Do Temporal Processing Deficits Cause Phonological Processing Problems?

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This study tested the hypothesis that temporal processing deficits underlie phonological processing problems. The subjects were children aged 8 to 10 years (N = 110) who were separated into 2 groups on the basis of whether their reading scores were normal or poor. As predicted by many earlier studies, children with poor reading scores demonstrate poor abilities on tests of phonological awareness, as well as on 2 other language tasks that depend on phonological processing. Two specific tests of the temporal processing hypothesis were conducted. Children in both groups were tested (a) on their abilities to recall sequences of nonspeech tones presented at various rates and (b) on their abilities to make phonetic decisions using brief and transitional properties of the speech signal, especially formant transitions (the purported “trouble spot” in the speech signal for children with phonological processing problems). The children with poor phonological processing abilities showed no special difficulty recalling rapidly presented nonspeech stimuli, and, in their phonetic decisions, they were able to use brief and transitional signal properties, including formant transitions, at least as well as other children. Therefore, no evidence was found to support the hypothesis that temporal processing deficits cause phonological processing problems.

KEY WORDS: temporal processing deficits, phonological processing problems, speech perception

Why is it that some children who are developing normally in most respects nonetheless encounter difficulty learning language? This is the central question facing researchers and clinicians interested in ameliorating the problems of children with language-learning problems. One answer offered to this question is that these children have difficulty processing rapidly presented signals. For example, Tallal, Miller, and Fitch (1993) state “Research is now showing that dysfunction of higher level speech processing, necessary for normal language and reading development, may result from difficulties in the processing of basic sensory information entering the nervous system in rapid succession” (p. 27). This notion has been labeled a “temporal processing deficit” (Merzenich et al., 1996), and we use that term to designate the hypothesis here. However, a number of perceptual processing abilities have been classified as “temporal processing” in various studies, as Farmer and Klein (1995) describe, even though some do not meet any reasonable definition of the term, as Studdert-Kennedy and Mody (1995) explain. In this work the term “temporal processing” refers strictly to the processing of temporal properties of the signal, in particular, rate of presentation. Specifically the hypothesis is that deficits in processing rapidly arriving information make it difficult for children with this problem to apprehend phonological structure in the acoustic speech stream. In 1984, Tallal wrote "As data accumulate in the field, they continue to support the hypothesis that phonetic processing deficits themselves may result from inefficiencies or deficiencies of the processing mechanisms essential for processing the rapidly changing acoustic spectra which characterize the ongoing speech stream" (p. 168).

Certainly, a large body of data indicates that children and adults with a variety of language problems, especially reading, have difficulty with phonological processing (e.g., Bradley & Bryant, 1983; Fox & Routh, 1980; Gathercole & Baddeley, 1990; James, Van Steenbrugge, & Chiveralls, 1994; Mody, Studdert-Kennedy, & Brady, 1997; Pennington, Van Orden, Smith, Green, & Haith, 1990; Pratt & Brady, 1988; Wagner & Torgeson, 1987). The term "phonological processing" refers to any task that requires awareness and/or manipulation of the phonological structure of language, as well as tasks that require the use of a phonological code for representing language. For example, Fox and Routh (1980) found that first graders with reading problems had difficulty segmenting syllables into phonemes, although their normal-reading peers did not. This difference in phonological processing abilities between good and poor readers does not disappear with age: Pennington et al. (1990) demonstrated that adult dyslexics were poorer than normal adult readers on pig-Latin tasks. Similarly, both children and adults categorized as poor readers have more difficulty recalling strings of linguistic items (usually words or digits) than do normal readers (e.g., Brady, Shankweiler, & Mann, 1983; Hall, Wilson, Humphreys, Tinzmann, & Bowyer, 1983; Mann & Liberman, 1984; Pennington et al., 1990; Spring & Perry, 1983). These investigators conclude that being able to use a phonological code to store items in working memory allows for the retention of long strings of linguistic materials. It is this relation that is proposed to explain the deficit in comprehension of sentences with complex syntax commonly observed for poor readers (Bar-Shalom, Crain, & Shankweiler, 1993; Byrne, 1981; Smith, Mann, & Shankweiler, 1986; Stein, Cairns, & Zurif, 1984). Poor readers clearly have problems accessing phonological structure in the speech signal, and using that structure to code linguistic materials in working memory. Consequently, they may have difficulty storing long sequences of words in working memory, as is needed for the comprehension of sentences with complex syntax. Thus, there is evidence from many different investigators that phonological processing problems may explain other language deficits, including reading. Not as widely accepted is the hypothesis that temporal processing deficits cause the phonological processing problems. The goal of the current study was to test that hypothesis.

The first consideration in designing a test of this hypothesis was the selection of participants. For this study, all participants needed to meet certain general criteria. They had to have normal hearing, normal nonverbal cognitive abilities, and no health history (prenatal or perinatal) that would put them at risk for a neurological problem. Children were then put into two categories based on their scores on the reading subtest of the Wide Range Achievement Test–Revised. Those children with standard scores better than 85 were considered to have normal reading abilities, and those children with scores of 85 or lower were considered to have poor reading abilities. Based on the demonstrated strong relations between reading and phonological processing abilities described above, we were confident that children in the two groups would differ significantly in phonological processing abilities. In particular, the relation between reading and phonological processing abilities has often been examined using phonological awareness tasks, so it was strongly expected that measures of this kind would especially differentiate normal and poor readers. Thus, appropriate experimental groups were obtained without specifically recruiting certain participants. A serendipitous benefit accrued from the method used: By including a large sample of children without specific selection criteria, experimenters were unaware during testing of which group any particular child would fit.

Another consideration in designing this study was the selection of tasks. In general, tasks were selected either to document differences in language abilities (specifically those based on phonological processing) between the two groups of children or to test explicitly the temporal processing hypothesis. For each task, several levels (usually three) of difficulty were incorporated into the procedures themselves. This approach was intended to avoid having any task that was generally too easy, so all children would score extremely well, or generally too hard, so all children would make numerous errors (i.e., traditional ceiling and floor effects).

