were selected on the basis of their reading scores on the Woodcock Johnson Reading Mastery Test and their performance on temporal order judgments (TOJ) of /bɑ/-/dɑ/, presented at short interstimulus intervals (ISI) (100, 50, 10 ms). Good readers were reading at least five months ahead of grade level, and made no errors on the TOJ task; poor readers were reading at least five months behind grade level, and had a minimum of three errors on the TOJ task (group mean= 7.4 errors out of 36 trials). However, poor readers had no difficulty with the TOJ task when /bɑ/ and /dɑ/ were presented in more easily discriminable pairs, as in /bɑ/-/sɑ/ and /dɑ/-/ʃɑ/, so that their

difficulties were evidently not intrinsic to the acoustic structure of /bɑ/ and /dɑ/, but depended on the context of their presentation. Moreover, the two groups did not differ significantly in their abilities either to discriminate sinewave analogs of the second and third formants of /bɑ/ and /dɑ/, or to identify members of a synthetic /seI-steI/ continuum, where a brief (40 ms) F_1 vocalic transition was a critical cue to the stop consonant. In short, poor readers did not differ from good readers in their ability to process rapid spectral changes. The results are consistent with the hypothesis that reading impaired children suffer from a deficit in phonological coding.

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CHAPTER 1: INTRODUCTION

Despite normal intelligence, some ten percent of school children have difficulties in learning to read and write. Reading is a complex skill and there are many reasons why some children fail (Bradley & Bryant, 1985). However, many researchers agree that among the main etiological factors in reading difficulties is the difficulty that some young children have in mastering phonemic awareness skills (Bradley & Bryant, 1983; Liberman, 1973; Liberman, Shankweiler, Liberman, Fowler & Fischer, 1977; Mann, 1986; Pennington, Van Orden, Kirson & Haith, 1992; Perfetti & Hogaboam, 1975; Vellutino, 1985).

In the simplest sense, reading is the conversion of print to speech. The alphabet represents speech at the level of the phoneme. Learning to read an alphabetic text therefore necessitates a knowledge of grapheme-to-phoneme correspondence rules. The beginning reader must be aware of the segmental nature of speech, that is, that phonemes exist and can be permuted and combined. It is here that the reading disabled child seems to be deficient.

1.1 Phonological awareness

The primary evidence for poor readers' deficiency in phonological awareness comes from their learning of phonologically-based games involving manipulation of phones (Liberman, 1973; Liberman et al., 1977). On one such task, groups of children were required to indicate the number of segments in a list of test words, by tapping a wooden dowel on a table (Liberman, Shankweiler, Liberman, Fischer & Carter, 1974). The point was to determine how well young children (4-, 5- and 6-year olds) could identify the number of syllables or the number of phones in a spoken word. The results clearly indicate that the awareness of phonemes is harder to achieve than awareness of syllable segments, and develops later. Later studies have shown that reading disabled children have greater difficulty than their normal reading peers not only in tapping out the number of phones in a word, but also in adding or omitting a phone or reversing the order of phones

in a word (Lundberg, Olofsson & Wall, 1980; Mann, 1984a; Mann & Liberman, 1982; Stanovich, 1986).

In a novel study, using a Pig Latin task, Pennington, Van Orden, Smith, Green and Haith (1990) found evidence for a deficit in phonemic awareness, even among adult dyslexics. Here, subjects were required to strip off the initial phoneme of a spoken word, move it to the end of a word and add "ay". The authors constructed two versions of the test: one that required the oral production of Pig Latin, and a control task that required recognition of the correct Pig Latin for a stimulus word, from a list containing the correct answer along with a number of foils. The purpose of the control task was to evaluate whether any group differences found on the production task were independent of articulatory output processes. A series of partial correlations showed, in fact, that these two measures were largely independent: each accounted for a significant amount of unique variance in nonword reading skill: Pig Latin production, r_p =.37; Pig Latin recognition, r_p=.40. In fact, phonemic awareness was found to make the single largest contribution to nonword reading, when compared with other phonological processing skills. Overall, then, poor readers appear to lack awareness of the phonological structure of words (Mann 1984b; Mann & Liberman, 1982).

But what is the role of phonemic segmentation ability in reading? Is it a prerequisite for reading acquisition or is it, as Morais and his colleagues (Morais, Cary, Alegria & Bertelson, 1979) argue, a consequence of reading instruction? In the course of their work with Portuguese peasants, these researchers found that illiterate adults could neither add nor delete a phone at the beginning of a nonword; however, these tasks were rather easily performed by people with similar environment and childhood experiences who had learned to read rudimentarily as adults. The authors concluded that an awareness of phones does not arise spontaneously, but is a consequence of reading instruction.

However, evidence for a causal connection between phonemic awareness and reading ability comes from the work of many independent researchers. There is substantial evidence now that such awareness of the phonological constituents of words is integral to the acquisition of reading skills and is predictive of reading success in young children

(Bradley & Bryant, 1983; Mann, 1984a; Pennington et al, 1990; Stanovich, Cunningham & Cramer, 1984; Treiman & Baron, 1981). For example, Lundberg, Olofsson and Wall (1980) assessed phonological skills in kindergarten children before any reading instruction was given and measured progress in reading acquisition. They found phonological awareness to be a prerequisite to the acquisition of reading skills. Early intervention using phonemic training strategies has also had positive effects on reading acquisition (Bradley & Bryant, 1985; Hurford, 1990). Similarly, reading and spelling performance greatly improved after remedial help by way of rhyming, alliteration and phonemic awareness training in children with sound categorization problems (Bradley, 1989). In fact, 4- and 5-year old children with such problems, who were not trained in sound categorization, were still delayed in reading by the time they were 8-years old, and did not catch up (Bradley & Bryant, 1983).

Before considering the possible origins of poor readers' difficulty in segmenting the speech stream into its components, we should briefly consider a further characteristic of the reading disabled child, namely a deficient verbal short-term memory.

1.2 Working memory

Poor readers have shorter verbal memory-spans than do good readers of comparable age (Jorm, 1983; Perfetti, 1985; Stanovich,1982). This pattern has been observed in tasks using digit-span, letter strings, syllables, word strings, sentence and picture recall, and holds good whether the material is presented visually in script, or auditorily (Cohen & Netley, 1981; Dreyer, 1989; Mann, Liberman & Shankeiler, 1980; Shankweiler & Liberman, 1977; Shankweiler, Liberman, Mark, Fowler and Fischer, 1979; Stone, 1993; Vellutino & Scanlon, 1982). The specificity of this memory deficit to verbal material is well established: When stimuli are not easy to represent linguistically (i.e. by using verbal labels), recall has not been found to be related to reading ability. This lack of correlation has been observed in memory tasks with nonsense figures, unfamiliar writing systems, photographs of strangers and a standard test of visual pattern recall, the Corsi

block design test (Brady, Shankweiler & Mann, 1983; Gould & Glencross, 1982; Katz, Shankweiler & Liberman, 1981; Liberman, Mann, Shankweiler & Werfelman, 1982). Further evidence of a link between reading and short-term memory comes from the work of Torgesen & Houck (1980). In a comparison of different kinds of learning disabilities, these authors reported that reading disabled children had verbal memory deficits, whereas learning disabled children without specific reading disabilities did not have memory impairments. These findings of a verbal short-term memory deficit in reading disabled children make sense in light of the fact that reading involves the interpretation of individual lexical items, which in turn is influenced by the structure of the clause or sentence in which the word is embedded. Hence, words must be held in a temporary "store" in order to extract meaning from longer utterances.

But what evidence is there for the use of a *phonetic* (rather than a visual or a semantic) memory code in reading? According to Conrad (1972) normal short-term storage in reading takes the form of a phonological code rather than a visual image of the written word. When lists of letters or alphabetically-written words had to be read and recalled, confusions in short-term memory were phonetic rather than optical (based on letter shapes) (Baddeley, 1966, 1968; Conrad & Hull, 1964; Sperling, 1963). Therefore, stimulus items had been stored in phonetic rather than visual form. Further evidence for a phonetic store comes from experiments with readers of Kanji, the logographic Japanese orthography. When presented with strings of Kanji characters for recall, readers made a significantly greater number of phonetic errors than of visual or semantic ones (Erickson, Mattingly & Turvey, 1973). Thus, even an orthography said to represent words in a non-phonetic form seems to be coded phonetically in short-term memory.

Similarly, errors in the recall of phonetically similar (phonetically confusable/ rhyming) versus phonetically dissimilar (phonetically non-confusable/ non-rhyming) letter strings by good and poor readers (Liberman, Shankweiler, Liberman, Fowler & Fischer, 1977) provide support for the use of a phonetic memory code in reading. Whereas poor readers made significantly more errors overall, they showed relatively smaller effects of phonetic confusability on recall of lists of phonetically similar items than did good readers.

This serves as evidence of their less effective phonetic coding strategy. By the same token, the fact that good readers found lists of phonetically dissimilar words easier to recall than phonetically-similar lists, appears to implicate a superior phonetic memory coding strategy on their part. For, while both reader groups did poorly on recall of lists of phonetically similar words, good readers were evidently able to use their greater phonological sensitivity to their advantage in the recall of phonetically dissimilar strings of phonemes.

Subsequent studies have confirmed that poor readers tend to be less sensitive than good readers to phonetic characteristics of stimulus items (Byrne & Shea, 1979; Mark, Shankweiler, Liberman & Fowler, 1977). But this difference between good and poor readers seems to be quantitative rather than qualitative. Brady, Shankweiler & Mann (1983) first replicated the "phonetic confusability effect," then performed a detailed error analysis of the data. Results yielded similar patterns of error for both good and poor readers, indicating use of similar phonetic coding strategies. Thus, although poor readers made more errors, reflecting their shorter memory span (Brady, Poggie & Rapala, 1990), a majority of these errors were transposition errors, as was also the case for good readers. Further, the overall proportion of transposition errors to correct responses did not significantly differ for the two groups and the transposition error pattern was similar for good and poor readers. For example, whenever a phonetic unit was transposed, it was recombined in the same syllable position in which it had originally occurred. e.g. "trait" and "plane" from "train" and "plate", where word-initial (or word-final) consonants traded places with each other. Such errors indicate a sensitivity to the segmental structure of the syllables in which they occur. Thus, poor readers were definitely getting the phonetic information, but were inferior in their retention of the correct combination of these phonetic sequences. This finding is consistent with other indications that poor readers encounter difficulty in preserving serial-order information in linguistic tasks, not only of syllables within a list, but of segments within a syllable (Katz, et al., 1981).

Now working memory is frequently viewed as a limited capacity system that encompasses both processing and storage functions (Brady, 1991; Daneman & Carpenter, 1980). These functions are served by the same limited pool of resources. As processing

becomes more efficient, more resources are freed up and become available for performing a storage function. Since poor readers are deficient in phonological processing, they have fewer resources available for storing phonological information. In summary, this explains poor readers' shorter verbal memory spans and its correlation with poor readers' performance on phonological processing tasks (Brady, Mann & Schmidt, 1987). Poor readers thus appear both to lack phonological awareness and to suffer from a short-term memory deficit for verbal material. This raises the question of a possible link between the two phenomena : Why do poor readers, who have a problem segmenting the speech stream also have difficulties in holding these segments in memory?

Before addressing this question, we should note that Pennington et al. (1990) challenge the role of a short-term memory deficit in reading disability. In a study with two differently ascertained adult dyslexic groups, familial dyslexics and clinic dyslexics, these authors found a clear deficit in phoneme awareness in both groups compared to chronological and reading age controls. (Familial dyslexics, for purposes of this study, refers to those subjects who were recruited from extended families with three-generation histories of dyslexia; clinic dyslexics were recruited from a reading disability program at a local community college). However, on a verbal short-term memory measure, only the clinic and not the familial dylexics showed a deficit. Moreover, the clinic dyslexics were not consistently worse than the reading age controls. The researchers therefore concluded that a deficit in verbal short-term memory may not be universal to reading disability. Pennington and his colleagues went on to argue that differences in short-term memory may be more important for differences in reading comprehension than in single word recognition (Jorm, Share, McLean and Matthews, 1984) and, since word recognition, rather than reading comprehension, is the generally accepted locus of dyslexia, short-term memory does not play a central role in explaining reading difficulties.

However, it is worth noting that the dyslexics in the Pennington study were significantly older (familial dyslexics: mean age= 25.6 years; clinic dyslexics: mean age: 30.9 years) than the reading age controls (mean age= 13.2 years). These large differences in age may have reduced group differences in verbal short-term memory due to some

degree of "developmental catch-up" in the dyslexic subjects. In fact, Shankweiler, Crain, Brady & Macaruso (1991) have argued that chronological age rather than reading age controls are the appropriate comparison groups.

Moreover, recent data collected by Donald Shankweiler and his colleagues. (personal communication, March 2, 1993) from a large cohort (n=500) of learning disabled children, including dyslexics, reinforce the notion of a short-term memory deficit in these children. They found verbal short-term memory to be significantly correlated with both word decoding (r=.47) and reading comprehension (r=.48) in the dyslexic children. Shankweiler proposes that verbal short-term memory may play an integral role when a child is first learning the phoneme-to-grapheme correspondences, but slowly decreases in importance as and when these rules are mastered. Furthermore, comprehension may also be affected if such deficits impair the ability to access the meaning of words or to store syntactic information (Mann, Shankweiler & Smith, 1984; Shankweiler, Smith & Mann, 1984). Similarly, Perfetti (1985) views the high correlation between verbal working memory and decoding to be particularly important in the initial stages of reading acquisition; however, he views the link between verbal short-term memory and comprehension as more characteristic of the skilled reader.

Finally, it has been proposed that the ability to code phonological information efficiently in working memory may play an important role in the development of phonemic awareness. Let us turn therefore to the question of the origins of deficits in verbal short-term memory and phoneme awareness in the poor reader, and to the nature of the relation between these variables. A fair body of evidence points to the possible causal role of deficits in speech perception.

1.3 Speech perception

"Given the relatively sophisticated ability of a six year old to perceive speech, the visual input from reading ought to be converted to a form appropriate for the speech perception system at the earliest stage possible."

Godfrey, Syrdal-Lasky, Millay & Knox, 1981, pp.401-402

Since reading entails, in the first instance, the conversion of print to speech, it is plausible to suppose that capacities for speech perception are relevant to the development of reading. Such a possible relation justifies a comparative study of speech perception abilities in normal and dyslexic children, as a possible locus of the latter's difficulties with reading. Studies of speech perception deficits in reading disability typically fall under two main heads: (a) categorical perception and (b) working memory. While the former points to poor phoneme perception as an underlying factor in reading difficulties, the latter implicates the resulting weak phonological percepts as a basis for poorly stored verbal information in memory. And, insofar as memory and reading are interdependent processes, a deficiency in the former (by way of perception) would manifest itself in the latter.

1.3.1 Categorical perception. Researchers have proposed that children with reading difficulties may have subtle deficits in their perception of the acoustic cues for speech (Savin, 1972; Shankweiler et al, 1979). In fact, young reading disabled children have been shown to perform poorly on an auditory phoneme discrimination task when compared to normal reading children (Hurford and Sanders, 1990). These children also have characteristically deviant patterns of identification and discrimination on tests of categorical perception (Godfrey, Syrdal-Lasky, Millay & Knox, 1981; Reed, 1989; Werker and Tees, 1987). Such tests, which use synthetic speech sounds, vary a single acoustic cue at a time to determine the discriminability of the change and its effect on the perceived identity of the stimulus. Godfrey et al. (1981) used two eight-step continua, /bɑ-dɑ/ and /dɑ-gɑ/. The first series varied in the onset frequencies of the second and third formants, whereas the /dɑ-gɑ/ continuum varied in the onset of the third formant only, the duration of the transitions being 40 ms. The dyslexic subjects were significantly less consistent than the normals in their identification of the stimuli and changed more gradually from one phoneme category to another. They also had significantly lower peaks on AX discrimination between stimuli belonging to different phonetic categories, compared to normals. These results indicate that synthetic speech categories are less sharply defined in reading disabled than in normal children. In an earlier study, however, Brandt and Rosen (1980) found that dyslexic children could identify and discriminate consonants

categorically, just as normal children and adults do, on tasks similar to those cited in the above study. Although the results of the two studies differ, "the findings are not necessarily in conflict." (Godfrey et al., 1981). According to Godfrey and his colleagues, the differences may be explained in terms of statistical analyses undertaken: Brandt and Rosen did not make statistical group comparisons of certain aspects of their data, such as the difference between the discrimination peaks of the normal and dyslexic children. If they had done so, the two studies would have yielded similar results.

Using a series of tasks, including the /bɑ-dɑ/ categorical perception task, Werker and Tees (1987) also tested the speech perception abilities of a group of severely disabled readers. Once again, poor readers showed a tendency toward less categorical perception on labeling and AX discrimination, as well as on a category change discrimination task. As the name suggests, the latter task required subjects to indicate whether a short series of stimuli (from a single phonetic category) was from the same category as, or from a different category than, the set of preceding stimuli.

The consistent findings, by both studies, of differences between normal and dyslexic children in speech perception suggest that speech perception abilities may be related to differences in the reading abilities of the two groups. Also, a point to note is the difference between the performances of the two groups on the within-category vs. between category judgment conditions on the discrimination task. Although the poor readers were significantly worse than the normal readers on between-category discrimination, the two groups were almost equal in their within-category discrimination ability, judging from an inspection of the graphs in these studies. However, members of a stimulus pair from within a phonetic category bear the same physical relation to each other, in acoustic terms,as do members of a between-category stimulus pair. The fact that poor readers can detect these physical differences as well as the good readers, in their discrimination of within category stimuli points to the adequacy of their auditory perceptual mechanism. Conversely, good readers do significantly better than poor readers in their discrimination of physically analogous stimulus pairs, when the stimuli are from different categories. As these stimuli have distinct phonological labels, good readers are able to take advantage of

their superior phonological coding skills in discriminating such stimuli. The availability of labels does not facilitate poor readers' performance, however; this may be viewed as evidence of their "fuzzy" phonological representations. Such a lack of clarity might result in difficulty in mapping the orthography onto internal representations, as must be done in reading, since phonemes are the units from which words are made. Thus, a deficit in speech perception at the level of the phoneme might limit the degree to which one could become a masterful user of phonological information, as is required in reading (Liberman & Shankweiler, 1978; Tallal,1980b).

1.3.2 Working memory. In another test of speech perception ability, poor readers were found to be significantly worse than good readers at repeating naturally spoken monosyllabic words presented in noise, but no worse when the same syllables were presented without noise (Brady et al., 1983). Both groups also did significantly worse on identifying non-speech sounds (e.g. environmental sounds like clapping, knocking on a door) under noisy than under quiet conditions. Although the decline in performance under noisy conditions compared to quiet conditions of presentation was almost equal between the two groups for non-speech, it was significantly greater among the reading disabled than among the normals in the case of speech.