Tests of Language Abilities

Three tests of phonological awareness were administered based on evidence from Stanovich, Cunningham, and Cramer (1984) about when normally developing children acquire each kind of skill. The easiest task was one in which children simply had to select the word (out of three) that had the same initial consonant as a target word. The task of intermediate difficulty was one in which children had to remove a designated segment from a nonsense word to make a real word. The hardest phonological awareness task was pig Latin: children had to remove a segment, move it to a different part of the word and combine it with a rime. One test of phonological coding in working memory was administered. It was similar to the test used by Brady et al. (1983), and required the children to recall strings of rhyming and nonrhyming words. However, strings of three lengths were used: four, five, and six words. Thus the difficulty of the task was again varied. Children's comprehension of complex syntax was evaluated by having children act out (with small objects) sentences with various sorts of embedded clauses. The combination of these tasks (phonological awareness, phonological coding in working memory, and sentence comprehension) provided us with evidence of how children in our two groups differed in language abilities involving phonological processing.

Tests of the Temporal Processing Hypothesis

At the heart of the development of the temporal processing hypothesis has been a task in which series of nonspeech, steady-state tones are presented at various rates. Children with language learning problems, including reading problems, are reported to have more difficulty than other children recalling the order of these tones, *when they are presented rapidly*. Specifically, when steady-state tones of 100 ms or shorter duration are presented with interstimulus intervals (ISIs) of 150 ms or less, children with language learning problems are reported to make more recall errors than children developing language normally (e.g., Tallal, 1980a, 1994; Tallal & Piercy, 1973a, 1973b, 1974; Tallal & Stark, 1982; Tallal, Stark, Kallman, & Mellits, 1981). These results provide the primary evidence for the position that children with language learning problems show "...poor performances at identifying or sequencing short-duration stimuli presented in rapid succession" (Merzenich et al., 1996, p. 77). Thus, we used this sequencing task. However, we did modify the task slightly from what was used in the early tests of this hypothesis. In those early studies (reviewed by Tallal, 1980b), sequences of two tones were presented with various length ISIs, or longer sequences were presented with just one, fairly long ISI. Consequently, the manipulations of ISI and sequence length were never crossed experimentally. In the current work, we did just that: presented sequences of two, three, or four tones with various ISIs. In this way, the level of difficulty was varied more than it had been in previous experiments.

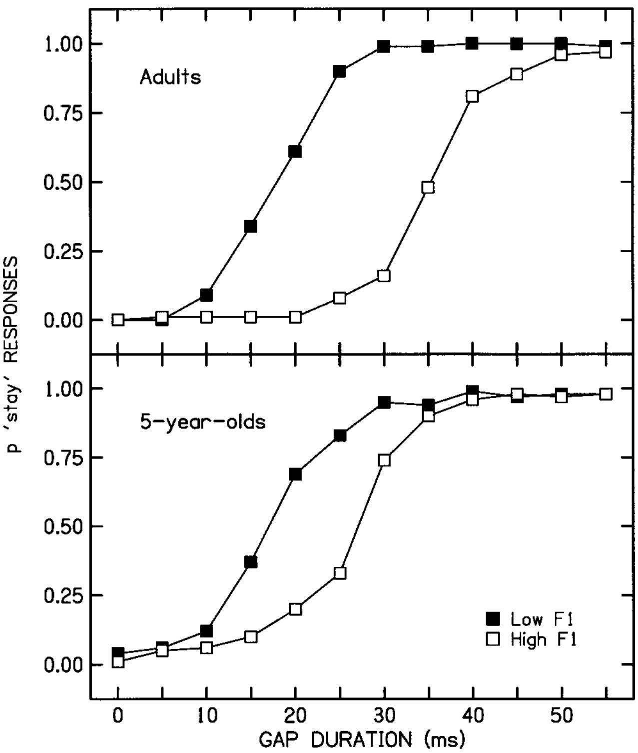
The second kind of task used to test the temporal processing hypothesis was speech perception. The decision to use this task was based on the hypothesized relation between temporal processing deficits and phonological processing problems described by Tallal and colleagues. These investigators propose that temporal processing deficits have their effect on phonological processing problems at the level of speech perception. For example, Tallal et al. (1996) wrote "Specifically, language-learning impaired children commonly cannot identify fast elements embedded in ongoing speech that have durations in the range of a few tens of milliseconds, a critical time frame over which many phonetic contrasts are signaled" (p. 81). Often these investigators describe the speech signal as consisting of long steady-state vowel regions, interspersed with briefer regions of formant transitions that correspond to the consonants, particularly stop consonants. For example, Tallal and Piercy (1978) describe the speech signal this way:

> The essential cue for the perception of vowels is the steady-state frequencies of the first three formants which are relatively long duration (e.g., 250 ms). The essential cue for stop-consonants differs from that for vowels in two important respects: it is briefer in duration (c. 50 ms) and the critical formants are not steady-state but transitional in character. (p. 71)

The brief and transitional character of formant transitions associated with stop consonants is highlighted frequently in the reports of Tallal and colleagues (e.g., Tallal, 1980a, 1980b, 1994; Tallal & Piercy, 1974, 1975; Tallal & Stark, 1981; Tallal et al., 1996). However, as Tallal and Piercy (1975) emphasize, the conclusion reached by this group is that "...it is the brevity not the transitional character of this component [the formant transition] of synthesized consonants which results in the impaired perception of children [with language learning impairments]" (p. 73). Thus the specific language skill purportedly affected by temporal processing deficits is speech perception, that is, the child's ability to process brief properties of the signal, such as formant transitions. In turn, this speech perception deficit gives rise to difficulty apprehending phonological structure. Accordingly, three tests of speech perception were designed to examine the abilities of children in this study to use formant transitions and other kinds of brief acoustic properties in phonetic decisions. If the temporal processing hypothesis is valid, children with poor phonological processing abilities should use these brief cues less than other children in making phonetic decisions.

In all three speech perception experiments, one acoustic cue was varied in multiple steps along a continuum extending from a setting appropriate for one response label to a setting appropriate for the other label. The other cue was set using binary values: it was simply appropriate for one of the two response labels. A labeling task was used in which listeners hear one stimulus at a time, and must assign one of two phonetic labels to it. Because multiple tokens of each stimulus are presented to the listeners, the probability of each label at each stimulus step is obtained for both settings of the binary cue, as shown in Figure 1. This figure displays labeling functions for adults and five-year-olds for "say" versus "stay" stimuli (Nittrouer, 1992), where the continuous cue is gap duration and the binary cue is F1-onset frequency. From plots such as this one, obtained for individual listeners, we may estimate the extent to which labeling responses were based on the continuous and the binary cues. If a listener was simply guessing at each response, the labeling functions would be flat across the plot, with all points at 0.50. If responses were largely based on the continuous cue, and hardly at all on the binary cue, then the functions would be steep (as is characteristic of categorical perception), and not separated very much based on the binary cue (indicating that little attention was paid to that cue). On the other hand, if responses were largely based on the binary cue and hardly at all on the continuous cue, then the functions would be flat and close to either the 0.00 or 1.00 levels, depending on the setting of the binary cue. Thus, the slope of the functions and separation between the functions indicates the extent to which each cue was used in the phonetic judgment. In this study, the labeling functions of the children with normal and poor phonological processing abilities were analyzed to ascertain the extent to which each group based their responses on formant transitions and on the other cue. If children with poor phonological processing abilities have difficulty processing formant transitions or other brief acoustic cues, those cues should not be used to any great extent in their phonetic decisions. Put simply, one cannot base responses on a cue that one cannot discern.

Figure 1. Labeling functions for adults and 5-year-olds for /seɪ/ versus /steɪ/ stimuli. The continuous cue was the gap duration, so that cue is represented on the *x* axis. The steepness of the functions indicates the extent to which phonetic judgments of /seɪ/ or /steɪ/ were based on that cue. The binary cue was the onset frequency of F1. The separation in functions indicates the extent to which phonetic judgments were based on that cue (from Nittrouer, 1992).



Two sets of stimuli each paired two kinds of brief acoustic cues. In both sets, formant transitions of 40 ms or less varied across the stimuli, as well as another brief cue that did not involve spectral change. The first set of stimuli examined the voicing distinction /dɑ/ versus /tɑ/. The manipulated cues were the duration of the first formant (F1) transition and the spectrum of a 10-ms release burst. In these stimuli, the longest F1 transition was 40 ms (most /dɑ/-like), but was cut back in nine 5-ms steps until there was no transition (most /tɑ/-like). Thus, this cue was continuous. Natural 10-ms bursts from a speaker saying *da* and *ta* served as the binary cue. Tallal and Stark (1981) reported that children with language learning impairments had more difficulty discriminating synthetic versions of /dɑ/ and /tɑ/ than did children with normal language, presumably due to the problems children with language learning impairments face processing formant transitions. Accordingly, the children in this experiment with poor phonological processing abilities were expected to show much shallower functions than the children with normal phonological processing abilities, indicating that the children with poor phonological processing abilities used formant transitions less in making voicing decisions. At the same time, little separation between functions depending on the burst was expected for children with poor phonological processing abilities in this study. That result would be consistent with the notion that these children are unable to use any brief cue in phonetic decisions. In sum, we would expect children with poor phonological processing abilities to show functions indicative of guessing (i.e., flat and at the 50% point) if temporal processing deficits underlie their language difficulties.

The second set of stimuli involved the perception of a stop closure following an /s/ (/seɪ/ versus /steɪ/). The cues to this distinction were the onset frequency of the F1 transition and the duration of the silent gap between the /s/ noise and the vocalic portion. The results shown in Figure 1 are from a study using these same stimuli. Tallal and Stark (1981) found no significant differences in performance between children with normal language and those with language learning impairments for synthetic versions of /sɑ/ versus /stɑ/, although this contrast gave both groups the most difficulty of any of the many contrasts tested. In that study, however, there were no formant transitions at the onset of voicing, a condition that would make these stimuli perceptually ambiguous and preclude the use of these stimuli specifically to test the temporal processing hypothesis. Experiments by others (Best, Morrongiello, & Robson, 1981; Morrongiello, Robson, Best, & Clifton, 1984; Nittrouer, 1992) have shown that the onset frequency of F1 (lower for /steɪ/ than for /seɪ/) is a salient cue to this distinction. According to the temporal processing hypothesis, children with any language problem, including poor phonological processing abilities, should not use the F1 transition as much as children with normal language (if they use it at all) because they are simply unable to process the information. In this experiment, F1 onset was the binary cue, so there should have been less separation between functions for the children with poor phonological processing abilities than between functions for the children with normal phonological processing abilities. At the same time, children with poor phonological processing abilities should require longer gaps to label stimuli as "stay," rather than "say," so we might expect labeling functions for these children to be shifted to longer gaps (i.e., to the right on Figure 1). In sum, the labeling functions of children with poor phonological processing abilities for these stimuli should show little separation based on the F1 onset, but should be generally located at longer gap durations than those of children with normal phonological processing abilities.

One other set of stimuli was used to examine differences in speech perception between children with normal and poor phonological processing abilities. A series of experiments has consistently demonstrated a developmental change in the extent to which formant transitions and fricative-noise spectra are used in the labeling of syllable-initial /s/ and /ʃ/: children use formant transitions more and fricative-noise spectra less than adults (Nittrouer, 1992, 1996a; Nittrouer & Miller, 1997; Nittrouer, Miller, Crowther, & Manhart, in press; Nittrouer & Studdert-Kennedy, 1987). Thus it seemed worthwhile to compare labeling of fricative-vowel syllables for children with normal and poor phonological processing abilities. The very cue that the temporal processing hypothesis would predict children with phonological processing problems would *not* be able to use (formant transitions) is precisely the cue that a developmental delay account of these problems would predict they would use. The continuous cue in this experiment was the center frequency of synthetic fricative noises. Vocalic portions were separated from natural samples of /sɑ/, /ʃɑ/, /su/, and /ʃu/, and recombined with the synthetic noises. Thus, the formant transitions of these vocalic portions (appropriate for /s/ or /ʃ/) formed the binary cue. If children with poor phonological processing abilities rely less on formant transitions than other children in making phonetic decisions, there should be less separation between their labeling functions than between those of the children with normal phonological processing abilities. A particularly attractive aspect of this experiment was that the fricative noises (the other cue) were steady state and 150 ms in duration; that is, they were neither brief nor transitional. Therefore, according to the temporal processing deficit account of language learning problems, children with such disorders should rely heavily on the noises themselves for decisions of fricative identity (because it is the only acoustic property they can properly discern), so their labeling functions should be as steep as (or steeper than) those of children with normal language. Again a developmental delay account of phonological processing problems would predict precisely the opposite result: children with such problems should rely less on these noises than children with normal phonological processing abilities. Evidence for this account would be provided if children with phonological processing problems demonstrated shallower labeling functions than children with normal phonological processing abilities.