In a related study, Snowling, Goulandris, Bowlby & Howell (1986) found poor readers to be significantly inferior to good readers on a repetition task, but only with nonwords. These authors concluded that dyslexics have difficulty with non-lexical processes in verbal repetition, but that their lexical processing is at least as good as would be predicted from their reading age. They attribute this to a difference in processing pathways, viz. a direct (semantic) route for lexical items and a phonological route for nonword (or non-lexical) items. Thus, while the perception of lexical items may be facilitated by semantic information stored in the lexicon, the repetition of non-lexical items is mediated solely by phonological information, received auditorily. This advantage of lexical over non-lexical items is further borne out by results on recall tasks using lists of varying word frequency: more familiar words are easier to recall. Thus, poor readers were found to be significantly worse than good readers on multisyllabic real words as well as on

pseudowords (Brady et al., 1990). The researchers concluded that poor readers' encoding difficulties were not specific to non-lexical items, but depended on how phonologically demanding the task was.

The fact that poor readers, compared to good readers, performed worse with words than with non-speech stimuli under noisy conditions of presentation clearly points to a speech-specific deficit. The results suggest that this deficit , not always evident under "ideal" listening conditions, may be greatly exacerbated under noisy listening conditions. These findings are consistent with the view that phonological categories are less robust among disabled than among normal readers, evident from poor readers' significantly shallower slopes on categorical perception tasks (Werker & Tees, 1987). Such poorly defined categories would be more vulnerable to degradation by noise. A related finding in normal adults, of poorer recall of digits presented in noise than in no-noise, was attributed by Rabbitt (1968) to a poorly stored signal: Adding noise to the signal appeared to have made it perceptually more demanding, thereby necessitating the use of increased resources. According to a limited capacity model of working memory, fewer resources would be available for performing a "storage" function. This could account for "weaker" representations in memory. Brady et al. link their speech-in-noise results to Rabbitt's short-term memory findings, and hypothesize that poor readers are deficient in both phonological awareness and short-term memory because they have "weak" (or fuzzy) perceptual representations.

1.4 Origins of perceptual deficit

What, then, might be the origin of this seemingly defective perceptual representation in poor readers? Is it specific to speech or does it arise from a general auditory processing deficit? Brady et al. propose the former, Tallal and her colleagues the latter.

1.4.1 Speech-Specific Hypothesis According to the speech-specific hypothesis, an inadequate perceptual representation results from a failure to encode the phonological form of perceived words as fully as normal listeners do. That is, poor readers have difficulty in

converting the acoustic stream of speech into the segments that make up the phonological form. The primary evidence for this view comes from the categorical perception studies reviewed above, and from the fact that poor readers' short term memory deficits are specific to speech. The consequence of their supposed deficit in phonological coding is not only a weak short-term memory but also weak and less rapidly accessible lexical representations (Katz & Shankweiler, 1985). Both these consequences then contribute to their reading difficulties. We know that poor readers resemble good readers on within-category discrimination judgments, but do significantly worse on between category judgments (Godfrey et al., 1981; Werker & Tees, 1987). If we assume that a between-category discrimination judgment engages a more active use of phonological labels, a lack of robust phonological categories in the poor readers could well explain their poorer performance than good readers on this task. Conversely, within category discrimination is not facilitated by phonological coding or labeling because within-category differences on a synthetic continuum are acoustic and not phonological. Since the two groups do not differ here, they must resemble each other in their auditory processing capabilities. In summary, poor readers' inferior performance, compared to the good readers, on between category discrimination tasks evidently arises from differences in the phonological processing skills of the two groups.

1.4.2 General auditory hypothesis In contrast, Tallal and her colleagues attribute the perceptual deficits of reading disabled children and other clinical populations to an impaired rate of auditory processing: the defective children are simply slower than normals in apprehending the auditory structure of a signal. "The greater the speed constraint, the fewer speech sounds will be accurately processed and hence, the greater the language disorder" (Tallal & Piercy, 1974; p. 91). If the children are slower, their deficit can show up in at least two ways: (i) they will be poor at perceiving signals that follow one another rapidly (i.e. that have short interstimulus intervals (ISI's); (ii) they will be poor at perceiving signals that are very brief. If the two properties, brief signal and short ISI, are combined, as in formant transitions, followed rapidly by another sound (i.e. the vowel), children with this characteristic deficit will be doubly disadvantaged. Thus, processing of

rapid spectral changes, such as those which occur in formant transitions at the onset of stop consonant-vowel syllables, pose a special problem for these children. Tallal draws on her findings with developmental dysphasics (Tallal & Piercy, 1973, 1974, 1975) and aphasic adults (Tallal & Newcombe, 1978) to support this position.

In the first of a series of studies, Tallal & Piercy (1973) found developmentally dysphasic children to be significantly impaired, in comparison to age-matched, normal controls, on tasks involving rapid auditory perceptual processing. The term "developmental dysphasics" refers to children who fail to learn language, despite the absence of peripheral impairments, general mental retardation, severe emotional disorder, autism or acquired childhood aphasia (Tallal, Stark & Mellitts, 1985). These children were unable (i) to discriminate between or (ii) to judge the temporal order of brief complex tones (75 ms in duration) differing only in their fundamental frequency. However, they had no problem with the task when the duration of the tones was increased to 250 ms. Similarly, performance improved on these tasks, when the interval between the brief tones was increased; only interstimulus interval (ISI) values of 150 ms or less posed a problem. These findings were viewed as evidence of an impaired rate of auditory processing in dysphasic children.

Tallal and Piercy (1974) extended their research to include verbal stimuli characterized by brief or rapid spectral cues, on the assumption that, if these children did have trouble perceiving rapid auditory information, it would be evident in their perception of such stimuli. Their stimuli consisted of the synthetic stop consonants,/bɑ/ and /dɑ/, for which the brief (approx. 40 ms) second formant transition at onset is a critical cue to the consonantal place of articulation, and synthetic three-formant steady-state vowels, /E/ and /ae/, 250 ms in duration. Repeating their earlier procedure, the investigators found that only five of the twelve dysphasic subjects reached identification training criterion (20 correct out of 24 consecutive trials, $p<.001$ Binomial)with with /bɑ/ and /dɑ/. Further, only two of these five reached criterion on the same/different judgment between these two stimuli at an ISI of 428 ms and only these two succeeded on the temporal ordering judgments (TOJ) at 428 ms, 305 ms, 150 ms, 60 ms, 30 ms, 15 ms and 8 ms interstimulus

intervals. In contrast, all twelve controls reached criterion performance on each of these tasks and performed perfectly on TOJ at all ISI's. On identical tasks (excluding the discrimination task at 428 ms ISI), using the synthetic vowel stimuli, there was no significant difference between the groups, however. In fact, the dysphasics' performance with vowel stimuli did not differ significantly from their performance with nonverbal tones of the same duration on any of the above tasks. Consequently, the authors concluded that "the dysphasic children's performance does not deteriorate simply as a consequence of changing from nonverbal to verbal auditory stimuli, when both are of a steady state character" (p. 91).

In a follow-up study, Tallal and Piercy (1975) showed that these same children had no problem with temporal ordering or discrimination of the /bɑ/-/dɑ/ stimuli, when the critical cue (i.e. F_2 transition) was extended from 43 ms to 95 ms. All twelve aphasic children and their matched controls reached criterion on TOJ and discrimination at 428 ms ISI. Even when the interval between these lengthened stimuli was reduced, the dysphasics continued to perform as well as the normals. There was no significant difference between the performance of the two groups at any of the ISI's on either of these tasks. That the dysphasics did worse when the syllables incorporated brief formant transitions is consistent with the earlier findings using tones and steady-state vowels suggesting that it is "the brevity of the [discriminable transitional] component of synthesized stop consonants, which results in the impaired perception of our dysphasic children" (Tallal & Piercy, 1975; p. 73).

Tallal and Newcombe (1978) also found that adult aphasics with focal brain lesions of the left hemisphere improved significantly in their perception of stop consonants when the stimuli incorporated extended formant transitions. Only 4 of 10 left hemisphere aphasics had been able to reach criterion on the association task (3 in the case of temporal ordering at 428 ms ISI) with the syllables /bɑ/-/dɑ/, when these syllables incorporated 40 ms transitions. The number of subjects reaching criterion increased (though not significantly) to 7 when the stimuli incorporated extended (80 ms) transitions. In contrast, nine of the ten subjects with right hemisphere lesions and five of the six control subjects

reached criterion on both association, and TOJ at 428 ms ISI, with the original 40-ms transition syllables. Extending the transition had no effect on the performance of the right hemisphere aphasics, although all six control subjects could now do the tasks. With the complex tone stimuli, the groups differed only at the short ISI's. Decreasing the interval between the tones had an adverse effect on the performance of the left hemisphere group only. There were no significant differences between the performances of the groups on any of the tasks with the steady-state vowel stimuli. Finally, because the number of errors on the Token Test (DeRenzi & Vignolo, 1962) correlated highly with the number of errors at the short ISI's, using the nonverbal tone stimuli, the authors concluded that a basic impairment in responding to rapid acoustic change is positively related to receptive language ability. Since it was the left hemisphere aphasics who performed poorly here, " ..the data demonstrate that the left hemisphere must play a primary role in the analysis of specific rapidly changing acoustic cues, verbal and nonverbal, and that such analysis is critically involved in both the development and maintenance of language" (Tallal & Newcombe, 1978). That the developmental dysphasic children in the earlier studies showed a similar pattern of impairment in verbal and nonverbal acoustic processing suggests "selective left hemisphere lesions."

In a later study (Tallal, 1980), 20 reading-disabled subjects were tested on discrimination and TOJ of "complex tones" at short ISI's. These subjects were all reading significantly below grade level (composite reading age at least 1 year below chronological age grade placement, as measured by the Metropolitan Reading Test). However, of these 20 reading-disabled children, 12 performed within normal limits on both tasks. Only the remaining eight subjects fell short of normal performance. Furthermore, there was no significant difference between the performances of these children on TOJ and discrimination. Tallal attributed the poor performance of these 8 subjects to a low level auditory dysfunction. Also, because these children's performances at the short ISI's correlated with their scores on a phonics test, she concluded that such an impairment could affect their ability to acquire phonic skills and hence to read.

The variability in the performance of these poor readers on the rapid perception

subtest raises questions about the reliability of this measure as a characteristic feature of the reading disabled. Similarly, a discriminant function analysis that identified six variables, all of which assessed "temporal" perceptual and production abilities, as correctly classifying as language-impaired 96% of Tallal's language-impaired children, failed to classify reliably a group of developmental dyslexic children in a separate study (Tallal, Stark & Mellits, 1985). This further undermines the use of such a measure in identifying poor readers.

Tallal attempts to resolve this inconsistency by arguing for the existence of dyslexic subgroups with varying perceptual profiles (Tallal & Stark, 1982). She identifies two supposedly distinct subtypes, among others, in reading disability: (1) Reading disabled children with concomitant oral language impairments (2) Reading disabled children without concomitant oral language impairments. That the specifically reading impaired subjects in their study (Tallal & Stark, 1982) were without oral language deficits and did not differ significantly from controls on a majority of the perceptual tasks (typically associated with weaker performance of poor readers) is cited as evidence for this view. Furthermore, these reading impaired subjects did not differ significantly from the controls on a test of phonic skills, leading the authors to conclude that "..difficulties in...learning phonic rules may occur more often in reading-impaired children with concomitant language deficits than those without a language disorder" (Tallal & Stark, 1982;p.174) However, such a differentiation is troublesome insofar as populations of specifically reading impaired children with intact phonic skills are rare. Furthermore, Pallay (1986) found that reading disabled children with poor phonic skills, although without language deficits, failed to show auditory perceptual deficits of the kind predicted by Tallal. Thus, the underpinnings of the hypothesized subgroup differentiation, as put forth by Tallal, remain weak. Also worth noting on the issue of subjects is that little of Tallal's work has been with specifically reading disabled children. Her subjects have typically consisted of developmental dysphasics. Extending her findings to include the reading disabled as part of her larger population of language impaired children has lead to an oversimplification of the poor reader's problem.

Attempts to replicate Tallal's findings have met with mixed results. Blumstein

(1984) failed to show an improvement in adult aphasics' perception of place of articulation in stop consonants using lengthened formant transitions. Similarly, Riedel & Studdert-Kennedy (1985) showed that extending formant transitions and increasing ISI's did not improve aphasics' performance on identification or discrimination of place of articulation in stop consonants. Brady et al. (1990) found no significant difference between the response times of good and poor readers on a word repetition task, using monosyllabic and multisyllabic words; however, there was a significant correlation between subjects' scores on the Word Attack subtest of the Woodcock Reading Mastery Test and errors on multisyllabic words. The authors concluded that although poor readers demonstrate less accuracy in processing phonologically complex stimuli (such as multisyllabic rather than monosyllabic words), the lack of difference between the two groups on response time suggests that speed of processing may not be a crucial factor in explaining linguistic processing differences between good and poor readers. Aram & Ekelman (1989) also failed to show a significant difference between left- and right-brain lesion children, compared to normals, on auditory temporal perception tasks developed by Tallal, using complex tones at short ISI's.

As we have seen, deficits in the processing of rapid formant transitions were inferred by Tallal from performance on tests with /bɑ/ and /dɑ/. In the first direct test of sensitivity to brief formant transitions, Pallay (1986) manipulated the extent of F_1 transitions along two synthetic continua: one ranging from /bɑ/ to /wa/ and the other, a nonspeech control, ranging across the isolated varying F_1 transitions from the /bɑ-wa/ continuum. The eight-step continua varied in the duration of the first formant transition from 30 ms (appropriate for /bɑ/) to 100 ms (appropriate for /wɑ/). The duration of each stimulus was 360 ms. Subjects had to identify stimuli as "[bɑ]" or "[wɑ]" for the speech series and as "long" or "short" on the nonspeech continuum. She found that none of the dyslexic children in her study needed a longer F_1 transition than the normal controls in order to identify stimuli as "[wɑ]" or as "long": There was no significant difference between her normal and dyslexic groups in the loci of their category boundaries on the synthetic /bɑ-wɑ/ continuum or on the corresponding non-speech continuum. Thus, on these tests, the

sensitivity of dyslexic and normal children to formant transitions did not differ.

Reed (1989), however, was able to replicate certain aspects of Tallal's results with reading-impaired children. In this study, reading disabled childen and matched controls were required to make TOJ's, at short ISI's, with three different stimulus types: a pair of three-formant steady state complex tones, 75 ms in duration (modeled after Tallal's), a pair of stop-consonant syllables /bɑ/ and /dɑ/ with 35 ms F_2 transitions, and the vowels /E/ and /ae/. Each speech stimulus was 250 ms in duration. The reading disabled children were significantly impaired on TOJ with both tones and stop consonant stimuli. However, the two groups did not differ significantly in their performances with vowels. Reed concluded that her reading disabled children "appeared to have had greater than average difficulty when the stimuli were differentiated by brief cues, especially when the additional time pressure of short ISI's was added." The reading disabled children also showed less sharply defined boundaries on a /bɑ-dɑ/ categorical perception task, evident from their significantly shallower identification slopes, compared to the good readers.

Although Reed's poor readers were significantly impaired on TOJ, we cannot tell whether their difficulty was indeed in sequencing rather than in simply discriminating the stimuli because they were not tested on discrimination. As we have seen, Tallal herself has dismissed the TOJ failure of 8 out of 20 of her own reading disabled subjects, at short ISI's, (Tallal, 1980) as resulting from a deficit of temporal ordering *per se*, proposing instead that deficits in TOJ may stem from deficits in discrimination. The question therefore remains as to whether the deficit underlying poor readers' inferior performances on these tasks arises from a true deficit in temporal sequencing or merely from a difficulty with discrimination.

1.5 Research Questions

The purpose of the present study was to investigate Tallal's general hypothesis regarding the bases of reading disabilities. According to this hypothesis, reading disabled children suffer from an impaired rate of auditory processing. They are unable to meet the perceptual demands of speech characterized by rapidly changing acoustic spectra (Tallal &

Piercy, 1973, 1974, 1975; Tallal & Newcombe, 1978).

However, given the replication failures and the fact that 60% of Tallal's (1980) own reading disabled subjects were able to perform within normal limits, further investigation seemed warranted. To this end, qualified subjects were screened and then tested over the course of three sessions on a variety of auditory perception tasks, using speech and nonspeech stimuli. Forty subjects (20 good readers and 20 poor readers) were selected on the bases of normal performance on an auditory screening, receptive language and performance I.Q tests (details of the tests and normal scores may be found in the "Subjects" section). The groups differed significantly only on their reading scores and on their performances on TOJ with /bɑ/ and /dɑ/, following Tallal's testing procedure. The latter selection criterion was intended to match the poor readers of the present study, with those of Tallal's poor readers who failed on this task. The experimental tasks were designed to examine the following issues.

1.5.1 Experiment I: (i) Do poor readers' difficulties with discriminating /bɑ/ and /dɑ/ arise from the context in which they are presented? (ii) Is poor readers' failure in temporal order judgments with these syllables, at short ISI's, due to a deficit in a capacity for temporal ordering *per se* or is it simply a consequence of their inability to discriminate between them, especially under time pressure? The experiment had two parts. Four of the stimuli (/bɑ/, /dɑ/, /sɑ/ and /ʃɑ/) used by Tallal (Tallal & Stark, 1981), were presented here for TOJ and same/different discrimination. The stimuli were presented in the same combination/pairings as Tallal used viz. (/bɑ/-/dɑ/) in part 1 (which formed part of the screening), as well as in more easily discriminable combinations (viz. /bɑ/-/sɑ/ or /dɑ/-/ʃɑ/), which constituted part 2. If poor readers' difficulties are intrinsic to the syllables /bɑ/ and /dɑ/ (i.e. if they arise from the readers' inability to process the rapid transitions) performance should not differ if the syllables are paired with fricatives, rather than with one another. (ii) If the poor readers' difficulties with TOJ are simply due to their difficulties in discriminating the syllables, performance on TOJ and discrimination should not differ. Further, poor readers should do as well as the controls on the more distinctive different

pairings, even at the short ISIs, in the sequencing task.

1.5.2 Experiment 2: Are poor readers' discrimination difficulties with /bɑ/-/dɑ/ due to the acoustic structure, i.e. the rapidly changing spectral characteristics of these syllables?

In this experiment, the tasks of Experiment 1 were repeated using non-speech auditory analogs of /bɑ/ and /dɑ/ (sine-wave syllables) as the stimuli. If the deficit is a general auditory one, as suggested by Tallal, there should be a significant group difference in discrimination performance, with poor readers doing significantly worse than good readers, exactly as in the corresponding speech task in the preceding session. If the deficit is specific to speech, however, these non-speech control patterns should yield no group differences.

1.5.3 Experiment 3: Are poor readers' phonological deficits specific to phonetic processing of rapid formant transitions?

The experiment was designed to assess the sensitivity of reading disabled children to formant transition information. It was based on the work of Morrongiello et al. (1984). In this study, adults and 5 year-old children identified members of a series of syllables ranging from /seI/ to /steI/, each consisting of a natural /s/ frication concatenated with a vocalic portion synthesized to sound either strongly or weakly as /deI/. Whereas the stronger /deI/ was cued by a more extensive F_1 rise to its steady state, the weaker sound was cued by a flatter transition. Various amounts of silence were inserted between the noise and the transition to generate a /seI-steI/ continuum. Because the children placed the boundary lower on the silence continuum, relative to adults, for the weak /deI/ transition, the authors concluded that five-year-olds were more sensitive to intrasyllabic formant transitions than adults. Even a weak formant transition preceded by a relatively brief silence period was a sufficient cue to stop closure for children. The experiment here, was a variation of the above study using a fixed ambiguous silent gap and manipulating the extent of the F_1 transition. According to Tallal's hypothesis, poor readers should be less sensitive

to such manipulations than good readers because of their inability to process rapid spectral change. They should therefore require a more extensive F_1 transition to switch their judgments from /seI/ to /steI/.