In summary, the purpose of this study was to test the hypothesis that temporal processing deficits underlie phonological processing problems. To that end, two kinds of tasks were designed: tasks that evaluated language differences between children with normal and poor phonological processing abilities and tasks that explicitly tested the hypothesis that temporal processing deficits account for phonological processing problems.

Method

Participants

Children between the ages of 8 and 10 years were recruited through the Omaha Public Schools. To participate, children had to meet several criteria. First, they had to pass a hearing screening of the pure tones of 0.5, 1.0, 2.0, 4.0, and 6.0 kHz presented at 25 dB HL (ANSI, 1989). They had to have normal tympanograms. They had to score at or better than one standard deviation below the mean on the Block Design of the Wechsler Intelligence Scale for Children–III (WISC–III; Wechsler, 1991). This subtest has a mean of 10 and a standard deviation of 3. Children also had to score at or better than the 30th percentile on the Sounds-in-Words subtest of the Goldman-Fristoe Test of Articulation (Goldman & Fristoe, 1986). English had to be the only language spoken in the home. Children had to have been full-term births with normal deliveries and no serious health problems since their births. A total of 110 children were recruited who met these criteria.

The reading subtest of the Wide Range Achievement Test–Revised (WRAT–R; Jastak & Wilkinson, 1984) was used to evaluate the reading abilities of these children and to assign them to either the "normal" or "poor" phonological processing group (NPP or PPP). Children who scored better than one standard deviation below the mean were assigned to the NPP group. Children who scored at or greater than one standard deviation below the mean were assigned to the PPP group. Dividing groups in this way is similar to (or stricter than) procedures of other studies. For example, Reed (1989) divided children into two groups based on the reading subtest of the WRAT–R in a test of the temporal processing hypothesis, but classified children as poor readers if they scored at or below the 22nd percentile, which corresponds to a standard score of 88. In this study, 93 children were in the NPP group, and 17 were in the PPP group. These proportions are precisely what would be expected in the population as a whole; that is, nearly 16% of these children had reading abilities more than one standard deviation below the mean. Actual means (and standard deviations), given in standard scores, for the two groups in this study on the reading subtest of the WRAT–R were 107.9 (11.9) for the NPP group and 76.8 (8.3) for the PPP group. This mean score for the PPP group indicates that these children were, on average, 2 years behind grade level in reading abilities. Mean scores (and standard deviations) on the Block Design subtest of the WISC–III were 11.5 (2.9) for the NPP group and 9.6 (2.6) for the PPP group. Mean percentages (and standard deviations) on the the Sounds-in-Words subtest of the Goldman-Fristoe Test of Articulation were 96.0 (10.6) for the NPP group and 95.1 (16.2) for the PPP group. Thus, children in both groups had normal nonverbal cognitive abilities and motor control for speech, as measured by these two standardized tests. Regarding articulation abilities, it is important to note that the Goldman-Fristoe Test of Articulation does not tax production abilities. There is some evidence that children with phonological processing problems have production difficulties on more difficult tasks, such as repeating pseudowords (e.g., Brady, Poggie, & Rapala, 1989). However, speech production is not the focus of this study. The purpose of using the Goldman-Fristoe Test of Articulation in this context was to ensure that there were no motor control problems for children in the PPP group that might be viewed as affecting the development of phonological representations.

Equipment and Materials

All testing took place in a sound-attenuated booth. Hearing was screened and tympanograms were obtained with a Welch Allyn TM262 audiometer/tympanometer with TDH-39 earphones. For the phonological awareness and sentence comprehension tasks, recorded stimuli were presented with a Nakamichi MR-2 audiocassette player, a Tascam PA-30B amplifier, and a Realistic speaker. For the working memory, temporal processing, and speech perception tasks, stimuli were stored on a computer. Presentation of stimuli and recording of the responses in these tasks were controlled by a computer. A Data Translation 2801A digital-to-analog converter, a Frequency Devices 901F analog filter, a Crown D-75 amplifier, and AKG 141 headphones were used to present the stimuli to participants in these tasks. Stimuli in all experiments were presented at a peak intensity level of 70 dB SPL. For the temporal processing task, a board 24×8 inches with two buttons on it was used. This board had two handles on either side of the buttons and was connected to the computer. For the working memory task, pictures 3×3 inches were used. For the speech perception tasks, pictures 8×8 inches were used. In these last three tasks, displays of cartoon characters were presented on a color-graphics monitor after each block of stimuli as a reward and to indicate that another block was completed.

Stimuli and Procedures

Phonological Awareness

Three tasks of phonological awareness were used. The first (and developmentally easiest) was one obtained from A. Fowler at Wesleyan University in Connecticut. This task is one in which children must decide which word, out of three, begins with the same initial consonant as a target word, and is termed the initial-consonant-the-same task. This task is similar to the one reported by Stanovich et al. (1984), except that some of the words have consonant clusters at the beginning, making it slightly more difficult than what Stanovich et al. used. There were 24 items in this task, and these are shown in Appendix A.

The other two tasks examined skills that would be expected to be learned at slightly older ages and came from B. Pennington at the University of Denver. The phoneme deletion task had 32 items and required that the child provide the word that would result if a specified segment was removed from a nonsense item. This task was considered more difficult than the first because the child not only had to access the phonological structure of an item, but remove one segment from that structure. The pig-Latin task was considered the most difficult because the child had to remove a segment from one part of the item and synthesize a new syllable with that segment. One aspect of this task that differed from traditional pig Latin was that children were instructed to move only the first segment of consonant clusters, rather than the entire cluster. There were 48 items in this task. All children were asked if they had any experience with pig Latin, and none of these children reported ever having experience with it. Thus, all children came to the task with no prior experience. The items on the phoneme deletion and pig-Latin tasks are provided in Appendixes B and C, respectively.

For all three tasks, training was provided in which the child received feedback about the response given. Once testing started, no feedback was provided. The use of recorded materials decreased the possibility of experimenter bias being introduced. In all three phonological processing tasks, the number of items correct was the dependent measure.

Working Memory for Linguistic Materials

Stimuli and procedures for this task were similar to those of several other studies on the serial recall of linguistic materials (e.g., Brady et al., 1983). Both rhyming and nonrhyming consonant-vowel-consonant nouns were used. The four-word lists consisted of the words *dog*, *coat*, *ham*, *rake* (nonrhyming) and *hat*, *cat*, *mat*, *rat* (rhyming). The words *ball* and *bat* (nonrhyming and rhyming, respectively) were added to create the five-word lists. The words *pack* and *gnat* (nonrhyming and rhyming, respectively) were added to create the six-word lists. Thus, there were six kinds of lists presented: two rhyming conditions × three list lengths. Four-word lists were presented first, followed by five-word then six-word lists. The order of presentation of the rhyming and nonrhyming lists at each list length was randomized across participants. For each presentation of each list, the order of the words was randomized by the program. Words were presented at the rate of one per second. Because the words were all roughly 600 ms in length, the ISI was always roughly 400 ms, longer than ISIs at which children with language learning impairments are reported to encounter difficulty (e.g., Tallal, 1980b).

A child listened to a list and then rearranged the pictures to replicate the order heard. Ten presentations of each kind of list (nonrhyming or rhyming, at each list length) were presented as separate blocks. Before testing, children were provided with five practice lists of rhyming or nonrhyming letters, depending on whether the list that was about to be presented contained rhyming or nonrhyming words. The experimenter listened to the presentation of the practice lists and then removed the headphones so that the order of the words presented during testing was not known. The experimenter wrote down the order of the pictures after the child rearranged them, using the first letter of each word only (to save time). These lists were then compared to the lists of word orders actually presented, which were generated by the program anew for each participant. The mean number of errors across each list position for each kind of list was used in further analysis. In this case, using the mean instead of the sum allowed for comparison across list lengths.

Comprehension of Complex Syntax

The stimuli and procedures used in this task were adapted from Smith, Macaruso, Shankweiler, and Crain (1989). Five sets of stimuli were developed, consisting of five sentences each. All five sentences in each set could be enacted using the same set of materials. For this task, small toys that could be manipulated easily by a child were used. Four of the five sentences in each set were constructed with relative clauses. In these sentences, the interaction of two animate nouns is described, as well as another action involving an inanimate object. All sentences represented possible events. The four kinds of clause structures, with examples of each, are listed below. These sentence types are classified by a two-letter code ("S" for subject; "O" for object), and these codes indicate the roles (in the main and relative clauses, respectively) of the noun occupying the "empty" position in the relative clause. For example, in the OS sentence below, *the bear* is the noun for the empty position in the relative clause. The "O" indicates the role of *the bear* in the main clause; the "S" indicates the role of *the bear* in the relative clause. The noun phrase whose roles are described is italicized in the examples below.

SS: *The bear* who wore a hat chased the dog.

SO: *The dog* that the bear chased wore a hat.

OS: The dog chased *the bear* who wore a hat.

OO: The bear chased *the dog* that a hat was on.

The fifth sentence in each set consisted of cojoined clauses. For the examples above, the fifth sentence was "The dog chased the bear and wore a hat." The other four sets of sentences are provided in Appendix D.

Before testing, children were provided with a demonstration of what was expected of them. This demonstration consisted of one set of sentences, of the types described above, acted out by the experimenter after the sentence was heard. Next, the child was provided with four practice sentences: three with no relative or cojoined clauses, and one with cojoined clauses. This practice provided an opportunity to act out what was heard. Finally, the five sets of sentences were presented. Each set had different objects associated with it. The experimenter scored whether the child had acted out the sentence correctly or not. The total number of errors to each kind of sentence was used for further analysis.

Temporal Processing

Two sinusoids were generated for this experiment, each 75 ms in duration. One was 800 Hz and the other was 1200 Hz, and both had 5-ms on/off ramps. Werner

(1992) reported mean difference limens for 12-month-olds of 36 Hz for standard tones of 1000 Hz, so we concluded that a frequency difference of 400 Hz should be easily discriminated by all children by 8 years of age.

The use of sinusoids meant that these stimuli differed slightly from those used in earlier experiments testing the temporal processing deficit hypothesis. Traditionally, nonspeech tones created on a speech synthesizer that consist of broad-band spectra with harmonic structure and resonant poles at designated frequencies have been used (see in particular Tallal & Piercy, 1974, for a description of stimuli). Consequently, those tones are exactly like vowels produced by a human vocal tract, but the poles are not those of any English vowel. The reason for synthesizing nonspeech stimuli that way was never explained in the published work of Tallal and her colleagues. However, the character of the nonspeech stimuli used in this temporal processing task should not be essential to a test of the theoretical position. The hypothesis proposes that children with language learning impairments have difficulty processing rapidly presented information, and this difficulty is not specific to verbal materials. It is never suggested by Tallal and colleagues that the perceptual problem of these children is specific to spectrally complex signals. In fact, if these temporal processing limitations were only observed for complex spectral stimuli, such evidence would run counter to the proposal. That is, it could then be proposed that the difficulty encountered by children with language learning impairments involves a problem in the spectral, rather than the temporal, domain.