1.5.4 Experiment 4: Do poor readers' difficulties stem from a delayed development of their phonetic processing skills?

The experiment assessed the sensitivity of reading disabled children to variations in phonetic context specified by vowel formant transitions. It was based on the findings of Mann & Repp (1980) and Whalen (1981), who have shown that the number of responses falling into a given class on a synthetic fricative continuum is increased if the fricative noises are followed by a natural vowel originally spoken after an instance of that class: for example, the number of /s/ responses on a /ʃ/-/s/ continuum increases when each item on the continuum is followed by a vowel excised from a naturally spoken /su/, while the number of /ʃ/ responses increases when the following vowel is excised from a naturally spoken /ʃu/. These effects reflect the influence on perception, of spectral changes due to overlap of a preceding fricative gesture with that of the following vowel.

Extending this paradigm to a developmental study, Nittrouer & Studdert-Kennedy (1987) and Nittrouer (1992) reported a shift toward greater segmental organization in the perception of fricatives in children between 5 and 7 years of age: 3-, 4- and 5-year-old children, based phonemic judgments of syllable-initial fricatives on the formant transitions of the following vowel to a greater extent than did 7-year-old children or adults. Adults, apparently, rely more on fricative noise in their identification of /s/ and /ʃ/ and are less influenced by the syllable transition information. If poor readers are relatively delayed in their development, we might expect that, far from being less sensitive, they might prove more sensitive to transitional information than good readers. We would expect their performance to reflect a greater effect of the vocalic transitions in the appended /u/ in accordance with the context from which the latter was extracted.

In summary then the hypotheses tested were as follows: (i) failures of discrimination by poor readers do not arise from problems with rapid spectral change, but

from the close acoustic-phonetic similarity of the stimuli to be discriminated; (ii) failures, by poor readers, in temporal order judgments (TOJ) at reduced ISIs, reflect failures of discrimination rather than of temporal sensitivity; (iii) poor readers do not differ significantly from good readers on a non-speech discrimination task with stimuli matched for rapid spectral changes to the formant patterns of /bɑ// and /dɑ/; (iv) poor readers are at least as sensitive to information conveyed by rapid spectral change as good readers; (v) if developmentally delayed, poor readers are more sensitive to information conveyed by formant transitions.

CHAPTER 2 : METHOD

2.1 SUBJECTS

The subjects consisted of forty second-grade children (mean grade level: 2.5 yrs), between the ages of 7;0 and 9;3 years, from a public school district in south central Connecticut. These were drawn from a larger pool of 220 children screened for the purpose of this study. Twenty (9 girls and 11 boys) of the subjects were poor readers, and twenty (11 girls and nine boys) were good readers, identified on the basis of their performance on the Word Attack and Word Identification subtests of the Woodcock-Johnson Reading Mastery Test-Revised (1987). To ensure appropriate classification, an individual was included as a good or poor reader, only if his/her score on the two Woodcock subtests were consistent (i.e. both scores indicated a comparable level of reading ability). The poor readers were at least an average of five months behind grade level in their reading (mean grade-equivalent reading level= 2.0; SD= .4, SEM=.07). The mean age of this group was 8;0 years (SD=6 months). The good readers were reading at least five months above grade level (mean grade-equivalent reading level = 6.7; SD= 2.7, SEM=.6). Their mean age was 7;9 years (SD=4 months). The two groups clearly did not overlap on their reading scores as measured by the Woodcock test. Further, 17 of the poor readers were receiving supplemental reading instruction, having been identified by their school's reading coordinator as having reading difficulties.

The two groups were then closely matched on receptive language. Mean scores and standard deviations on the Peabody Picture Vocabulary Test-Revised (1981) for the good and poor readers were 98.4 and 7.6 vs. 97.4 and 7.7, respectively. They were also matched on non-verbal I.Q., as measured by the Block Design subtest of the Wechsler Intelligence Scale for Children- Revised (1974). Mean scores and standard deviations on the WISC-R were 105.0 and 9.2 vs. 106.3 and 14.2, for good and poor readers, respectively, the scores falling within the normal range, i.e. 80-135. Thus, the two groups did not differ significantly on age [t (1,38)= .61, p=.547], PPVT-R scores [t(1,38)=.43, p=.668] or WISC-R scores [t(1,38)=.33, p=.743). However, reading ability was

significantly different in the two groups, as required by the study [Word Identification: $t(1,38)=11.97$, $p<.01$; Word Attack: $t(1,38)=6.80$, $p<.01$]. Individual and group data are given in Tables 1-3.

All subjects were monolingual, native speakers of English (i.e., English was the predominant language spoken in the home), from middle-income families and had no history of emotional or neurological disorders. They had normal hearing (25dB SPL at 500Hz, and 20 dB SPL at 1000Hz, 2000Hz, 4000Hz, 6000Hz and 8000Hz), and no dialect-related consonant substitutions or omissions relevant to the stimuli being used in the study. Except for two good readers, who were ambidextrous, all subjects were right-handed. (Handedness was determined on the basis of subject responses to an abbreviated five-question checklist drawn from Annett's (1970) original set of criteria for handedness. The checklist consisted of the following questions; which hand do you use for the following activities: writing, brushing your teeth, throwing a ball, swinging a bat, hammering a nail. Subjects were considered right handed if they used their right hand for all five tasks.)

The groups were further defined on the basis of their performance on Tallal's /bɑ/-/dɑ/ temporal order judgment task: only poor readers who made a minimum of three errors on the three shortened interstimulus interval (ISI) conditions combined, and good readers who scored 100% correct on the same were included. More specifically, whereas the good readers' mean number of errors was zero, on the temporal order judgment (TOJ) and discrimination tasks at the short ISI's, the poor readers' mean differed significantly from zero on both these tasks (TOJ: mean= 7.4, SD= 4.3, $t(19)=7.59$, $p<.001$; Discrimination: mean =5.8, SD =3.9, $t(19)=6.49$, $p<.001$). This was an essential part of the design, for purposes of matching the poor readers in this study with those of Tallal's (1980) poor readers who failed on temporal ordering at the short ISI's.

Table 1. Subject selection criteria: Good readers' profiles

SUB	AGE (mths)	PPVT-R	WISC-R*	GRADE	W.ID.	d_1	W.ATTK	d_2
1	92	97	105	2.2	2.7	0.5	2.8	0.6
2	93	105	120	2.2	3.9	1.7	16.9	14.7
3	84	106	105	2.2	3.4	1.2	2.5	0.3
4	92	87	100	2.5	4.6	2.1	8.0	5.5
5	93	105	115	2.5	3.5	1.0	4.7	2.2
6	98	108	85	2.5	4.8	2.3	6.7	4.2
7	94	106	115	2.6	4.9	2.3	13.1	10.5
8	94	87	95	2.6	3.8	1.2	5.9	3.3
9	93	94	100	2.6	4.1	1.5	5.9	3.3
10	111	91	100	2.6	5.3	2.7	8.0	5.4
11	94	107	110	2.6	4.0	1.4	9.7	7.1
12	97	90	105	2.6	3.9	1.3	5.3	2.7
13	95	105	115	2.7	4.8	2.1	9.7	7.0
14	96	97	115	2.7	4.4	1.7	16.9	14.2
15	97	93	105	2.7	5.9	3.2	13.1	10.4
16	95	94	100	2.6	4.0	1.4	4.7	2.1
17	99	106	115	2.7	5.9	3.2	16.9	14.2
18	102	103	90	2.7	5.1	2.4	13.1	10.4
19	103	86	100	2.6	4.8	2.2	6.7	4.1
20	95	102	105	2.8	4.8	2.0	8.0	5.2
Mean	95.9	98.5	105.0	2.6	4.4	1.8	8.9	6.3
(SD)	(5.3)	(7.7)	(9.2)		(.8)		(4.6)	

Note: PPVT-R: Peabody Picture Vocabulary Test -Revised
*Measure of non-verbal I.Q. based on Block Design subtest of the Wechsler Intelligence Scale for Children-Revised (WISC-R)
GRADE: grade level reading at the time of testing.
W.ID. and W.ATTK: Word Identification and Word Attack : grade equivalent scores
d_1 and d_2: discrepancy scores(grade equivalent vs grade level) on W.ID and W.ATTK

Table 2. Subject selection criteria: Poor readers' profiles

SUB	AGE (mths)	PPVT-R	WISC-R*	GRADE	W.ID.	d_1	W.ATTK	d_2
1	94	101	135	2.2	1.6	-.6	1.5	-0.7
2	84	110	100	2.2	1.9	-.3	1.7	-0.5
3	102	90	115	2.2	2.1	-.1	1.9	-0.3
4	95	99	100	2.2	1.7	-.5	1.2	-1.0
5	106	96	135	2.2	2.0	-.2	1.2	-1.0
6	93	102	110	2.2	2.2	0	1.6	-0.6
7	95	93	105	2.2	2.2	0	1.7	-0.5
8	97	108	115	2.5	2.2	-.3	1.9	-0.6
9	106	108	095	2.5	2.1	-.4	1.7	-0.8
10	94	89	100	2.5	2.3	-.2	2.0	-0.5
11	105	92	085	2.5	2.4	-.1	2.0	-0.5
12	88	94	100	2.6	1.7	-.9	1.5	-1.1
13	96	90	115	2.6	2.3	-.3	2.1	-0.5
14	94	105	095	2.7	2.4	-.3	1.7	-1.0
15	100	96	085	2.7	2.1	-.6	2.3	-0.4
16	105	92	120	2.7	2.6	-.1	2.2	-0.5
17	104	82	095	2.7	2.4	-.3	2.3	-0.4
18	98	107	120	2.7	2.4	-.3	2.3	-0.4
19	96	92	095	2.8	2.2	-.6	1.7	-1.1
20	98	102	105	2.8	2.0	-.8	2.4	-0.4
Mean	97	97.4	106.3	2.5	2.1	-.4	1.9	-.6
(SD)	(6.6)	(7.7)	(14.2)		(.3)		(.4)	

Note: PPVT-R: Peabody Picture Vocabulary Test -Revised
*Measure of non-verbal I.Q. based on Block Design subtest of the Wechsler Intelligence Scale for Children-Revised (WISC-R)
GRADE: grade level reading at the time of testing.
W.ID. and W.ATTK: Word Identification and Word Attack : grade equivalent scores
d1 and d2: discrepancy scores (grade equivalent vs. grade level) on W.ID and W.ATTK

Table 3. Subject selection criteria: Overall summary of group statistics

	GOOD READERS		POOR READERS		
VARIABLES	MEAN	STD. DEV.	MEAN	STD. DEV.	p-VALUE
AGE (mths)	95.9	5.3	97.0	6.6	.547
PPVT-R	98.5	7.7	97.4	7.7	.668
WISC-R*	105.9	9.2	106.3	14.2	.743
W. ID	4.4	0.8	2.1	0.3	<.001
W. ATTK	8.9	4.6	1.9	0.4	<.001
(/bɑ/-/dɑ/ tasks):					
TOJ (errors **)	0.0	0.0	7.4	4.4	<.001
DISCR (errors**)	0.0	0.0	5.8	3.9	<.001

Note: PPVT-R = Peabody Picture Vocabulary Test-Revised

*Measure of nonverbal I.Q. based on Block Design subtest of the Wechsler Intelligence Scale for Children- Revised (WISC-R)

W. ID and W. ATTK = Word Identification and Word Attack (two subtests of the Woodcock-Johnson Reading Mastery Test- Revised) =grade-equivalent reading level

TOJ = Temporal Order Judgments.

DISCR = Discrimination

** based on 36 trials per subject, across three short interstimulus intervals (ISI) combined. (ISI = 100 ms, 50 ms, 10 ms)

p-VALUEa= based on t-tests

2.2 STIMULI

Four speech perception tasks and one non-speech task were administered to the subjects over the course of the study. The synthetic speech stimuli for the first two tasks were generated on the serial synthesizer at Haskins Laboratories. The hybrid stimuli (part natural, part synthetic) for the remaining two speech tasks were prepared on the KLATT software serial synthesizer at the University of Nebraska at Boys Town (Nittrouer, 1992). The non-speech stimuli were prepared on the Haskins sinewave synthesizer.

2.2.1 Experiment 1:

The syllables /bɑ/, /dɑ/, /sɑ/ and /ʃɑ/ were generated on the Haskins serial synthesizer on a VAX 11/780. All four stimuli were presented in Experiment 1, although /bɑ/ and/dɑ/ were also used in the initial screening session. Spectrograms for each of these stimuli may be found in Figure 1.

The stimuli /bɑ/ and /dɑ/, each 250 ms in duration, were composed of three formants with no release burst. Values of the stimulus parameters were identical to those used by Reed (1984) in her successful replication of Tallal's experiments (Tallal, 1980; Tallal and Stark, 1981). Table 4 displays these values. The two syllables had identical steady-state portions with F_1 at 750 Hz, F_2 at 1200 Hz, and F_3 at 2350 Hz. The bandwidths of the three formants were 90 Hz, 90 Hz, and 130 Hz respectively. Each syllable started with F_0 at 121 Hz rising to 125 Hz in 40 ms and falling to 100 Hz at syllable end. Whereas F_1 began at 200 Hz for both syllables, reaching its steady-state value in 25 ms, F_2 and F_3 onsets differed for the two syllables. For /bɑ/, the second and third formants began at 825 Hz and 2000 Hz respectively, reaching their steady states in 35 ms. For /dɑ/, F_2 began at 1500 Hz and F_3 at 2630 Hz, both reaching their steady-states in 35 ms.

The /sɑ/ and /ʃɑ/ stimuli were each 400 ms long, the frication noise lasting 150 ms and the vowel formants, 250 ms (Tallal and Stark, 1981). /sa/ had a fricative noise high-pass cut-off at 4100 Hz, /ʃa/ at 2800 Hz. Amplitude of the frication noise rose from 20 dB

Table 4. Formant composition of synthesized consonant stimuli, /bɑ/ and /dɑ/

Time (in ms)	F_0	F_1	F_2		F_3	
			/bɑ/	/dɑ/	/bɑ/	/dɑ/
0	121	200	825	1500	2000	2630
25	121	750				
35	121	750	1200		2350	
40	125	750	1200		2350	
250	100	750	1200		2350	

Note: F_0, F_1, F_2, F_3 refer to the fundamental frequency and the first, second and third formants respectively. Note that F_0 and F_1, and the steady states of F_2 and F_3 are identical for the two syllables.

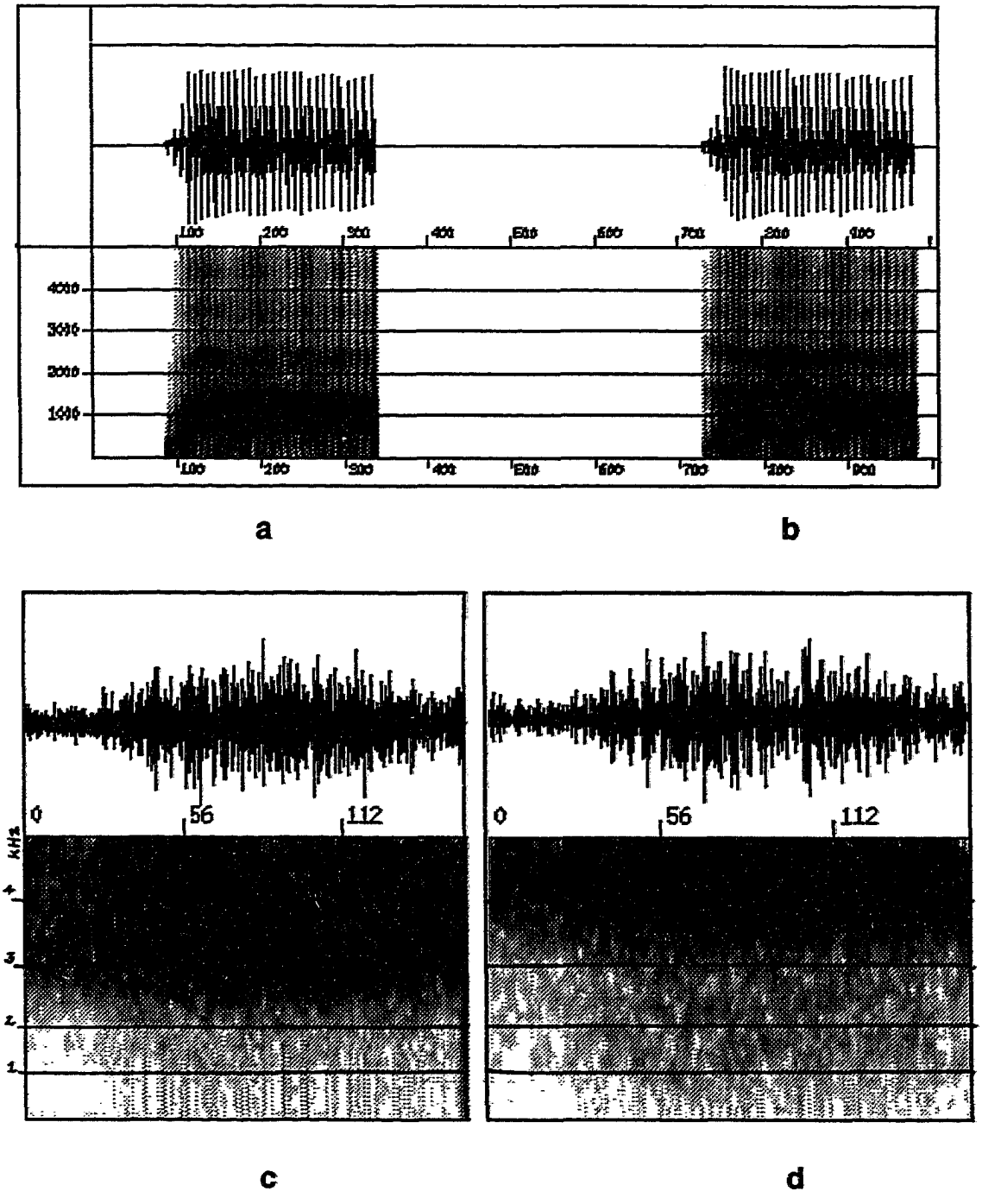

Figure 1. Spectrograms of (a) /bɑ/, (b) /dɑ/, (c) /ʃ/, and (d) /s/.

to 35 dB over the first 50 ms, and then fell to 30 dB over the last 50 ms of the frication duration. The vocalic portions were identical for both sounds, the formant frequency values being the same as those of the steady state vocalic portions of /bɑ/ and /dɑ/.

2.2.2 Experiment 2

The non-speech stimuli were generated on the Haskins sinewave synthesizer on a VAX 11/780. The two stimuli, each 250 ms in duration, were composed of two sinewaves with durations and frequency trajectories identical to those of F_2 and F_3 in the synthetic /bɑ/ and /dɑ/ described above. Perceptually, they did not resemble their speech models. They were heard as unfamiliar non-speech sounds and were assigned the descriptive labels of "up" and "down", respectively. The selection of these labels was based on a pilot run of the stimuli with normal children and their unanimous preference for the use of these labels, i.e., "up" and "down" over "high" and "low".