Procedures for this task were similar to those described as part of the "Repetition Test" in several papers by Tallal and colleagues. (Tallal, 1980b, provides the most detailed account.) First, the board was placed in front of the child, and the child was instructed to hold the handles until after the tone(s) were heard. Then the child was introduced to Tone 1. Whether Tone 1 was the 800-Hz or the 1200-Hz tone varied across children randomly. After the child had listened to and pressed the button corresponding to this tone ten times, Tone 2 was presented and the same familiarity procedure followed. Next, the two tones were presented one at a time in random order, and the child had to push the corresponding button. In this phase of training, feedback was provided in the form of hearing the tone that corresponded to the button pressed *after* it was pressed. In this way, the child could compare the target tone with the tone corresponding to the button that was pressed to determine whether the correct response was made. After six consecutive correct responses, the next training phase was introduced. This phase was the same as the one just previous, except that the child did not hear the tone after the button was pressed. If the child made an error, the experimenter explained it and played the target tone again. Again, six consecutive correct responses were required before the next training phase. In the next and final training phase, the child heard a series of two tones with an ISI of 320 ms. The child had to press the buttons in the order corresponding to the order heard. The experimenter provided feedback as to the correctness of the response and played the sequence again if an error was made. When the child had given six consecutive correct responses, testing began. Again, the experimenter listened under headphones to the presentation of tones during practice and then removed her headphones for testing.

In the first block of testing, series of two tones were presented with an ISI of 320 ms. No feedback was provided to the child from this point forward. The program randomized which of the four possible two-element patterns was presented and recorded whether the child's response was correct. Ten trials of two tones at this ISI constituted one block. The second block consisted of two-tone sequences with an ISI of 160 ms. Testing continued in this way for the two-tone sequences for blocks with ISIs of 80 ms, 40 ms, and 20 ms. Pilot testing had shown that even children learning language normally had great difficulty with ISIs shorter than 20 ms, so shorter ISIs were not used. However, ISIs of 20 ms should have been short enough to reveal any difference between groups in temporal processing. Earlier work has shown degraded recall for children with language learning impairments at any ISI of 150 ms or less (e.g., Tallal & Piercy, 1973a, 1973b, 1974). After the series of blocks with two-tone sequences, testing was repeated with the same ISIs using three-tone sequences. Finally, this set of ISIs was used with four-tone sequences. Thus there were 15 blocks in all, five ISIs × three sequence lengths. The number of errors in each block was used as the dependent measure.

Speech Perception

All stimuli were generated at a 10-kHz sampling rate and presented with low-pass filtering below 4.8 kHz.

/dɑ/ versus /tɑ/

Synthetic vocalic portions were 270 ms long, and stimulus construction was based on that of Mann (1980) and Nittrouer (1992). The F1 transition took place over the first 40 ms, and F1 changed during that time from 200 Hz to its steady-state frequency of 650 Hz. The second and third formants (F2 and F3) changed over the first 70 ms of the vocalic portions. F2 started at 1800 Hz and fell to its steady-state frequency of 1130 Hz. F3 started at 3000 Hz and fell to its steady-state frequency of 2500 Hz. F4 and F5 were held constant at their default frequencies of 3250 Hz and 3700 Hz, respectively. The fundamental frequency (f_0) was constant at 120 Hz for the first 70 ms and then fell linearly through the rest of the vocalic portion to an ending frequency of 100 Hz. The onset of voicing was cut back in 5-ms steps from 0 ms to 40 ms, making nine vocalic portions. There was no source provided to F1 before the onset of voicing. Aspiration noise was the source to the formants higher than F1 before the onset of voicing. Ten milliseconds of burst noise was excised from natural tokens of a male speaker saying /dɑ/ and /tɑ/, and added to the front of each vocalic portion. As would be expected given their common place of closure, the spectra of these noises did not differ greatly: the /t/ noise simply had a bit more high-frequency energy than the /d/ noise. In all then, there were 18 stimuli, nine vocalic portions × two bursts.

/seɪ/ versus /steɪ/

These stimuli were the same as those of Nittrouer (1992). A natural /s/ noise, 120 ms long, was followed by one of two synthetic vocalic portions. Both portions were 300 ms long, with f_0 falling throughout from 120 Hz to 100 Hz. F3 fell over the first 40 ms from 3196 Hz to 2694 Hz, where it remained for the next 120 ms. It then rose to 2929 Hz over 90 ms, where it remained for the final 50 ms. F2 remained constant at 1840 Hz over the first 160 ms and then rose to 2240 Hz over the next 90 ms, where it remained for the final 50 ms. F1 started at either 230 Hz (most /steɪ/-like) or 430 Hz (most /seɪ/-like). In both cases, F1 rose to 611 Hz over the first 40 ms. It remained there for 120 ms, and then fell to 304 Hz over 90 ms, where it stayed for the final 50 ms. Thus, there were two vocalic portions, each paired with the /s/ noise. Silent gaps, varying in length from 0 ms to 55 ms in 5-ms steps, were placed between the /s/ noise and the vocalic portions. Consequently, there were 24 stimuli in all, two F1 onsets × 12 gap durations.

Syllable-initial /s/ versus /ʃ/

These very same stimuli have been used in a number of studies (Nittrouer, 1992, 1996b; Nittrouer & Miller, 1997). In Nittrouer (1996a), the same vocalic portions were used, with a truncated fricative-noise continuum. The vocalic portions were taken from natural tokens of a male speaker saying /sɑ/, /ʃɑ/, /su/, and /ʃu/. Thus, there were two vowels, each with two kinds of formant transitions, those appropriate for a preceding /s/ and those appropriate for a preceding /ʃ/. The synthetic noises were single pole noises, 150 ms in duration. The center frequencies of these noises varied from 2.2 kHz to 3.8 kHz in 200-Hz steps. Each of these noises was paired with each of the vocalic portions. Thus there were 36 stimuli in all, nine noises × two vowels × two kinds of formant transitions. However, /ɑ/ and /u/ stimuli were presented separately.