2.2.3 Experiment 3

The stimuli were drawn from a /seI-steI/ continuum, each step made up of a natural sample of /s/ frication noise, followed by a synthetic vocalic portion (see spectrograms for endpoints in lower half of Figure 2). These stimuli were identical to those used by Nittrouer (1992), which were modeled after those of Best et al. (1981) and Morrongiello et al. (1984). The duration of the frication noise was 120 ms and that of the vocalic portion, 300 ms, accompanied by a falling F_0 from 120 Hz to 100 Hz. F_3 fell from 3196 Hz to 2694 Hz in the first 40 ms, remained there for the next 120 ms and rose to 2929 Hz over a 90 ms period where it remained steady for the last 50 ms. F_2 remained constant at 1840 Hz during the first 160 ms and then rose to 2240 Hz over the next 90 ms, where it remained steady for the final 50 ms. F_1 onset varied from 211 Hz to 611 Hz in 50Hz steps, rising to 611 Hz over the first 40 ms, where it remained for the next 120 ms. Then it fell to 304 Hz over 90 ms where it stayed for the final 50 ms. However, a 230 Hz F_1 onset was used as a training token for /steI/ because of the consistency with which it was correctly identified by naive adult listeners as /deI/ in the study by Best et al. (1981). A silent gap of 20 ms was

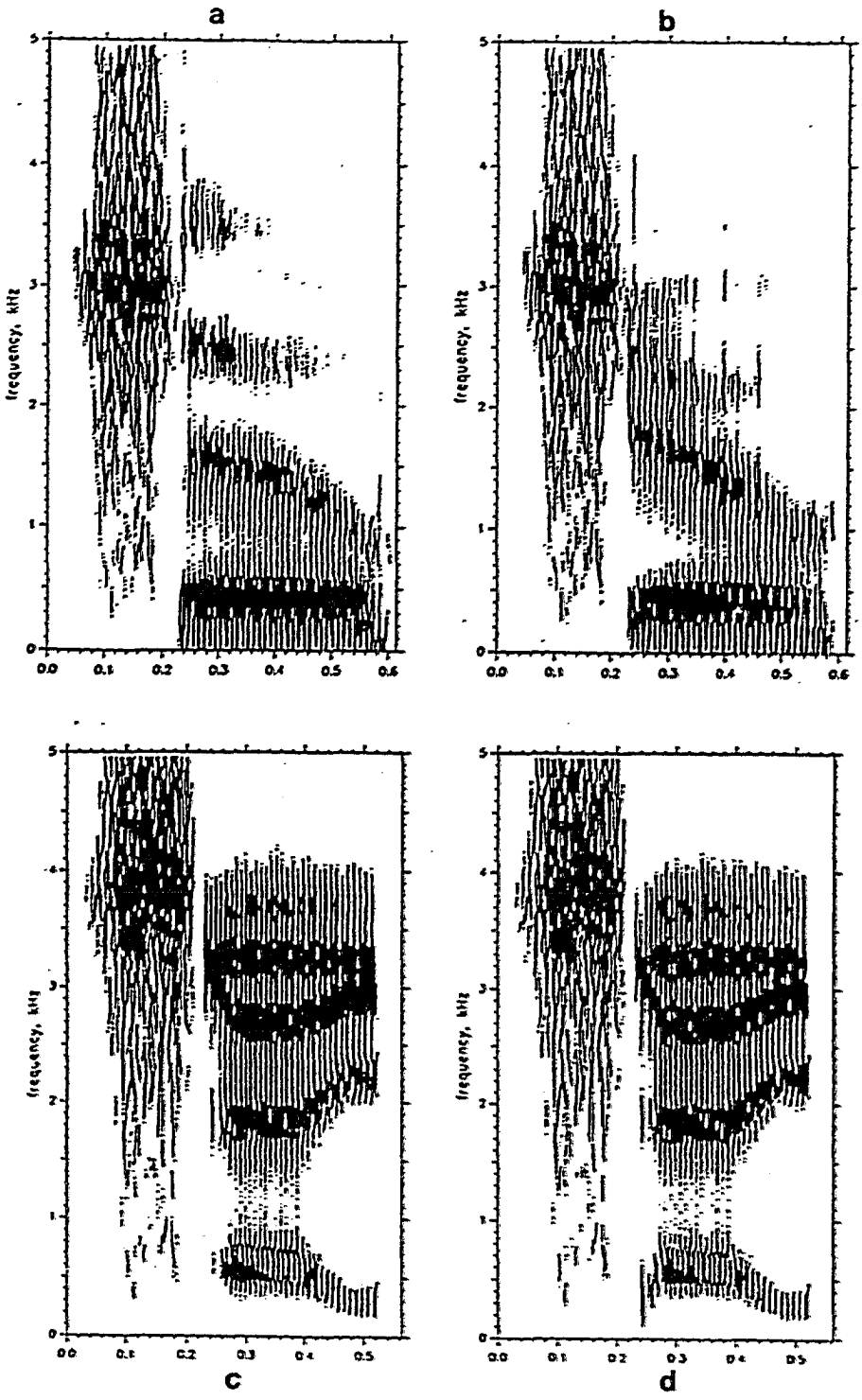

Figure 2: Top: Spectrograms of synthetic frication from the midpoint of the continuum followed by natural tokens of /u/ spoken (a) after /s/ and (b) after /ʃ/ Bottom: Spectrograms of the endpoints of the (c) /seI/ to (d) /steI/ continuum.

inserted between each /s/ noise and the following vocalic nucleus. There were a total of 90 trials (9 tokens X 10 repetitions/per token).

2.2.5 Experiment 4

The synthetic stimuli here were modeled after those of Nittrouer and Studdert-Kennedy (1987) and Nittrouer (1992). The basic stimuli in Experiment 4 were a set of fricative noises, each having a duration of 230 ms and varying in high-pass cut-off along a continuum from 2.2kHz (/ʃ/) to 3.8 kHz (/s/) in eight 200-Hz steps. Amplitude of the fricative noise rose from zero to its maximum value over the first 90 ms, stayed at this value over the next 90 ms and then fell linearly to near-zero over the last 50 ms. The noises were synthesized at a 10 kHz sampling rate and were low-pass filtered at 5kHz on output. To each fricative stimulus there was appended a token of the vowel /u/, excised from one of two syllables, /ʃu/ or /su/, naturally produced by a male speaker (see top half of Figure 2 for spectrograms of sample vowel tokens, from an /ʃ/ context and an /s/ context, appended to the midpoint (an ambiguous value) of the frication continuum). Five different tokens of /u/ from each context were used to ensure that perceptual responses were not a function of any particular intonation contour. The vocalic segments were approximately 348 ms in duration. The 180 hybrid stimuli (9 fricative noises X 2 vocalic portions X 5 tokens/vowel context X 2 repetitions) resulting from the concatenation of the synthetic fricative noises and the natural vocalic portions were then tested with adults to ensure that no significant differences in response patterns were observed among tokens of the same vocalic portions The results matched those of Mann and Repp (1981) for accepted range of token variability (approx. 4%).

2.3 PROCEDURE

All testing was conducted in the children's schools. A total of 220 second graders from four schools within a Connecticut public school district were initially screened. Forty of these were selected to participate in the study; twenty good readers and twenty poor

readers. Following the screening tests, qualified subjects met with the experimenter three more times.

In the first experimental session, subjects were given two tasks: a discrimination and a temporal ordering task, using speech stimuli, the order of these tasks being counterbalanced across subjects within each group (Experiment 1). In session two, the discrimination task was repeated with non-speech stimuli (Experiment 2). The third session consisted of two tests of sensitivity to phonetic information cued by formant transitions (Experiments 3 and 4). All testing was done individually, in a quiet room. The stimuli were presented through TDH-39 headphones at a comfortable listening level. Subjects were reinforced with colorful stickers and/or pencils. Written consent was obtained from the parents of all participants.

There were four sessions in all, one screening and three test sessions. Each of these lasted about 45 minutes.

2.3.1 Initial Screening:

The initial pool of 220 subjects comprised monolingual, native speakers of English (i.e. English was the predominant language spoken at home), from middle-income families, with no history of neurological or emotional problems. These children were given a series of tests to determine their eligibility for inclusion in the study. The tests consisted of:

(1) An auditory screening test for normal hearing (25 dB SPL at 500 Hz, 20 dB SPL at 1000Hz, 2000Hz, 4000Hz, 6000Hz, 8000Hz)

(2) The Word Identification and Word Attack subtests of the Woodcock-Johnson Reading Mastery Test-Revised for selection of good and poor readers, using test norms. Poor readers, for purposes of this study, were defined as those who were, on an average, at least five months delayed in reading. Similarly, good readers were defined here as those children who scored, at a minimum, five months ahead of grade level reading.

(3) The Peabody Picture Vocabulary Test- Revised (PPVT-R), a test of vocabulary comprehension to measure language ability. The results of this test (which is correlated

with verbal I.Q.), and consultations with the school speech pathologist were used to rule out any cases of language delay. Only those subjects whose performance scores fell between 80-120 were used in the study.

(4) The Wechsler Intelligence Scale for Children-Revised (WISC-R): Here, the Block Design subtest was used to measure nonverbal IQ. Only subjects with performance scores of 80 - 135 were considered for inclusion in the study.

Selection of the good and poor readers depended on matching the two groups, as closely as possible, on their performances on the PPVT-R and the WISC-R. This entailed first forming the group of poor readers and then selecting the group of good readers in such a way that their mean PPVT-R and WISC-R scores matched those of the poor readers. Finally, in order to match the poor readers with those of Tallal (1980), the two groups were further defined on the basis of their performance on Tallal's /bɑ-dɑ/ TOJ task: only poor readers who made three or more errors on the shortened ISI conditions, combined, and good readers who scored 100% correct on the same, were retained. This final screening test was actually carried out as the first part of session 1, described below.

2.3.2 Session 1:

The session was divided into two parts. The procedures closely followed those developed by Tallal (1980) with the minor adaptations incorporated by Reed (1989), in her successful replication of Tallal's findings These are summarized in Table 5. The first part of the session consisted of a TOJ task and a discrimination task with a stimulus pair also used by Tallal, /bɑ/-/dɑ/ (Tallal & Piercy, 1974; Tallal & Stark, 1981). In the second part, the subjects repeated the TOJ and discrimination tasks, this time with a different stimulus pair in which either one member was /bɑ/ and the other /sɑ/ or one member was /dɑ/ and the other /ʃɑ/. The order of presentation of these tasks was counterbalanced across subjects within a group. All stimuli were presented with a Panasonic SV-3700 digital audio tape recorder over TDH-39 headphones. Following Tallal's protocol, a written log of subjects' responses was maintained throughout the session. The tasks summarized in Table 5 were as follows:

Table 5. Summary outline of session 1(part 1): association, temporal ordering and discrimination tasks, modeled after Tallal's method (Tallal & Piercy, '73), using as stimuli the syllables, /bɑ/ and /dɑ/.

1. *Association Subtest:* Subjects had to identify two different stimuli (for example, /bɑ/ and /dɑ/), by pointing to a red-colored dot for /bɑ/ and a green-colored dot for /dɑ/. Training consisted of six repetitions of one sound followed by six of the other. Training continued with the two syllables, presented in a quasi-random order, until a criterion of 12 correct out of 16 consecutive trials was reached ($p<.001$,Binomial), within 48 trials. If after 48 trails a subject failed to reach criterion ,(s0he was dropped from the study. During the latter portion of the training, subjects were required both to point to the appropriate dot and say the syllable they heard.

2. *Temporal Ordering:* Subjects were trained to respond to the two stimuli, successively presented with an interstimulus interval of 400 ms, by pointing to the appropriate dots in the correct order of presentation of the sounds. There were four possible two-stimulus patterns: 1-1,1-2,2-1,2-2. The experimenter gave four demonstrations, one of each of these patterns, and then eight training trials with feedback. Training continued with an additional 24 trials, without feedback, until a criterion of 12 correct out of 16 consecutive trials was reached.

3. *Rapid Perception Test:* Three series of 12 two-stimulus patterns were presented for temporal ordering, one at each of three reduced ISI's viz. 100ms, 50 ms, 10 ms. Thus, each subject received a total of 36 trials, in an order of decreasing ISI, and had to respond as before, by pointing to the colored dots in the correct order.

4. *Discrimination Test:* The task was to indicate whether stimulus pairs presented with a 400ms ISI, were the same or different. Training began with six repetitions of stimulus pairs that were the same (subjects learned to point to two dots of the same color , i.e. two blue dots), followed by six repetitions of stimulus pairs that were different, (subjects were trained to point to two dots of a different color, i.e. a blue dot and a yellow dot). Training continued until a criterion of 12 correct out of 16 consecutive trials was reached ($p<.001$, Binomial), within 48 quasi-randomly presented trials. If and only if a subject achieved criterion-related performance, s/he was readministered the rapid perception subtest; this time, however, the subject had merely to indicate whether the two syllables were the same or different.

The order of presentation of the TOJ and discrimination tasks was counterbalanced across subjects within each group.

2.3.2.1 Part 1: Subjects were told that they would hear two syllables, /bɑ/ and /dɑ/. Their task was to identify these syllables by associating a specific response with each one. More specifically, subjects were told to point to a red dot, on the board before them, if they heard /bɑ/ and to a green dot, if they heard /dɑ/. The session consisted of a number of subtests, as follows:

Association task: Each child was presented with six repetitions of the syllable /bɑ/ and six repetitions of the syllable /dɑ/ to familiarize them with the sounds and the correct association response, unaided by any verbal identification of the stimuli by the experimenter. Training then continued with 48 trials, 24 of each stimulus quasi-randomly presented one at a time (with the restriction of a maximum of three of a kind in succession), with an unlimited interval for responding. The subject was required to identify the sound by pointing to the appropriate colored dot. (For this identification training only (i.e. not for any of the subsequent tasks), the experimenter switched to a 'say and point' response method, after the first two subjects, because this seemed to engage the child's attention more fully and increased response reliability). Once the subject attained the criterion of 12 correct out of 16 consecutive trials ($p < .001$, Binomial test) within the 48 trials, it was assumed that the (s)he could discriminate the two stimuli from each other and had learned to associate each stimulus with the correct response choice, and so could proceed to the temporal order judgment task. If after 48 trials, a subject failed to reach criterion (s)he was dropped from the study.

Temporal Order Judgment (TOJ): Here the subject was trained to respond to two stimuli presented in succession separated by a 400 ms interstimulus interval (ISI), by pointing to the red and green dots in the correct order of presentation of the two sounds. There were four possible order patterns: 1-1, 1-2 , 2-1, 2-2 (where 1 and 2 represent /bɑ/ and /dɑ/ respectively). Four demonstrations by the experimenter were followed by eight training trials during which subjects received feedback on their performance, and by 24 test trials without feedback.

In the short ISI temporal order judgment tasks, that came next, a series of 12 two-stimulus patterns were presented at each of three shorter ISI's viz. 100 ms, 50 ms, 10 ms., making a total of 36 trials at the reduced ISI's. The series were presented in the same order

of decreasing ISI, for all subjects. Once again, the subject had merely to point to the dots in the order in which he heard the two sounds on each trial.

Discrimination Task: A same/different task was used. The training procedure was similar and the test tapes identical to those in the temporal ordering task. The subject was initially presented with six repetitions of two identical syllables, /bɑ/-/bɑ/ or /dɑ/-/dɑ/, with an ISI of 400 ms and was trained to point to two blue dots (i.e., two dots of the same color). Then came six presentations of two different syllables, on which the subject was trained to point to two different colored dots (i.e., a blue dot and a yellow dot). Next, 48 trials consisting of an equal number of identical and different syllable-pairs, were presented in a quasi-random order, with the proviso that there be a maximum of three of a kind in succession. Training continued until a criterion of 12 correct out of 16 consecutive trials ($p<.001$, Binomial), within the 48 trials, was reached. If after 48 trials, a subject failed to reach criterion, s/he was excluded from the study. If criterion was reached, however, the subject was presented with the same series of 12 trials at each of the three reduced ISI's, as were used in the TOJ task. This time, however, the subject had merely to indicate if the pair of syllables presented was the same or different, by pointing to the dots.

2.3.2.2. Part 2: For half the subjects in each group, the TOJ and discrimination tasks were repeated with the stimulus pair, /bɑ-sɑ/, and for the other half they were repeated with the stimulus pair /dɑ/-/ʃɑ/ (Experiment 1). (Ideally, each subject should have completed these tasks with both stimulus pairs, but this would have made the procedure unacceptably long). Once again, the order of presentation of the TOJ and discrimination tasks was counterbalanced across the groups of good and poor readers, and the subjects had to respond by using a "point only" technique.

2.3.3. Session 2

Here, the procedures of the first part of session 1 were repeated, with non-speech auditory analogs of the synthetic /bɑ/ and /dɑ/, viz. sinewave syllables (Experiment 2). The red dot and the green dot were replaced by an upward-pointing and a downward-

pointing arrow, respectively, to match the "up" and "down" identification labels given these auditory analogs of F_2 and F_3 of /bɑ/ and /dɑ/.

2.3.4 Session 3

This involved two identification tasks: /ʃu-su/ and /seI-steI/. The /ʃu-su/ task was split into two parts, one half being administered before the /seI-steI/ identification task, the other, after it. This division was intended to break the monotony of the task and help keep the child's attention.

Experiment 3 consisted of 90 stimuli from the /seI-steI/ continuum. Subjects were initially trained with ten repetitions of each of the two end-points on the continuum, to a 90% correct criterion. They were then presented with the test stimuli, one at a time, in a random order, with an unlimited interval in which to respond. The stimuli were presented by a Compaq 386 portable computer (IBM-clone) via a 901F Frequency Devices filter and TDH-39 headphones. Subjects responded both by saying aloud what they heard and by pointing to a picture of a little girl with an empty blurb balloon for the word "say" and of a man appearing to admonish a dog to stay put, with a raised hand-like gesture, for "stay". Responses were registered directly to the computer on a Koala digitization pad, operated by the experimenter who monitored the stimuli over headphones. Board games were used to maintain subject interest in the task. Play moves were allowed only during block intervals of the stimulus presentations.

Experiment 4 consisted of 180 stimuli from the /ʃu-su/ continuum, which were administered following the same procedure described above. Once again subjects were trained to a 90% correct criterion and were then presented the test stimuli. This time the pictures consisted of a shoe or of a little girl said to be named "Sue".

CHAPTER 3 : RESULTS

3.1 EXPERIMENT 1: Discrimination and temporal order judgments of syllable pairs varying in degree of phonetic contrast, by good and poor readers.

Training: All twenty poor readers and the twenty controls met criterion performance (12 correct out of 16 consecutive trials, $p<.001$, Binomial Test) on the training portions of the screening tasks, with stimulus pair /bɑ/-/dɑ/, as noted in the preceding section. However, by two-tailed t-test the poor readers made significantly more errors in achieving the criterion, on identification (good readers: mean= .2, SD= .4; poor readers: mean=1.1, SD=1.7, t (21)*= 2.47, p=.02), on discrimination (good readers: mean=0, SD= 0; poor readers: mean=.6, SD=.9, t (19)*=2.60, p=.02), and on temporal ordering (good readers: mean= .1, SD= .2; poor readers: mean=1.0, SD=1.3, t (20)*= 3.33, p<.01), the latter two at 400 ms interstimulus intervals (ISI). (*Note*: The use of the * indicates reduced degrees of freedom for the t-test on the assumption of unequal population variances (Levene, 1960).

In contrast, good and poor readers performed equally well on the identification and temporal ordering tasks with stimulus pairs /bɑ/-/sɑ/ or /dɑ/-/ʃɑ/, depending on the subgroup to which they belonged (refer to the Methods section) (Mean number of errors=0, SD=0). Performance on discrimination at 400 ms ISI was almost error-free too, with the exception of a single error by one poor reader in the /dɑ/-/ʃɑ/ subgroup. Thus, there were no significant differences between the groups on any of these tasks. Table 6 contains a summary of the mean performances of the two groups.

Perception under reduced interstimulus interval conditions: As described earlier (see Subjects), only poor readers who scored a minimum of three errors out of 36 trials on /bɑ/-/dɑ/ temporal order judgments (TOJ) at short interstimulus intervals, i.e. rapid rates of presentation, and only good readers with no errors on the same, were included in the study. Figure 3 displays the mean number of errors on discrimination and TOJ of /bɑ/-/dɑ/ at short ISI's by the two groups. Whereas poor readers show an increase in their error rate at

Table 6. Mean number of errors of good and poor readers on training portion of screening and Experiment 1 tasks: identification, discrimination at 400 ms ISI and temporal ordering at 400 ms ISI. Standard deviations are in parentheses.

		GOOD READERS			POOR READERS		
Stimulus pair	Group Size	IDEN	D400	T400	IDEN	D400	T400
/bɑ/-/dɑ/	20	.2 (.4)	0 (0)	.1 (.2)	1.1 (1.7)	.6 (.9)	1.0 (1.3)
/bɑ/-/sɑ/	10	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
/dɑ/-/ʃɑ/	10	0 (0)	0 (0)	0 (0)	0 (0)	.1 (.3)	0 (0)

Note: IDEN= Identification;
D400 = Discrimination at 400 ms ISI
T400 = Temporal Order Judgments at 400 ms ISI
(ISI= interstimulus interval)

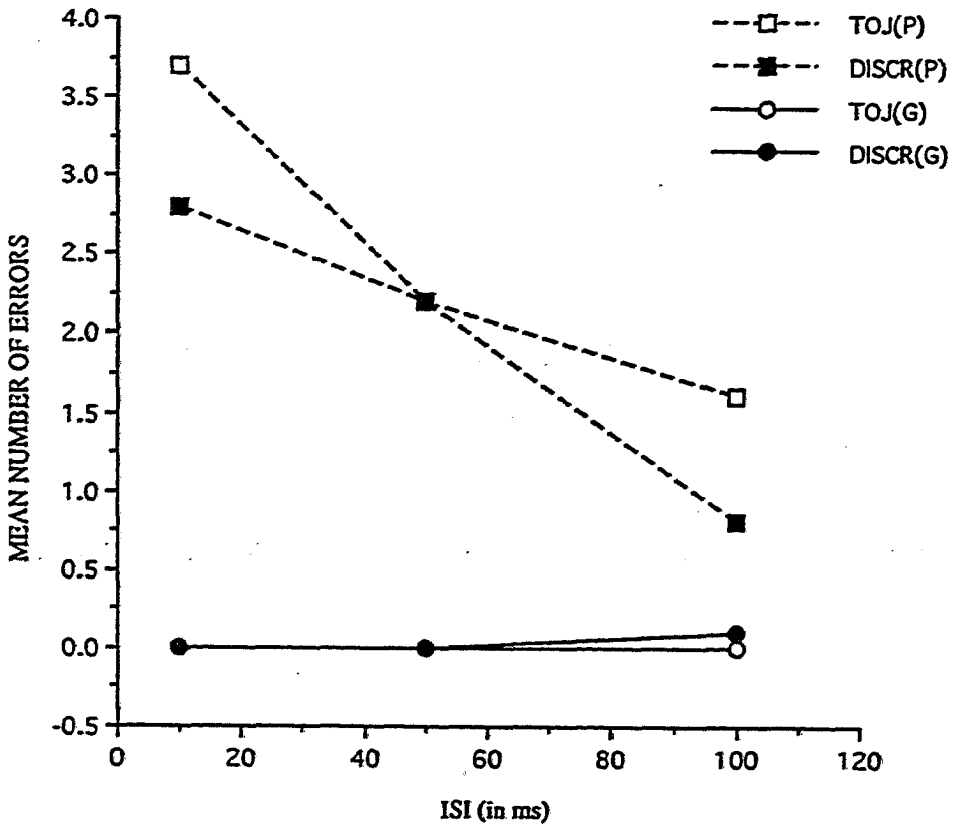

Figure 3: Mean number of errors by good (G) and poor (P) readers, at individual ISI's, on /bɑ/-/dɑ/ discrimination and temporal ordering tasks.

decreasing interval durations on both tasks, good readers were unaffected by the change in ISI, their performance being almost identical on the two tasks. Poor readers also made more errors on TOJ than discrimination at 100 ms and 10 ms but, curiously, not at the intermediate ISI of 50 ms. A two-way ANOVA (Task X ISI) for the poor readers yielded main effects of ISI ($F=11.26$, $p<.001$) and task ($F=4.30$, $p=.05$), but no significant interaction between the two variables ($F=1.64$, $p=.21$). Thus, ISI had the same effect on both tasks.

For the temporal ordering and discrimination tasks, when the syllable pair was changed to /bɑ/-/sɑ/ or /dɑ/-/ʃɑ/, Table 7 presents the mean scores of the two groups at short ISI's, together with the corresponding /bɑ/-/dɑ/ data for comparison. Here, poor readers performed almost as well as the controls with the exception of one temporal ordering error and two discrimination errors, both at the shortest ISI and on syllable pair /dɑ/-/ʃɑ/. Good readers continued to make no errors at any ISI. Overall, there was no significant difference between the good and poor readers on discrimination or temporal ordering at the short ISI's, with these stimuli.

In summary, then, while the two groups differed significantly on the /bɑ/-/dɑ/ discrimination and TOJ of /bɑ/-/dɑ/ at all ISI's studied (see Figure 1 and Table 7), there was no significant difference between their performances on the same tasks, with stimulus pairs /bɑ/-/sɑ/ or /dɑ/-/ʃɑ/. Further, whereas a change in the stimulus pair from /bɑ/-/dɑ/ to /bɑ/-/sɑ/ or /dɑ/-/ʃɑ/ significantly improved the performance of the poor readers on the two tasks, the good readers were unaffected, performing equally well under both conditions. These findings demonstrate that the poor readers' difficulties in judgments of /bɑ/ and /dɑ/ do not derive from any intrinsic properties of the individual syllables themselves, but depend on the context in which they are presented.

Table 7. Mean number of errors of good and poor readers on phonetic-pair discrimination and temporal ordering at individual ISI's. Standard deviations are in parentheses.

		GOOD READERS			POOR READERS		
ISI		100ms	50m	10ms	100 ms	50 ms	10ms
Stimulus pair	Group Size		Discrimination				
/bɑ/-/dɑ/	20	0	0	0	.8	2.2	2.8
		(0)	(0)	(0)	(1.4)	(2.3)	(1.9)
/bɑ/-/sɑ/	10	0	0	0	0	0	0
		(0)	(0)	(0)	(0)	(0)	(0)
/dɑ/-/ʃɑ/	10	0	0	0	0	0	.2
		(0)	(0)	(0)	(0)	(0)	(.4)
Stimulus pair	Group Size		Temporal Order Judgments (TOJ)				
/bɑ/-/dɑ/	20	0	0	0	1.6	2.2	3.7
		(0)	(0)	(0)	(1.9)	(1.9)	(1.9)
/bɑ/-/sɑ/	10	0	0	0	0	0	0
		(0)	(0)	(0)	(0)	(0)	(0)
/dɑ/-/ʃɑ/	10	0	0	0	0	0	.1
		(0)	(0)	(0)	(0)	(0)	(.3)

Note: ISI = interstimulus interval

3.2 EXPERIMENT 2: Discrimination, by good and poor readers, of acoustically similar non-speech sinewave analogs of the second and third formants of /ba/ and /da/ which carry the crucial place of articulation information.

Training: Good and poor readers were further compared on identification and discrimination tasks using non-speech auditory analogs of the F_2 and F_3 of /ba/ and /da/. Table 8 presents the training results. All members of both groups met training criterion (12 correct out of 16 consecutive trials, $p<.001$, Binomial Test), although with higher mean error scores than on /ba/-/da/. There were no significant differences between the groups' error performances on the identification subtest [$t(38)= .70$, $p=.49$] or discrimination at 400 ms ISI [$t(38)=.24$, $p=.81$]. This is in direct contrast with our findings on these tasks, earlier in this study, using /ba/ and /da/, in which the poor readers were consistently and significantly worse than the good readers.

Discrimination under reduced ISI conditions: The task here was one of discriminating the non-speech stimulus pair at the short ISI's used in the previous experiment. Table 9 presents the mean error scores of the two groups at the individual ISI's, and Figure 4 displays the relative performances of the two groups as a function of ISI with speech data graphed for comparison. On the average, the poor readers (mean number of errors: 1.4, S.D.=1.5)) outperformed the good readers (mean number of errors: 2.3, S.D.=1.9) on the non-speech discrimination at short ISI's. Also contrary to their performance on /ba/-/da/, the poor readers were unaffected by changes in ISI. The two groups performed similarly at the two longer ISI's, 100ms and 50 ms, but good readers showed a sharp increase in error rate at the shortest ISI . A two way ANOVA (Group X ISI) on the non-speech data found the difference between the groups was not significant ($F=3.5$, $p=.06$). There was also no main effect for ISI ($F=2.42$, $p=.09$). However, the interaction between group and ISI was significant ($F=4.12$, $p=.02$), reflecting the effect of the shortest ISI on good readers, and the lack of such an effect on poor readers. A post hoc t-test of the error difference between the shortest and the two longer ISI's for the good readers was not significant by Scheffe's criterion[$t(19)= 2.75$, $p>.05$].

Table 8. Mean numbers of errors of good and poor readers on non-speech identification and discrimination training tasks. Standard deviations are in parentheses.

TASK	GOOD READERS	POOR READERS
Identification	6.4 (3.5)	7.3 (4.5)
Discrimination at 400ms ISI	2.2 (2.9)	2.0 (2.4)

Table 9. Mean numbers of errors of good and poor readers on non-speech discrimination at three interstimulus intervals (ISI's). Standard deviations are in parentheses.

ISI (in ms)	GOOD READERS	POOR READERS
100	1.9 (2.0)	1.3 (1.8)
50	2.0.(1.9)	1.6 (1.5)
10	2.9.(1.8)	1.3 (1.3)
Mean of total errors across all ISI's	6.8	4.2
Grand Mean	2.3 (1.9)	1.4 (1.5)

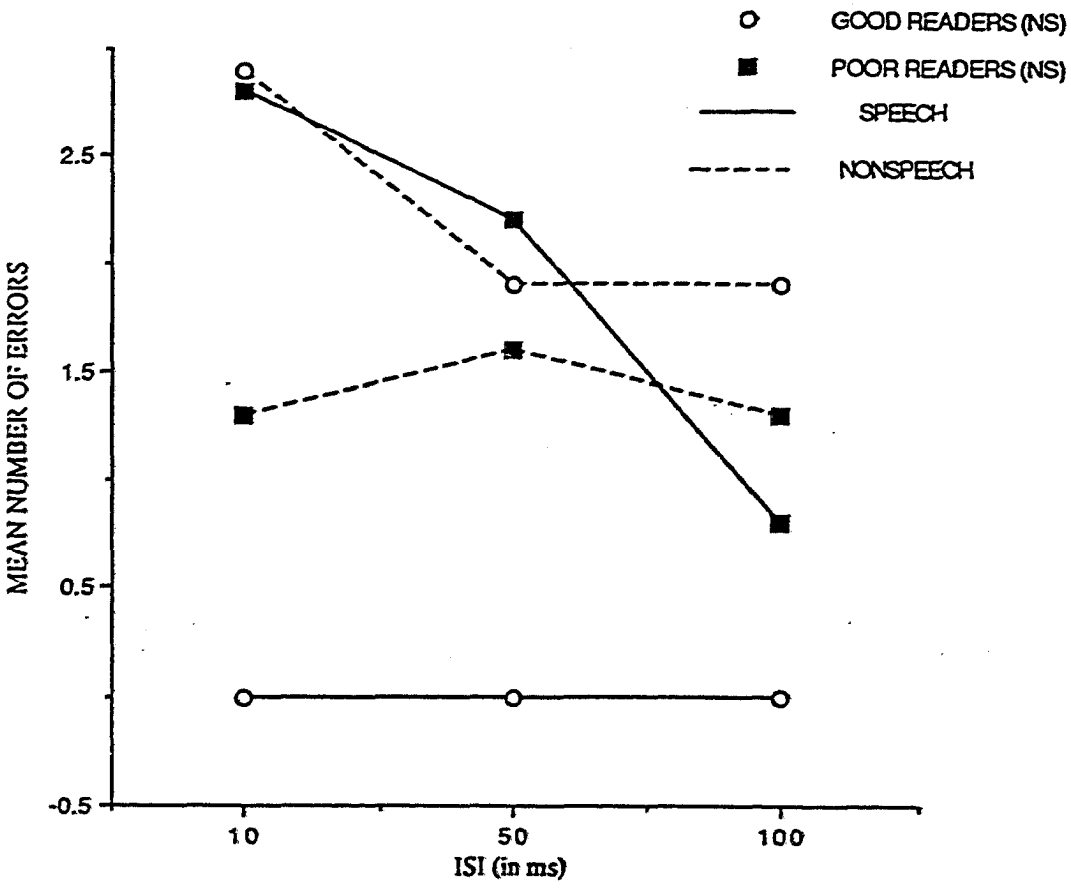

Figure 4: Mean number of errors by good and poor readers, at individual ISI's, on nonspeech and speech discrimination.

3.2.1 Comparison of speech (/bɑ/-/dɑ/) and non-speech (sinewave syllables) performances

Training: Table 10 provides a summary profile of good and poor readers' mean performances on the speech and non-speech training tasks. The table lists, for each group, the mean number of errors to criterion under each condition, together with the increase in these scores due to the switch from speech to non-speech. This increase is equal for each group, on the identification training task (6.2) and is displayed in Figure 5a, which compares the mean error performances of the two groups, for speech (/bɑ/-/dɑ/) and non-speech, on this task. A two way ANOVA (Group X Condition) of the speech and non-speech identification training data yielded a main effect for condition ($F=96.04$, $p<.001$) but not for group ($F=1.64$, $p=.2$). The absence of a significant interaction between group and condition indicates that non-speech training, although more difficult, was consistently harder than speech training to the same degree for both good and poor readers.

Good and poor readers were further compared on their speech-nonspeech performances on discrimination training, at 400 ms ISI. Table 10 also includes the mean number of errors to criterion, for the two groups, under these conditions. Both groups found the non-speech stimuli harder, as reflected by their higher mean number of errors to criterion on non-speech than speech. Figure 5b compares the relative performances of the two groups on this task, for speech and non-speech . A two way ANOVA (Group X Condition) produced a main effect for condition ($F=15.68$, $p=.0003$), but not for group ($F=.17$, $p=.7$); there was also no significant interaction between the two variables ($F=.7$, $p=.4$). Thus, while discrimination was harder with the sinewave syllables than with /bɑ/-/dɑ/ for both groups, the task was not significantly harder for any one group.

Discrimination under reduced ISI conditions: Table 11 compares the mean error performances of the two groups on discrimination of speech (/bɑ/-/dɑ/) and the corresponding nonspeech analogs at the short ISI's. (As already described, Figure 4 compares mean error performances on the two stimulus types .) Changing the stimuli from speech to non-speech improved the performance of the poor readers, particularly at the shorter ISI's, but lowered the performance of the good readers. Thus, stimulus condition

Table 10. Comparison of mean number of errors to criterion, by good and poor readers, on training tasks for identification and for discrimination at 400 ms ISI, under speech and non-speech conditions.

TASK	GOOD READERS			POOR READERS		
	SPEECH	NSPEECH	DIFF	SPEECH	NSPEECH	DIFF
Identification	.2 (.4)	6.4 (3.5)	+6.2	1.1 (1.7)	7.3(4.5)	+6.2
Discrimination *(at 400 ms ISI)*	0 (0)	2.2 (2.9)	+2.2	0.6 (0.9)	2.0 (2.4)	+1.4

Note: NSPEECH= NONSPEECH

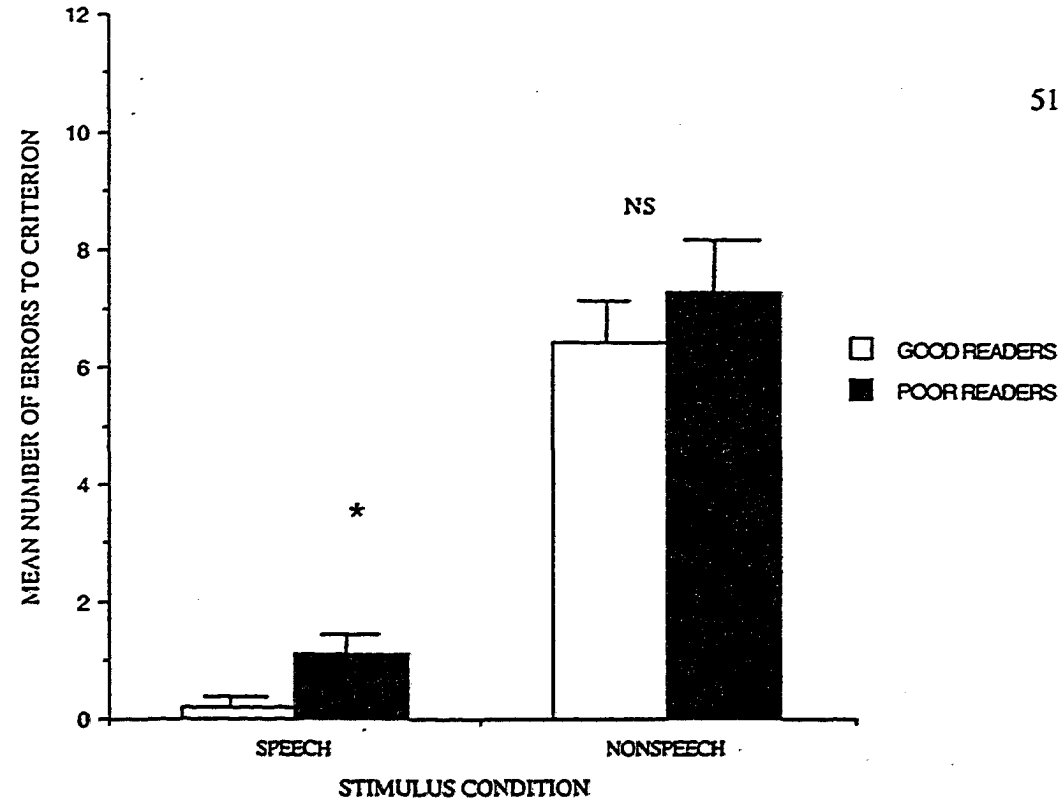

Figure 5a: Mean number of errors and standard errors of the mean on speech and nonspeech identification training, by good and poor readers. (* p<.05, NS= not significant)

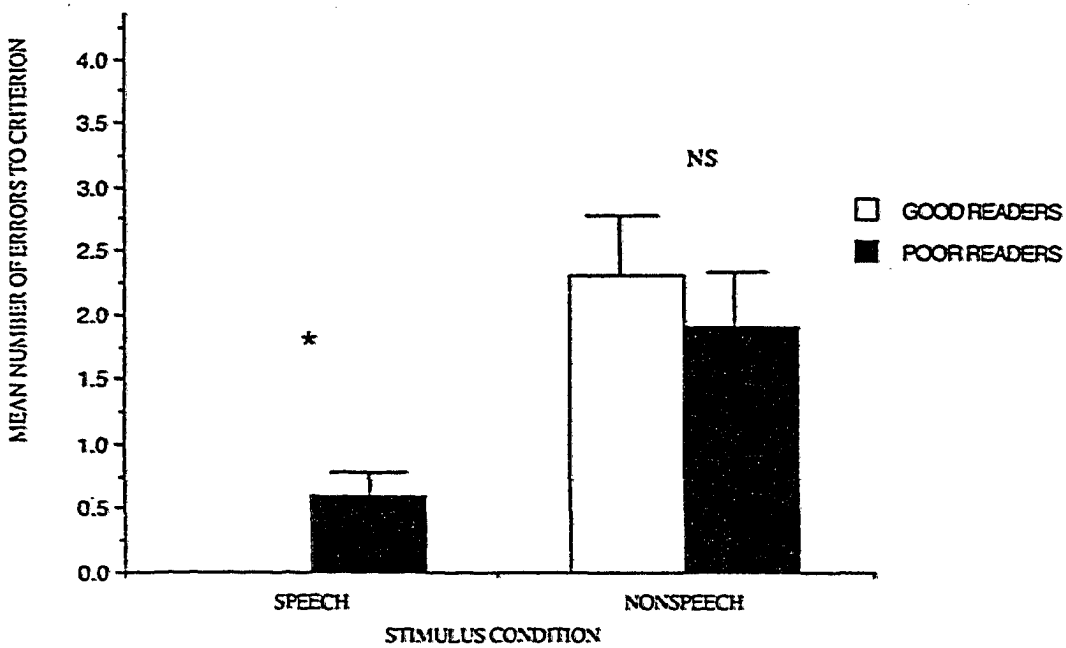

Figure 5b: Mean number of errors and standard errors of the mean on speech and nonspeech discrimination training at 400 ms ISI, by good and poor readers. (* p<.05, NS= not significant)

Table 11. Comparison of mean number of errors by good and poor readers on discrimination at three interstimulus intervals, under speech and nonspeech conditions.