For each of the speech perception tasks, a single stimulus was presented, and children had to assign one of two response labels to it. They indicated their choice by pointing to one of two pictures and saying the "name" of that picture. The experimenter entered their responses into the computer. Training consisted of the presentation of the best exemplars for each contrast. For example, in /dɑ/ versus /tɑ/, the best exemplars were the stimulus with the 0-ms VOT and the /dɑ/ burst, and the stimulus with the 40-ms VOT and the /tɑ/ burst. The best exemplars were presented five times each in random order. The child had to respond correctly to 9 out of 10 to proceed to testing. During testing, stimuli were presented in blocks consisting of however many stimuli there were in the set. Ten blocks in all were presented for each set. Again, the experimenter listened to stimuli during practice and then removed the headphones during testing.

Probit functions were fit to the resulting data. These functions are effectively z transformations, only with 5 added to each z score so that no value is negative. From this distribution, a mean (i.e., the point on the function where the probability of either response is 0.50) and a slope is derived. The mean was considered the phoneme boundary. The separation between functions was measured as the difference in phoneme boundaries.

Results

Phonological Awareness

Table 1 displays group means for the number of items correct on the three phonological awareness tasks. For all three tasks, t tests were done. Significant differences between groups were found for the phoneme deletion task, $t(108) = 5.15$, $p < .001$, and for the pig-Latin task, $t(108) = 4.04$, $p < .001$. Thus it may be concluded that children in the PPP group had poorer phonological processing abilities than what would normally be expected of them for their age, so the label "poor phonological processing" fits for children with scores on the reading subtest of the WRAT–R of 85 or less.

Table 1. Mean number of items correct on the three tests of phonological awareness for children in the NPP and PPP groups. Standard deviations are given in parentheses after the means. Total number of items on each task were 24 for initial consonant the same, 32 for phoneme deletion, and 48 for pig Latin.

	NPP	PPP
Initial consonant the same	22.7 (2.0)	22.3 (2.2)
Phoneme deletion	23.6 (7.2)	13.8 (7.5)
Pig Latin	26.6 (15.9)	10.2 (12.4)

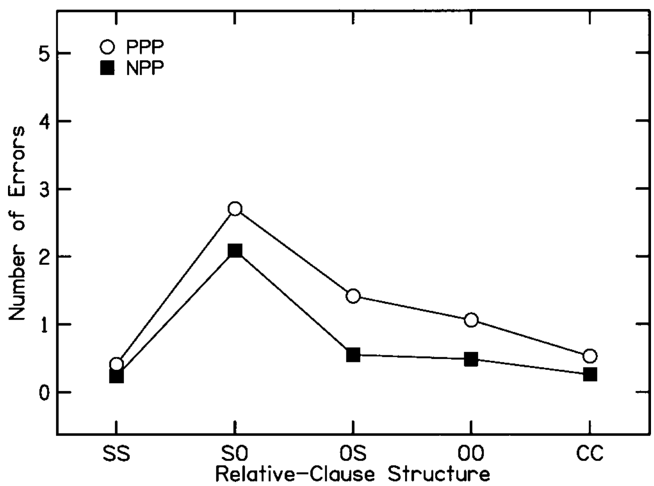
Working Memory for Linguistic Materials

A three-way analysis of variance (ANOVA) was performed on these data, with group as the between-subjects factor and list length and rhyming condition as within-subjects factors. The main effect of group was significant, $F(1, 108) = 8.65$, $p = .004$, as were the main effects of list length, $F(2, 216) = 519.70$, $p < .001$, and rhyming condition, $F(1, 108) = 155.53$, $p < .001$. The interaction of Group × List Length was also significant, $F(2, 216) = 4.56$, $p = .012$. Because the interaction of Group × Rhyming Condition was not significant, group means for the number of errors were computed across rhyming conditions and are presented on Table 2. A simple effects analysis was done next, in which the main effect of group was tested for each list length. Results showed that the two groups differed significantly for lists of five words, $F(1, 108) = 10.49$, $p = .002$, and for lists of six words, $F(1, 108) = 6.72$, $p = .011$. No significant difference was found between groups for the shortest word lists, those of four words. From these results, it can be concluded that children with poor phonological processing abilities had more difficulty recalling longer lists of words, whether rhyming or not, than children with normal phonological processing abilities. These results were obtained in spite of the fact that the words were not presented at a rapid rate; that is, ISIs were much longer than those for which Tallal and colleagues report finding differences for the recall of stimulus order between children with normal language and children with language learning impairments.

Table 2. Mean number of errors (across list positions and rhyming conditions) on the working memory task, for children in the NPP and PPP groups, for each list length. Standard deviations are given in parentheses after the means. Total number of mean errors possible was ten.

	NPP		PPP	
Four words	0.76	(0.78)	1.02	(0.52)
Five words	2.43	(1.21)	3.44	(0.92)
Six words	4.58	(1.16)	5.35	(0.84)

Figure 2. Number of errors made on the comprehension of sentences with complex syntax task for children with normal phonological processing (NPP) abilities and for those with poor phonological processing (PPP) abilities.