TASKS	GOOD READERS			POOR READERS		
	SPEECH	NSPEECH	DIFF	SPEECH	NSPEECH	DIFF
Discrimination						
ISI: 100 ms	0	1.9	+1.9	0.8	1.3	+0.5
50 ms	0	2.0	+2.0	2.2	1.6	-0.6
10 ms	0	2.9	+2.9	2.8	1.3	-1.5
Mean of total errors across all ISI's	0	6.8	+6.8	5.8	4.2	-1.6
Grand Mean	0	2.3	+2.3	1.9	1.4	-.5

Note: NSPEECH= NONSPEECH

ISI = interstimulus interval

had an opposite effect on the two groups, an outcome confirmed by a three-way ANOVA (Group X ISI X Stimulus Condition) on the error data, with ISI and stimulus condition as within-subject variables. The analysis yielded main effects for condition ($F=11.90$, $p=.001$) and ISI ($F=11.21$, $p=.0001$). However, the two way interactions between group and condition ($F=33.58$, $p<.001$) and between group and ISI ($F=3.11$, $p=.05$), and the three-way interaction between group, ISI and condition were also significant, ($F=8.13$, $p=.0006$). The most striking finding, then, is the group by condition interaction across the shorter ISI's: increased time pressure disadvantaged poor readers on speech, good readers on non-speech. More positively, good readers' performance improved when the sound patterns were amenable to phonological representation, while poor readers' performance improved when they were not.

3.3 EXPERIMENT 3: Sensitivity of good and poor readers to brief first formant transitions in fricative stop clusters

Figure 6 displays the mean probability of /steI/ responses as a function of F_1 transition onset frequency for the two groups. The two group functions are very similar, although poor readers give a somewhat shallower slope. Cumulative normal distributions were fit to individual data by the method of least squares (Finney, 1964) and yielded means and standard deviations of the individual distributions. The mean is an estimate of the phoneme boundary, the value of the F_1 transition for which "say" and "stay" responses are equally likely; the standard deviation corresponds to the reciprocal of the slope of the cumulative function. Table 12 lists the means of the phoneme boundaries and the means of the slopes for each group. Whereas the good and poor readers have almost the same phoneme boundaries (398 Hz and 396 Hz, respectively), the latter have a shallower slope. Standard deviations are slightly, but not significantly greater for the poor readers. However, the differences between the groups were not significant in either phoneme boundary [$t(38)=.18$, $p= .86$] or slope[$t(38)=1.16$, $p=.25$].

Many of the individual data were not well fit by the cumulative normal curve. This

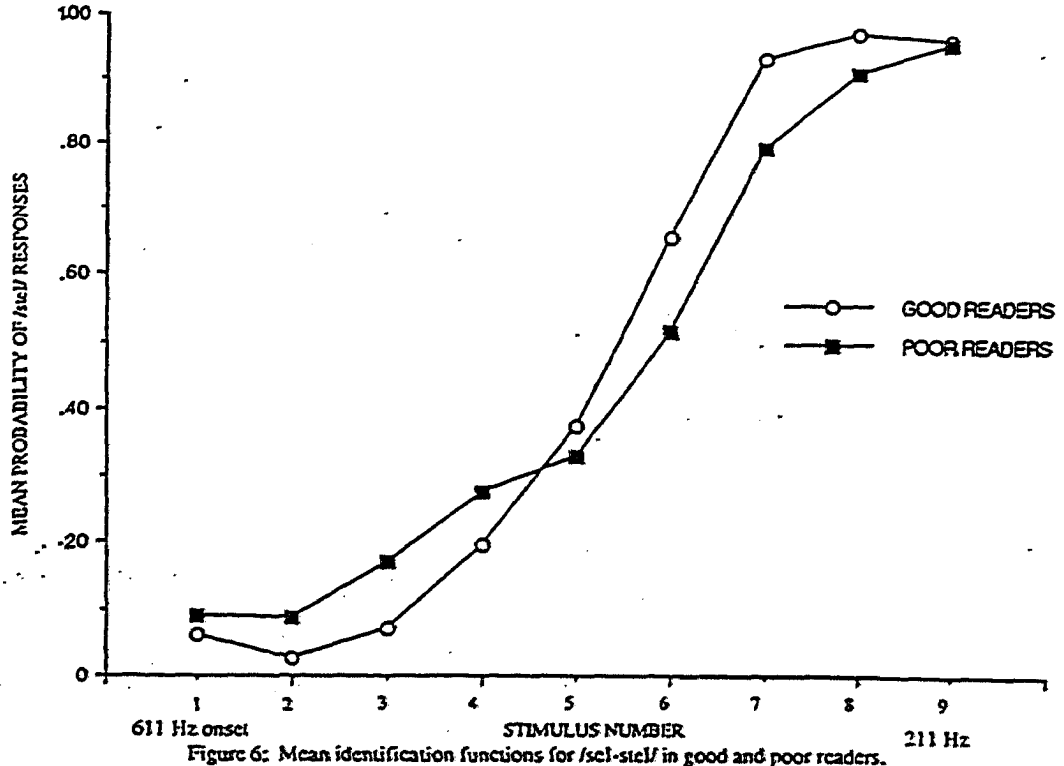

Figure 6: Mean identification functions for /sel-stel/ in good and poor readers.
(stimulus numbers refer to F onset frequencies ranging from 611 to 211 Hz in 50 Hz steps)

Table 12. Mean performances of good and poor readers on /seI-steI/ continuum. Standard deviations are in parentheses.

GROUP	MEAN PHONEME BOUNDARY (Hz)	MEAN SLOPE (Probits X 1000/Hz)
Good readers(n=20)	398.05 (39.1)	15.5 (6.9)
Poor readers (n=20)	395.61 (45.5)	12.4 (9.5)

raises some doubt as to the propriety of the use of probit analysis. Hence, an alternative, though coarser, measure of response to F_1 onset variations was computed, namely the total number of "stay" responses across the continuum. Once again, the groups did not differ significantly; the mean number of "stay" responses by the good readers (42.3) was almost equal to that of the poor readers (41.1) [t(38)=.47, p=.63]. Good and poor readers were also equally variable on this measure: both groups had the same standard deviations (7.7).

3.4 EXPERIMENT 4: Sensitivity of good and poor readers to variations in vocalic formant transitions, as a function of fricative context, for fricative-vowel syllables.

Figure 7 displays the mean probability of /s/ responses for good and poor readers, as a function of the major pole in the synthetic fricative spectrum; variations in naturally-spoken vocalic formant transitions, as a function of preceding fricative (viz. /ʃ/ and /s/), are parameters of the curves. Manipulating the fricative context of the vocalic F_1 transition, had a substantial effect on the response patterns of both groups: When the fricative context of the vowel was /s/, subjects' identification bias was clearly toward /s/, and when the fricative context was /ʃ/, the bias switched toward /ʃ/. Further, the magnitude of this effect was almost identical, in both good and poor readers.

As in the previous experiment, cumulative normal distributions were fit to the individual data, by the method of least squares (Finney, 1964), to yield phoneme boundaries and slopes for the individual distributions. The phoneme boundary, here, is the crossover point on the continuum for which "Sue" and "shoe" responses are equally likely. Table 13 presents the group means of the phoneme boundaries, together with the differences between these means as a function of fricative context. (Note: One good reader was dropped from the experiment because she was unable to do the task). By contrast with the relative performances of the two groups on the previous experiment, the standard deviations were consistently smaller for the poor readers. A two-way ANOVA (Group X Fricative Context) yielded a main effect for fricative context (F=153.61, p<.001), but not for group (F=.38, p=.54), and no significant interaction (F=.17, p=.69). Thus, the

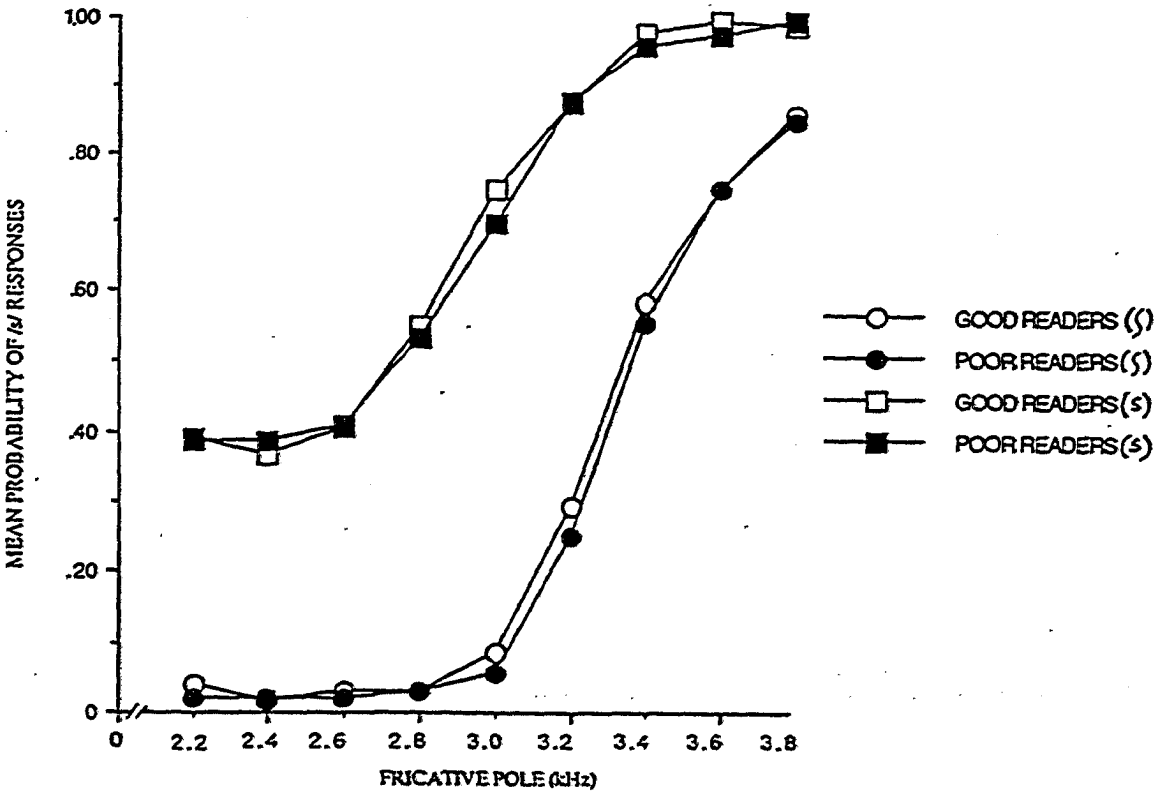

Figure 7: Mean identification functions of good and poor readers, for hybrid fricative-vowels syllables, constructed from synthetic fricative noises and natural vowel (/u/), spoken after /ʃ/ or /s/

Table 13. Mean phoneme boundaries on synthetic fricative continuum for good and poor readers, as a function of the fricative context of vocalic formant transitions Standard deviations are in parentheses.

GROUP	FRICATIVE CONTEXT (Hz)		DIFFERENCE (Hz)
	/ʃ/	/s/	
Good Readers (n=19)	3343.17 (260.5)	2523.66 (445.2)	819.15
Poor Readers (n=20)	3419.15 (136.6)	2543.86 (370.4)	875.29

Table 14. Mean slopes of /ʃ/ and /s/ identification functions in good and poor readers Standard deviations are in parentheses.

GROUP	FRICATIVE CONTEXT	
	/ʃ/	/s/
	(Probits X 1000/Hz)	
Good Readers (n=19)	4.30 (1.6)	3.17 (3.3)
Poor Readers (n=20)	3.04 (1.1)	2.55 (1.7)

difference between the /ʃ/ - /s/ phoneme boundaries in good readers was not significantly different from that in the poor readers.

Table 14 gives the mean slopes of the two groups for the different transition types. Once again, the poor readers evidence a shallower slope, indicating a tendency for individual poor readers to be less consistent than individual good readers. At the same time, the smaller standard deviations of the slopes of the poor readers, demonstrate their greater consistency as a group. A two-way ANOVA (Group X Fricative Context) on the slopes yielded a main effect for group ($F=4.04$, $p=.05$), but not for fricative context ($F=2.96$, $p=.09$) and no significant interaction ($F=.46$, $p=.50$). Thus, poor readers displayed greater uncertainty in their labelling of stimuli for both fricative contexts.

Once again, many of the individual data sets were not well fit by the cumulative normal curve. An alternative measure of response was therefore computed, namely, the total number of /s/ responses in each group, as a function of fricative context. Table 15 presents the group means of the number of /s/ responses, together with the differences between these means, as a function of fricative context. A two way ANOVA (Group X Fricative Context) yielded a main effect for stimulus type ($F=215.41$, $p=<.001$), but not for group ($F= .28$, $p=.60$) and no significant interaction ($F=.13$, $p=.72$). Note that here too, the poor readers were less variable than the good readers, with lower standard deviations, particularly in the /ʃ/ context.

Table 16 provides an overview of subjects' performances in the four experiments. Poor readers, in this study, do not suffer from a temporal processing deficit as described by Tallal. Although the two groups differed significantly on temporal order judgments of /bɑ/ and /dɑ/ at short ISI's (failure on this task was a characteristic feature of Tallal's language-impaired and a number of her reading-impaired children), they did not differ when these syllables were presented in more easily discriminable pairings, as in /bɑ/-/sɑ/ and /dɑ/-/ʃɑ/. The fact that poor readers resembled good readers on non-speech discrimination of the sinewave analogs of /bɑ/ and /dɑ/ at short ISI's (Experiment 2), rules out an auditory account of the group differences on the corresponding full syllables in Experiment 1.

Evidently, the poor readers in this study did not suffer from the "temporal processing deficit" posited by Tallal.

Good and poor readers also did not differ significantly in their ability to identify other syllables in which rapidly changing acoustic spectra specified a phonetic contrast, as was evident from their similar performances on the /seI-steI/ categorical perception task (Experiment 3). Finally, there was no significant difference between the /ʃu/ vs /su/ crossover points of the two groups on the /ʃu-su/ continuum (Experiment 4), indicating that at least by this measure poor readers do not appear to be developmentally delayed in their phonetic processing abilities. However, the slopes of the identification functions on the fricative continua were significantly shallower for poor readers than for good readers, suggesting that poor readers may, indeed, have less well defined (or "fuzzy") phonological categories.

Table 15. Mean number of /su/ responses, as a function of fricative context, in good and poor readers. Standard deviations are in parentheses.

GROUP	FRICATIVE CONTEXT		
	/ʃ/	/s/	DIFFERENCE
Good Readers (n=19)	27.8 (11.9)	62.7 (14.2)	34.9
Poor Readers (n=20)	25.4 (5.1)	62.1 (13.5)	36.7

Table 16. Summary profile of good and poor readers performances on all tasks.

	GOOD READERS			POOR READERS		
Experiment 1:	/bɑ/-/dɑ/	/bɑ/-/sɑ/	/dɑ/-/ʃɑ/	/bɑ/-/dɑ/	/bɑ/-/sɑ/	/dɑ/-/ʃɑ/
DISCR (errors)						
ISI: 100	0	0	0	.8	0	0
50	0	0	0	2.2.	0	0
10	0	0	0	2.8	0	.2
Mean of total errors across all ISI's	0	0	0	**5.8**	0	.2
TOJ (errors)						
ISI: 100	0	0	0	1.6	0	0
50	0	0	0	2.2.	0	0
10	0	0	0	3.7	0	.1
Mean of total errors across all ISI's	0	0	0	**7.4**	0	.1

Note: Group size=20, except under /bɑ/-/sɑ/ and /dɑ/-/ʃɑ/ conditions, where n=10.
DISCR= discrimination; TOJ= temporal order judgment; ISI=interstimulus interval.

Experiment 2 (non-speech)	Identification	Discrimination	Identification	Discrimination
Training (errors)	6.4	2.2	7.3	2.0
Testing condition (errors)		Discrimination		Discrimination
ISI: 100		1.9		1.3
50		2.0		1.6
10		2.9		1.3
Mean of total errors across all ISI's		**6.8**		**4.2**

Experiment 3 /seI-steI/		
Mean phoneme boundary*	398.05	395.61
Mean slope**	15.5	12.4

Experiment 4						
Fricative context	/ʃ/	/s/	DIFF	/ʃ/	/s/	DIFF
Mean phoneme boundary*	3343.17	2523.66	819.15	3419.15	2543.86	875.29
Mean number of /su/ responses	27.80	62.70	34.90	25.40	62.10	36.70
Mean slope**	4.30	3.17		3.04	2.55	

(Note: * Hz; ** Probits X 1000/Hz)

CHAPTER 4 : DISCUSSION

The present findings are inconsistent with the causal role of a general auditory processing deficit in reading impairments, as put forth by Tallal (1980). Specifically, poor readers' difficulties with /bɑ/-/dɑ/ are not intrinsic to the acoustic structure of these syllables, that is to say, they do not arise from difficulties in processing rapid formant transitions *per se*, but from the close phonetic similarity between the syllables and the resulting difficulty in discriminating between them. The argument for the role of *phonetic* rather than acoustic similarity has two components, as developed in the next section.

4.1 Comparison of performance of poor readers on a syllable pair differing on a single feature with their performance on syllable pairs differing on three features.

That poor readers were significantly worse than good readers on all tasks (i.e. identification, discrimination and temporal ordering) involving the syllable pair, /bɑ/-/dɑ, demonstrates that poor readers have difficulty with these sounds. However, the fact that these same sounds were no longer difficult to perceive (mean number of errors almost zero) when paired with other stimuli (/bɑ/-/sɑ/ and /dɑ/-/ʃɑ/), demonstrates that the difficulty is not intrinsic to the stop-vowel syllables, but depends on the context in which they are presented. The close acoustic and/or phonetic similarity of the /bɑ/-/dɑ/ pair may underlie poor readers' confusion. Note that the syllables differ only on a single feature, i.e., place of articulation (/bɑ/ is a voiced, bilabial stop; /dɑ/ is a voiced, alveolar stop). In contrast, members of the syllable pairs, /bɑ/-/sɑ/ and /dɑ/-/ʃɑ/, differ on place, manner and voice features (/sa/ is a voiceless, alveolar fricative; /ʃa/ is a voiceless, palatal fricative). The latter pairs, then, represent a greater degree of acoustic-phonetic contrast than /bɑ/-/dɑ/, thereby making them more easily discriminable.

Are poor readers' difficulties eliminated because the new syllable pairs are acoustically distinct, or because they are phonetically distinct? Experiment 2 attempted to resolve this issue.

4.1.1 Comparison of poor readers' performance on /bɑ/-/dɑ/ with their performance on non-speech sinewave analogs of the second and third formants of bɑ/ and /dɑ/.

Here the two groups did not differ significantly on the identification or discrimination of sinewave analogs of the second and third formants of /bɑ/ and /dɑ/. In fact, it was the poor readers (mean number of errors: 1.4) who outperformed the good readers (mean number of errors: 2.3), although the difference between the groups fell short of significance. Since these analogs differ from each other only in the transitions of the tone analogs of the second and third formant transitions, they are as acoustically similar as the synthetic syllables on which they were modeled. However, the two stimulus types differ radically in phonetic status: the model syllables were perceived as speech, their analogs were not. Presumably, it is to this difference between the stimulus types that the difference in the poor readers' performance is to be attributed. We conclude that the poor readers' deficit is speech-related: It is phonological rather than auditory in origin.

4.1.2 An analogy between the effects on good and poor readers of switching from nonspeech to speech (/bɑ/-/dɑ/) and certain effects observed in short-term memory studies.

As noted earlier, both groups found non-speech harder, in terms of the mean number of errors to criterion performance, on the training tasks. However, the increase in training errors due to the switch from speech to non-speech was roughly equal for each group. It was only at short ISI's that the change in stimulus conditions had an opposite effect on the performance of the two groups: whereas poor readers were adversely affected by speech, good readers were adversely affected by non-speech. This difference between the speech-non-speech performances of the two groups, at reduced ISI's, provides an interesting parallel to the phonetic confusability effect in good and poor readers. A study of recall errors of phonetically similar (rhyming) vs phonetically dissimilar (nonrhyming) letter strings, found considerable difference between the groups: Whereas poor readers made significantly more errors than good readers on the non-rhyming condition, the two

groups did not differ significantly on rhyme (Liberman, Shankweiler, Liberman, Fowler & Fischer, 1977). Good readers, who found the lists of phonetically dissimilar words relatively easy to recall, fell dramatically in their performance on phonetically similar lists; poor readers, by contrast, found the phonetically similar and phonetically dissimilar lists equally difficult, and so showed smaller effects of the list's phonetic properties than good readers. Thus, while both groups did poorly in recalling lists of phonetically similar words, good readers, unlike poor readers, were able to exploit their phonological sensitivity in recalling lists of phonetically distinct words.

We have here, then, an analogy between the speech-non-speech performances of good and poor readers in the present study and the corresponding performances under the non-rhyme and rhyme conditions of the previous study. Here, as in the case of non-rhyme, the two groups differed significantly on the speech condition: poor readers made significantly more errors than good readers. On non-speech, by contrast, as in the case of rhyme, the difference between the groups was not significant. Moreover, good readers performed significantly better on speech than on non-speech (as also on non-rhyme than on rhyme), while poor readers did not differ significantly on the two conditions. This suggests that the speech-non-speech difference between the two groups may be attributed to a difference in their phonetic coding abilities. The fact that poor readers performed identically whether the stimuli were speech or non-speech, might well be viewed as support for the auditory deficit hypothesis. However, when examined in light of the performance of good readers on identical tasks, a different picture emerges. That good readers' superior performance on speech than on non-speech tasks may be attributed to their phonetic coding strategy, just as in their non-rhyme vs. rhyme performances. Similarly, poor readers' relatively weak performance on speech may be viewed as evidence of their poor use of a phonetic coding strategy.

4.2 Is the poor readers' deficit in phonetic coding due to difficulty in *phonetic* processing of rapid formant transitions?

From the above findings, we can conclude that poor readers' difficulties are

phonetic rather than auditory. Nonetheless, these difficulties may be peculiar to the phonetic coding of rapid formant transitions: poor readers may have no difficulty with speech sounds provided they are steady- state. The following evidence argues against this view.

4.2.1 Discrimination of /sɑ/-/ʃɑ/

Tallal and Stark (1981) found that language-impaired children who had difficulty in discriminating /bɑ/-/dɑ/ also had difficulty in discriminating /sɑ/-/ʃɑ/. The authors had hypothesized that "as these syllables differed spectrally, throughout the initial 130 ms of frication noise, this difference would be of sufficient duration to allow these children to discriminate normally between these syllables". However, in the event, the children made significantly more errors on discriminating between these fricative CV syllables than the controls. It was evident, then, that their deficit was not confined to rapid transitions. Tallal and Stark offered a different explanation for this unexpected result, proposing that in addition to their temporal processing deficit, their subjects had difficulty in "discriminating certain spectral cues". They hypothesized that "these children (may) have more difficulty in discriminating high-frequency than low-frequency spectral cues within speech...", quoting Ewing (1930), who suggested that language-impaired children may have intermittent high-frequency hearing loss.

Unfortunately, time constraints prevented a /sa/-/ʃa/ discrimination test in the present study. Nonetheless, on the basis of the findings reported above, we might propose an alternative acount, that /sa/-/ʃɑ/ were difficult for Tallal and Stark's children simply because, like /bɑ/-/dɑ/, they are phonetically similar, differing on a single feature,viz. place of articulation.

4.2.2 Sensitivity to phonetic contrast conveyed by rapid F_1 transitions.

The fact that good and poor readers do not differ in their ability to process rapid formant transitions, is also evident from their essentially identical identification functions

/seI-steI/ continuum. Previous work in English (Fitch, Halwes, Erickson, & Liberman 1981; Morrongiello et al., 1984) has demonstrated two reciprocally covarying cues to the presence or absence of a stop between an initial alveolar fricative and its following vowel: (1) duration of the silent interval between fricative and vowel, (2) the onset frequency of the vowel first formant. For a given steady state value of vowel F_1, variations in onset frequency of F_1 are equivalent to variations in the frequency extent of the F_1 transition. If F_1 steady-state is set at 611 Hz, as it was here, variation of F_1 onset frequency from 211 to 611 Hz in 50 Hz steps is equivalent to varying the extent of F_1 transition from 400 Hz to 0 Hz. For a transition lasting 40 ms, the rate of frequency change then ranges from 10,000 Hz/sec to 0 Hz/sec.

According to Tallal, poor readers resemble language-impaired children who have "specific difficulty processing brief acoustic cues that are followed in rapid succession by other acoustic cues." Such stimuli include, for example, the stop-consonant syllables /bɑ/ and /dɑ/, and intermediate stimuli along a /sɑ/ to /stɑ/ continuum, differing in the duration of the silent gap between the frication and the vowel formants, with F_1 fixed (Tallal & Stark, 1978). That these children needed a significantly longer silent period between the fricative and the following vowel than did normal children, to shift from categorizing stimuli along this continuum as /sɑ/ to categorizing them as /stɑ/ is cited as evidence of their temporal processing deficit. Consequently, one might also predict an analogous problem for the poor readers in the current study, on the /seI-steI/ continuum.

Here, we should note that the stimuli of the present study directly tested sensitivity to rapid spectral change by varying F_1 transition, while keeping the silent interval constant. Tallal's stimuli, on the other hand, tested sensitivity to gap duration by varying its duration, while keeping F_1 fixed. In the event, good and poor readers displayed equal sensitivity to the phonetic contrast conveyed by the rapid F_1 transitions. The two groups had equal phoneme boundaries, and although poor readers were somewhat less consistent, (that is to say, they exhibited shallower slopes), the difference between the groups was not significant. The performance of these poor readers closely resembled that of the dyslexics in the study by Godfrey et al. (1981). There, too, dyslexic and control groups did not

differ significantly in their phoneme boundaries on categorical perception tests with synthetic /bɑ-dɑ/ and /dɑ-gɑ/ continua. However, like the dyslexics, the poor readers here "were less certain, hence more variable in their identification of the speech sounds." (Godfrey et al., 1981; Reed, 1989); they had significantly shallower identification slopes compared to the good readers. Evidently poor readers' difficulties do not lie in the phonetic coding of rapid formant transitions, but in discriminating phonetically similar syllables.

4.3 Are poor readers' difficulties due to a temporal processing deficit?

According to Tallal, poor readers suffer from a primary auditory deficit in temporal analysis. She interprets her findings (Tallal, 1980) as indicating that of the several auditory perceptual skills tested, "the ability to respond to rapidly presented information proved to be the most difficult for reading-impaired children as a group". She concludes that these children's "difficulty with temporal pattern perception may stem from a more primary perceptual deficit that affects the rate at which they can process perceptual information". She adduces as evidence poor readers' difficulties in judging the temporal order of two brief acoustic events (whether "rapidly changing spectra" or short complex tones) presented at ISI's of less than 150 ms. Here, as elsewhere, Tallal confuses the processing of temporal aspects of a signal with the auditory processing of nontemporal aspects at rapid rates of presentation (i.e. under time pressure). If we are to isolate a genuine deficit in the capacity for temporal analysis, we must distinguish among (i) the brevity of the events to be judged, (ii) the brevity of the intervals between the events, and (iii) judgments of temporal order of the events. Only a deficit in the last might, under normal linguistic usage, be considered a deficit in "temporal analysis". Difficulties in perceptual processing of very brief events and/or of events with very brief intervals between them constitute evidence of a deficit not in a capacity for temporal analysis, but rather in a capacity to process information rapidly.

Experiments 1 and 2 demonstrated that the poor readers' difficulties with TOJ and discrimination of /bɑ/ and /dɑ/ (i) were not due to the brief stop consonant transitions

("rapidly changing spectra"), followed in rapid succession by other acoustic cues, i.e., the steady-state vowel formant, but (ii) were peculiar to speech at short ISI's. We may now ask whether these poor readers' difficulties with /bɑ/-/dɑ/ were due to a deficit in a capacity for temporal analysis (that is, for temporal order judgment) or to a difficulty in discrimination. Support for the latter interpretation comes from the following evidence.

4.3.1 TOJ with /bɑ/-/sɑ/ and /dɑ/-/ʃɑ/

Poor readers' essentially errorless performance on TOJ with /bɑ/-/sɑ/ and /dɑ/-/ʃɑ/ at the short ISI's, when compared with their marked difficulties on the same with /bɑ/-/dɑ/, demonstrates that their TOJ deficit varies with the relation between the stimuli to be judged. From this we may infer that their difficulties with /bɑ/-/dɑ/ were discriminative rather than temporal.

4.3.2 Are poor readers' difficulties in temporal order judgments of syllables a consequence of difficulties in temporal analysis, in discrimination or in phonetic coding ?

According to Tallal, when the rate of presentation of acoustic events is increased, some reading-impaired children experience difficulty in processing them. Further, this difficulty is not confined to sequencing tasks, but also occurs on discrimination at short ISI's. That these reading-impaired children performed equally poorly on TOJ and discrimination suggested to Tallal "that the rate of presentation of perceptual stimuli interferes with discrimination of the stimulus items to be processed" (Tallal, 1980) and consequently affects their TOJ performance. The author also notes, in an earlier study, that the language-impaired children who failed on TOJ were the ones that failed on discrimination of these syllables (only 2 out of 12 subjects passes on TOJ, and the same two on discrimination.). However, individual data for these subjects' performances on TOJ and discrimination with /bɑ/-/dɑ/ are not reported, thereby precluding the possibility of comparing their precise levels of performance on the two tasks. However, by this account,

secondary to (that is, an automatic consequence of) difficulties in discrimination. In other words, Tallal here abandoned the notion of a deficit in 'temporal analysis' for these reading impaired children.

However, we cannot always equate TOJ and discrimination. For while it is necessary to discriminate between items in order to be able to recall their order of presentation, discrimination itself entails phonetic coding/labeling merely to enable "same/different" judgments of the items to be discriminated. TOJ, by contrast, not only has a labeling requirement, but entails storage and recall of the items to be ordered. Now, the stimuli in Tallal's (1980) study were non-verbal complex tones which could perhaps be labeled (e.g. "high"/"low"), but could not be coded phonologically; if poor readers do indeed suffer from a deficit in phonological coding, they might be expected to have less trouble with the tones than with phonologically codable syllables. This advantage for noncodable stimuli would be more evident on TOJ than on discrimination, because TOJ makes more demands on a subject's phonological coding ability by way of identification and temporary storage of the stimulus items. Hence, TOJ is more vulnerable than discrimination to the weak phonological coding strategy, posited as characteristic of the poor reader. By this argument, we would expect greater similarity between poor readers' TOJ and discrimination performances on nonspeech than on speech, and this is precisely what has been found.

In the present study, poor readers performed significantly worse on TOJ than on discrimination, with the syllable pair /bɑ/-/dɑ/. This raises the question of a temporal processing deficit in poor readers. However, this effect was significant only at 100ms and 10 ms ISI's; the groups' performances did not differ at 50 ms ISI. One could hypothesize that their problem at these intervals could have arisen from their trying to use a phonetic coding strategy. Thus, poor readers' difficulties with phonological coding became evident only when their system was stressed i.e., under time constrained performance. This is consistent with the results obtained by Brady et al. (1983), who found poor readers' identification of verbal stimuli significantly worse than that of good readers under noisy presentation conditions, but not when these stimuli were presented without noise or were

non-speech. However, the reason for the lack of difference between the groups' performances at 50 ms is still unclear.

In conclusion then, poor readers suffer from a general deficit in phonetic coding that is exacerbated by time pressure. But, there is no evidence of any specifically temporal processing deficit. Taken together, poor readers' inferior performance on TOJ over discrimination with /bɑ/-/dɑ/, along with their weaker performance on the same as against good readers, and their lack of significant difference on discrimination with non-speech also in comparison with good readers, clearly implicates a phonological rather than an auditory deficit.

4.4 Are poor readers developmentally delayed?

The results of Experiment 4 failed to uphold the developmental lag hypothesis. Previous studies (Morrongiello, Robson, Best & Clifton, 1984; Nittrouer, 1992; Nittrouer & Studdert-Kennedy, 1987), have shown that younger (3-, 4- and 5-year old) children base their phonemic judgments of CVsyllable-initial fricatives on the formant transitions of the following vowel to a greater extent than do 7-year-old children or adults, who rely more on the fricative noise (see Introduction). If poor readers' difficulties stem from delayed development of phonetic processing skills, we might expect them (like the younger children in the studies just mentioned) to place more weight on vocalic transitions than on the fricative noise in fricative-vowel syllables, and so to show greater differences than the controls between their phoneme boundaries on the /ʃu-su/ continuum, as a function of the two fricative contexts (/ʃ/ and /s/) of the vocalic transitions. However, there were no significant differences between the crossover points of the two groups, for either transition type (/ʃ / vs. /s/), and the magnitude of the /ʃu/-/su/ crossover gap was almost equal in the two groups. Thus good and poor readers demonstrate a comparable sensitivity to variations in phonetic category conveyed by vocalic formant transitions. At the same time, poor readers' slopes were significantly shallower than those of good readers, a finding that fits neatly with our earlier explanation that phonetic similarity poses a problem for the poor

reader. Since /ʃu/ and /su/ differ only on a single feature (i.e., place), poor readers show greater confusion and uncertainty in their identification function of the same.

The results here are consistent then with those of Godfrey et al.(1981) and Werker and Tees (1987) who also showed that reading impaired subjects tend to be inconsistent in their phonetic judgments.

An overview of the relative performances of the good and poor readers on each of these tasks may be found in Table 17.

Table 17. Overview of the relative performances of good and poor readers on all tasks.

Experiment	Task	Good Readers vs Poor Readers
1	/ba/-/da/ TOJ (at short ISI's)	GR > PR
	/ba/-/da/ DISCR (at short ISI's)	GR > PR
	/ba/-/sa/ TOJ (at short ISI's)	GR = PR
	/ba/-/sa/ DISCR (at short ISI's)	GR = PR
	/da/-/ʃa/ TOJ (at short ISI's)	GR = PR
	/da/-/ʃa/ DISCR (at short ISI's)	GR = PR
2	/ba/-/da/ sinewave analogs DISCR (at short ISI's)	GR = PR
3	/seɪ-steɪ/: phoneme boundary	GR = PR
	: slopes	GR =PR
4	/ʃu-su/: phoneme boundary	GR = PR
	: slopes	GR >PR*

Note: GR= Good reader; PR= Poor reader.
TOJ= Temporal Order Judgment
DISCR = Discrimination
ISI = interstimulus interval
= : No significant difference
> :better than (i.e. fewer number of errors or * steeper slopes due to greater consistency of performance)

CHAPTER 5 : CONCLUSIONS AND IMPLICATIONS

5.1 Summary

In summary, poor readers, chosen for their weak performance on Tallal's /bɑ/-/dɑ/ TOJ task, did not display the "auditory temporal processing deficit" hypothesized by Tallal. These subjects did not differ from good readers on TOJ at short ISI's, when /bɑ/ and /dɑ/ were presented in more easily discriminable pairs, either /bɑ/-/sɑ/ or /dɑ/-/ʃɑ/. Moreover, they had no problem discriminating between acoustically similar non-speech sinewave analogs of the rapidly changing second and third formants of /bɑ/ and /dɑ/, although they were significantly worse than the good readers when they were asked to discriminate the corresponding full synthetic syllables. Finally, good and poor readers had similar identification functions on a /seɪ-steɪ/ continuum where a brief F_1 transition (40 ms) at vowel onset served as the cue to the presence of a stop consonant. However, the slopes of poor readers' identification functions were significantly shallower than that of good readers on a /ʃu-su/ categorical perception task that necessitated discriminating phonetically similar /su/ and /ʃu/. The current findings are consistent with the view that poor readers have normal auditory capacities, but have less well defined phonological categories than good readers and thereby support a phonological over an auditory account of these children's perceptual difficulties.

5.2 Directions for future research

The findings provide additional evidence for the existence of poorly defined (or "fuzzy") phonological categories in the impaired reader. The fact that the poor readers had problems discriminating easily-confused phonetically similar pairs of speech sounds (/bɑ/-/dɑ/ and /ʃu-su/), but none with more phonetically distinct pairs, /bɑ/-/sɑ/ and /dɑ/-/ʃɑ/, points to a lack of clarity in their phonological percepts. Future research might further test the hypothesis that poor readers have difficulty discriminating phonetically similar pairs by

systematically varying the degree of phonetic contrast within a syllable pair. For example, the initial sounds in the syllable pairs /bɑ/-/sɑ/, /bɑ/-/kɑ/ and /bɑ/-/pɑ/ share the feature "consonantal", but differ in three, two and one features, respectively. The phonetic similarity hypothesis would predict an increasing decrement in poor readers' performance with these stimuli as they represent a continuum of increasing phonetic similarity. Thus, a test of this hypothesis would entail selection of a group of poor readers who are significantly worse than otherwise appropriately matched good readers on the discrimination of /bɑ/and /dɑ/ at short ISI's, as they were in this study and in Tallal's, and replication of the task with different syllables presented in pairs that vary in phonetic discriminability.

The results of the present study invite testing of the "fuzzy" phonological categories hypothesis in yet another way: If poor readers' deficit is indeed speech-specific, as also suggested by previous findings on categorical perception tasks (Godfrey et al., 1981; Werker & Tees, 1987), one should expect systematic differences between the slopes of the identification functions in good and poor readers for speech, but not for non-speech. A possible line of investigation would be to compare the two groups on categorical perception tasks using synthetic speech continuua, for example, /bɑ-dɑ/ or /bɑ-pa/, and corresponding non-speech continuua made up of appropriate sinewave analogs. The expectation here would be one of systematic differences between good and poor readers in the slopes of their identification functions for speech, but not for non-speech continuua, since the identification of the latter does not call for the use of phonological labels. Furthermore, poor readers would be expected to show less consistency on between-category rather than within-category discrimination for speech compared to good readers. This would be evident from the lower peaks of their discrimination functions. There should, however, be no such differences between the groups on the corresponding non-speech tasks.

5.3 Implications for remedial reading instruction

Subtle phonological coding problems appear, then, to make it hard for the poor reader to discriminate among various phonemes. This is especially evident under demanding

conditions as is the case when speech sounds are presented in noise (Brady et al., 1983) or in phonetically-similar contexts (Brady et al., 1987). These subtle perceptual deficits pose a problem for the beginning reader, who must then struggle to learn the grapheme-to-phoneme correspondences essential to learning to read. Knowledge of children's abilities on such tasks involving the discrimination of syllable pairs differing on a single feature vs. more than one feature may thus serve as an evaluation tool for predicting their later reading success. Children deficient on such tasks, who are identified early, may be given systematic phoneme discrimination training using syllable pairs of increasing phonetic similarity, and therefore, of increasing difficulty. Such training would help the child to attend to small differences between syllables and so to clarify his/her phonological representations. Furthermore, because these deficits appear to surface primarily under demanding conditions, it is essential that the child be trained to transfer its skills to progressively more demanding phonological tasks, as with pseudowords or words of increasing length. Such gradual increase in the difficulty level (i.e. in terms of phonological complexity) of the training tasks may be a means of strengthening the child's mastery over the full range of phonemes in its language. In short, the results of this study have useful implications for the development of diagnostic and training material for remedial reading programs.

APPENDIX

Table A. Performance of good readers on training tasks with /bɑ/-/dɑ/: identification, discrimination at 400 ms ISI and temporal order judgment at 400 ms ISI.

SUBJECT	NUMBER OF TRIALS TO CRITERION*			NUMBER OF ERRORS TO CRITERION*		
	IDENT	DISCR400	TOJ400	IDENT	DISCR400	TOJ400
1	12	12	12	1	0	0
2	12	12	12	0	0	0
3	12	12	12	0	0	0
4	12	12	12	0	0	0
5	12	12	12	0	0	0
6	12	12	12	0	0	0
7	12	12	12	0	0	0
8	12	12	12	0	0	0
9	12	12	12	0	0	0
10	12	12	12	0	0	0
11	12	12	12	0	0	0
12	13	12	12	1	0	0
13	12	12	12	0	0	0
14	12	12	12	0	0	0
15	12	12	12	0	0	0
16	12	12	12	0	0	0
17	13	12	12	1	0	0
18	12	12	12	0	0	0
19	12	12	12	0	0	0
20	13	12	13	1	0	1
Mean	12.2	12	12.1	.2	0	.1
(SD)	(.4)	(0)	(.2)	(.4)	(0)	(.2)

Note:* Criterion of 12 correct out of 16 consecutive trials ($p<.001$, Binomial)
IDENT : Identification
DISCR400: Discrimination at 400ms ISI
TOJ400: Temporal Order Judgments at 400 ms ISI
(ISI = interstimulus interval)

Table B. Performance of poor readers on training tasks with /bɑ/-/dɑ/ : identification, discrimination at 400 ms ISI and temporal order judgment at 400 ms

SUBJECT	NUMBER OF TRIALS TO CRITERION*			NUMBER OF ERRORS TO CRITERION*		
	IDENT	DISCR400	TOJ400	IDENT	DISCR400	TOJ400
1	13	12	12	1	0	1
2	12	12	12	0	0	0
3	12	12	13	0	0	1
4	16	15	13	4	3	1
5	12	12	16	0	0	4
6	12	13	13	0	1	1
7	24	15	15	6	3	3
8	15	12	14	3	0	2
9	14	12	12	2	0	0
10	12	12	12	0	0	0
11	14	13	12	2	1	0
12	12	12	12	0	0	0
13	12	12	12	0	0	0
14	12	13	12	0	1	0
15	14	13	12	2	1	0
16	12	12	14	0	0	2
17	14	12	15	2	0	3
18	12	12	12	0	0	0
19	12	13	14	0	1	2
20	12	12	12	0	0	0
Mean	13.4	12.6	13.0	1.1	.6	1
(SD)	(2.8)	(.9)	(1.3)	(1.7)	(.9)	(1.3)

Note:* Criterion of 12 correct out of 16 consecutive trials ($p<.001$, Binomial)
IDENT : Identification
DISCR400: Discrimination at 400ms ISI
TOJ400: Temporal Order Judgments at 400 ms ISI
(ISI= interstimulus interval)

Table C. Error performance of good and poor readers on temporal ordering of /bɑ/-/dɑ/ under the three reduced ISI conditions: 100 ms, 50 ms, 10 ms.

	GOOD READERS			POOR READERS			
SUB	TOJ100	TOJ50	TOJ10	TOJ100	TOJ50	TOJ10	Σ
1	0	0	0	0	0	7	7
2	0	0	0	0	1	2	3
3	0	0	0	3	3	6	12
4	0	0	0	1	4	0	5
5	0	0	0	1	0	2	3
6	0	0	0	0	1	6	7
7	0	0	0	1	1	4	6
8	0	0	0	2	2	2	6
9	0	0	0	4	7	3	14
10	0	0	0	1	3	5	9
11	0	0	0	2	0	2	4
12	0	0	0	0	1	5	6
13	0	0	0	0	2	2	4
14	0	0	0	1	2	4	7
15	0	0	0	7	5	6	18
16	0	0	0	5	4	4	13
17	0	0	0	0	2	3	5
18	0	0	0	0	1	2	3
19	0	0	0	3	4	6	13
20	0	0	0	1	0	2	3
Mean	0	0	0	1.6	2.2	3.7	7.4 *
(SD)	(0)	(0)	(0)	(1.9)	(1.9)	(1.9)	(4.4)

Note: * Mean of total errors across all ISI's.
(ISI=interstimulus interval)

Table D. Error performance of good and poor readers on discrimination of /bɑ/-/dɑ/ under the three reduced ISI conditions: 100 ms, 50 ms, 10 ms.

	GOOD READERS			POOR READERS			
SUB	DIS100	DIS50	DIS10	DIS100	DIS50	DIS10	Σ
1	0	0	0	0	1	2	3
2	0	0	0	0	0	2	2
3	0	0	0	1	2	7	10
4	0	0	0	4	7	2	13
5	0	0	0	0	1	1	2
6	0	0	0	0	0	3	3
7	0	0	0	1	0	3	4
8	0	0	0	0	0	2	2
9	0	0	0	5	5	1	11
10	0	0	0	0	1	6	7
11	0	0	0	0	1	1	2
12	0	0	0	0	2	2	4
13	0	0	0	1	4	3	8
14	0	0	0	0	3	2	5
15	0	0	0	1	8	6	15
16	0	0	0	1	2	1	4
17	0	0	0	1	2	4	7
18	0	0	0	0	2	2	4
19	0	0	0	0	2	5	7
20	0	0	0	1	0	1	2
Mean	0	0	0	.8	2.2	2.8	5.8*
(SD)	(0)	(0)	(0)	(1.4)	(2.3)	(1.9)	(3.9)

Note: * Mean of total errors across al ISI's.
(ISI = interstimulus interval)

Table E. Performance of good readers on training tasks with non-speech sinewave patterns: identification and discrimination at 400 ms ISI.

SUBJECT	NUMBER OF TRIALS TO CRITERION*		NUMBER OF ERRORS TO CRITERION*		
	IDENT	DISCR400	IDENT	DISCR400	
1	30		12	11	0
2	18		13	6	1
3	26		16	7	4
4	22		12	6	0
5	32		12	11	0
6	16		12	4	0
7	25		12	6	0
8	16		30	4	9
9	26		16	8	4
10	35		12	15	0
11	16		13	4	1
12	33		13	12	1
13	16		14	4	2
14	16		24	4	6
15	16		26	4	7
16	13		12	1	0
17	16		24	4	7
18	16		12	4	0
19	18		13	5	1
20	28		12	8	0
Mean	21.7	15.5	6.4	2.2	
(SD)	(7.0)	(5.6)	(3.5)	(2.9)	

* Criterion of 12 correct out of 16 consecutive trials ($p<.001$, Binomial)
DISCR400 = Discrimination at 400 ms interstimulus interval.

Table F. Performance of poor readers on training tasks with non-speech sinewave patterns: identification and discrimination at 400 ms ISI.

SUBJECT	NUMBER OF TRIALS TO CRITERION*		NUMBER OF ERRORS TO CRITERION*	
	IDENT	DISCR400	IDENT	DISCR400
1	16	14	4	2
2	18	12	5	0
3	30	14	11	2
4	18	12	6	0
5	16	12	4	0
6	26	12	7	0
7	24	12	10	0
8	15	12	3	0
9	15	13	3	1
10	24	13	6	1
11	46	13	21	1
12	16	30	4	9
13	16	16	4	4
14	27	15	11	3
15	25	16	8	4
16	24	15	6	3
17	41	15	13	3
18	29	12	12	0
19	22	24	5	6
20	15	12	3	0
Mean	23.2	14.7	7.3	2.0
(SD)	(8.6)	(4.5)	(4.5)	(2.4)

Note:* Criterion of 12 correct out of 16 consecutive trials ($p<.001$, Binomial)
DISCR400 = Discrimination at 400 ms interstimulus interval.

Table G. Error performance of good and poor readers on non-speech discrimination under the three reduced ISI conditions: 100 ms, 50 ms, 10 ms.

SUBJECT	GOOD READERS			POOR READERS		
	DISCR100	DISCR 50	DISCR 10	DISCR 100	DISCR 50	DISCR 10
1	0	0	2	0	2	1
2	0	0	0	0	0	0
3	5	4	6	1	1	0
4	0	0	1	0	1	1
5	1	1	5	0	0	0
6	0	0	0	0	1	0
7	1	1	2	0	2	2
8	6	4	5	0	0	0
9	1	2	4	1	2	2
10	0	0	4	0	0	0
11	0	2	2	0	0	0
12	2	2	3	4	2	3
13	3	3	4	1	3	2
14	6	3	5	2	5	1
15	3	4	3	6	4	3
16	0	2	3	3	2	3
17	4	7	4	4	2	4
18	1	0	3	0	0	0
19	3	1	0	3	4	2
20	2	3	2	0	0	1
Mean:	1.9	2.0	2.9	1.3	1.6	1.3
(SD)	(2.0)	(1.9)	(1.8)	(1.8)	(1.5)	(1.3)
Mean of total errors across all ISI's		6.8			4.2	

(ISI = interstimulus interval)

Table H. Phoneme boundaries on /seI-steI/ continuum for good and poor readers, determined by probit analysis.

SUBJECT	GOOD READERS	POOR READERS
	(in Hz)	
1	463.375	441.605
2	327.890	426.523
3	391.119	336.247
4	461.282	455.104
5	423.465	361.772
6	379.675	418.700
7	442.296	410.165
8	414.641	351.916
9	389.441	388.568
10	370.046	486.943
11	347.600	426.040
12	371.576	365.782
13	333.147	365.739
14	420.466	422.365
15	382.216	367.908
16	427.572	442.035
17	396.065	408.314
18	433.079	375.077
19	368.099	359.167
20	417.897	302.261
Mean	398.05	395.61
(SD)	(39.1)	(45.5)

Table I. Slopes of psychometric functions on /seI-steI/ continuum, determined by probit analysis, for good and poor readers.

SUBJECT	SLOPES (Probit values X 1000/Hz)	
	GOOD READERS	POOR READERS
1	9.569	4.856
2	20.048	14.577
3	26.089	10.577
4	10.408	18.554
5	12.421	7.423
6	14.218	6.186
7	17.582	4.372
8	5.953	22.063
9	18.956	10.165
10	26.959	45.462
11	8.919	10.074
12	17.610	6.518
13	11.067	8.670
14	10.531	24.659
15	25.480	3.513
16	14.615	8.606
17	9.171	11.015
18	9.753	10.922
19	10.999	10.585
20	29.464	9.387
Mean	15.5	12.4
(SD)	(6.9)	(9.5)

Table J. Number of /steI/ responses out of a possible 90, on the /seI-steI/ continuum, for good and poor readers.

SUBJECT	NUMBER OF /steI/ RESPONSES	
	GOOD READERS	POOR READERS
1	55	49
2	28	48
3	41	30
4	55	54
5	48	36
6	39	46
7	51	45
8	45	33
9	41	40
10	36	43
11	33	48
12	37	37
13	30	36
14	47	47
15	39	40
16	48	51
17	42	44
18	48	37
19	36	34
20	46	24
Mean	42.3	41.1
(SD)	(7.7)	(7.7)

Table K. Phoneme boundaries on /ʃu-su/ continuum with (ʃ)-vowel, for good and poor readers, determined by probit analysis.

SUBJECT	GOOD READERS (in Hz)	POOR READERS
1	3466.05	3488.57
2	3321.88	3253.99
3	3352.09	3224.48
4	3505.14	3759.87
5	3708.99	3432.52
6	3322.66	3277.67
7	3616.64	3437.67
8	3418.65	3518.13
9	3465.32	3314.22
10	3297.72	3452.82
11	3222.84	3341.03
12	3270.74	3413.30
13	3130.22	3306.50
14	3179.18	3287.92
15	3188.39	3354.76
16	3408.41	3440.50
17	3824.21	3524.35
18	3242.57	3409.38
19	2577.70	3456.53
20		3688.88
Mean	3343.17	3419.15
(SD)	(260.5)	(136.6)

Table L. Slopes of psychometric functions on /ʃu-su/ continuum with /ʃ/-vowel, for good and poor reader, determined by probit analysis.

SUBJECT	SLOPES (Probit values X 1000/Hz)	
	GOOD READERS	POOR READERS
1	3.030	3.282
2	6.100	3.007
3	3.679	5.365
4	2.855	2.502
5	1.887	2.825
6	5.405	3.212
7	7.776	2.161
8	4.648	2.479
9	4.239	2.615
10	5.160	3.700
11	5.265	4.748
12	3.703	3.592
13	6.666	2.927
14	3.357	5.402
15	3.858	1.795
16	5.090	2.423
17	2.223	1.399
18	5.227	3.161
19	1.607	2.367
20		2.007
Mean	4.3	3.04
(SD)	(1.6)	(1.1)

Table M. Number of /su/ responses out of a possible 180 on /ʃu-su/ continuum, with /ʃ/-vowel, for good and poor readers.

SUBJECT	NUMBER OF /su/ RESPONSES	
	GOOD READERS	POOR READERS
1	22	21
2	29	33
3	28	31
4	21	12
5	16	24
6	29	31
7	05	25
8	24	23
9	23	29
10	30	23
11	34	28
12	32	25
13	38	29
14	35	31
15	36	29
16	24	24
17	11	25
18	29	25
19	62	24
20		16
Mean	27.8	25.4
(SD)	(11.9)	(5.1)

Table N. Phoneme boundaries on /ʃu-su/ continuum with (s)-vowel, for good and poor readers, determined by probit analysis.

SUBJECT	GOOD READERS (in Hz)	POOR READERS
1	2864.169	2971.446
2	3137.899	2555.949
3	2016.103	3095.567
4	3110.131	2638.062
5	2603.249	2979.186
6	2193.473	2356.132
7	1619.317	2896.407
8	2486.103	3008.488
9	3058.465	2612.906
10	2511.244	2054.310
11	2485.700	2006.167
12	2657.080	2430.407
13	2669.339	1728.040
14	2418.214	2143.184
15	1545.558	2372.263
16	2957.370	2622.573
17	2681.841	2679.953
18	2575.984	2840.065
19	2358.309	2515.399
20		2370.853
Mean	2523.66	2543.86
(SD)	(445.2)	(370.4)

Table O. Slopes of psychometric functions on /ʃu-su/ continuum with /s/-vowel, for good and poor readers, determined by probit analysis.

SUBJECT	SLOPES (Probit values X 1000/Hz)	
	GOOD READERS	POOR READERS
1	2.199	3.099
2	4.243	2.905
3	1.550	6.754
4	4.622	1.120
5	1.620	5.900
6	2.068	1.245
7	.911	2.388
8	1.228	2.470
9	2.976	2.071
10	2.960	2.784
11	2.218	1.141
12	2.793	1.383
13	3.652	1.233
14	15.783	1.379
15	1.135	1.680
16	4.583	2.688
17	1.972	1.180
18	2.161	2.889
19	1.605	.935
20		5.833
Mean	3.17	2.55
(SD)	(3.3)	(1.7)

Table P. Number of /su/ responses out of a possible 180 on /ʃu-su/ continuum, with /s/-vowel, for good and poor readers.

SUBJECT	NUMBER OF /su/ RESPONSES	
	GOOD READERS	POOR READERS
1	51	46
2	39	66
3	79	40
4	39	57
5	61	46
6	78	67
7	78	50
8	63	43
9	41	62
10	68	84
11	68	75
12	61	66
13	61	81
14	83	74
15	82	70
16	47	63
17	59	56
18	64	52
19	70	59
20		85
Mean	62.7	62.1
(SD)	(14.2)	(13.5)

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