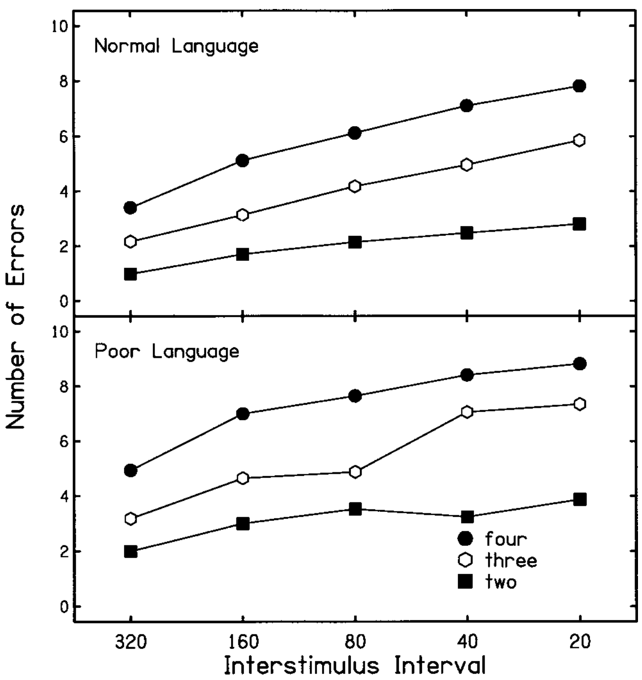
Comprehension of Complex Syntax

A two-way ANOVA was done on these data, with group as the between-subjects factor and sentence type as the within-subjects factor. Significant effects were found for both group, $F(1, 108) = 9.76$, $p = .002$, and sentence type, $F(4, 432) = 50.85$, $p < .001$. Thus, children in the PPP group generally made more errors in comprehension than children in the NPP group. Means (and standard deviations) across sentence types were 3.62 (2.85) for the NPP group and 6.12 (3.89) for the PPP group. Figure 2 displays the pattern of errors across sentence types and shows that the this pattern was the same for both groups of children. This result replicates those of others, such as Smith et al. (1983) and Bar-Shalom et al. (1993).

Temporal Processing

Figure 3 displays mean number of errors obtained during testing, for each group at each ISI, for the two-, three-, and four-tone sequences. A three-way ANOVA was done, with group as the between-subjects factor and ISI and sequence length as the within-subjects factors. The main effect of ISI was significant, $F(4, 432) = 105.01$, $p < .001$, as was the main effect of list length, $F(2, 216) = 112.53$, $p < .001$. The interaction of these two terms was also significant, $F(8, 864) = 8.07$, $p < .001$. Therefore it can be concluded that all children made more errors for shorter ISIs and for longer sequences and that the longer the sequence, the greater the effect of ISI on error rate. Regarding the main effect of group, it was not found to be significant, although it was close, $F(1, 108) = 3.87$, $p = .052$. This result reflects the fact that children in the PPP group made somewhat more errors than children in the NPP group. Means (and standard deviations) across ISIs and sequence lengths were 4.00 (3.68) for children in the NPP group and 5.31 (3.75) for children in the PPP group. Of most interest to the current study, however, was the finding that there was no significant interaction of group with ISI. In other words, children in the PPP group were not disproportionately affected by the rate at which tones were presented. The interaction of group and sequence length was similarly nonsignificant.

Figure 3. The number of errors made in the temporal processing task for children in the NPP and the PPP groups.



Because this task was the most critical to the hypothesis being tested (that temporal processing deficits account for phonological processing problems), it seemed important to make absolutely certain that the children in the PPP group did not show even the slightest hint of a greater disadvantage for the rapidly presented stimuli than the children in the NPP group showed. Therefore, *t* tests were performed on error rates for stimuli with the shortest (20 ms) ISI for each sequence length. None of these tests was significant.

Speech Perception

Table 3 shows mean slopes for each of the four pairs of stimuli, and Table 4 shows mean phoneme boundaries. Again, the slope of the function estimates the extent to which phonetic judgments were based on the continuous cue (that which is represented on the abscissa). Given the categorical nature of speech perception, if responses are based largely on this cue, functions will be steep. The separation in functions (measured at the phoneme boundaries) estimates the extent to which phonetic judgments were based on the binary cue. If functions are well-separated, responses were based to a great extent on the binary cue. For each contrast, two *t* tests were done, one on the mean slope across the two functions (e.g., /dɑ/ and /tɑ/), and one on the separation between the two functions (e.g., /dɑ/ phoneme boundary minus /tɑ/ phoneme boundary).

Table 3. Mean slope across conditions for children in the NPP and PPP groups. Standard deviations are given in parentheses after the means. Slope is given as change in probits per ms of F1 cutback for /tɑ/ & /dɑ/, change in probits per ms of gap for /steɪ/ & /seɪ/, and change in probits per kilohertz of noise for /sɑ/ & /ʃɑ/ and /su/ & /ʃu/.

	NPP	PPP
/tɑ/ & /dɑ/	0.17 (0.046)	0.15 (0.048)
/steɪ/ & /seɪ/	0.09 (0.033)	0.08 (0.035)
/sɑ/ & /ʃɑ/	3.35 (1.29)	2.45 (0.71)
/su/ & /ʃu/	3.39 (1.27)	2.24 (0.89)

Table 4. Mean phoneme boundary for each condition for children in the NPP and PPP groups. Standard deviations are given in parentheses under the means. Phoneme boundaries represent ms of F1 cutback for /tɑ/ : /dɑ/, ms of gap for /steɪ/ : /seɪ/, and center frequency of fricative noise for /sɑ/ : /ʃɑ/ and /su/ : /ʃu/.

	NPP	PPP
/tɑ/ : /dɑ/	23.1 : 25.6 (3.2 : 3.5)	24.0 : 27.0 (3.4 : 3.8)
/steɪ/ : /seɪ/	16.5 : 27.0 (6.6 : 8.5)	14.4 : 26.6 (5.4 : 8.2)
/sɑ/ : /ʃɑ/	2943 : 3449 (189 : 232)	2865 : 3468 (204 : 208)
/su/ : /ʃu/	2706 : 3274 (375 : 159)	2552 : 3341 (348 : 122)

/dɑ/ versus /tɑ/

There was no significant difference between groups in either the mean slope of the functions or in the separation between the functions for these stimuli. Therefore, we may conclude that the children in the PPP group were able to use both the formant transitions and the brief bursts to the same extent as children in the NPP group in making these voicing decisions.

/seɪ/ versus /steɪ/

There was no significant difference in either the mean slope of the functions or in the separation between the functions for these stimuli. Thus there is evidence that the children in the PPP group were able to use both the formant transitions and the gaps to the same extent as the children in the NPP group in making decisions about the presence of a stop closure. For these stimuli, however, results for *t* tests on the phoneme boundaries themselves were also of interest because the question may be asked whether children in the PPP group needed longer gaps to judge stimuli as having a stop between the /s/ noise and the vocalic portion. That is, if children with phonological processing problems have difficulty with brief acoustic cues, then these children may have required longer gaps to change their phonetic judgments from /seɪ/ to /steɪ/. Neither the *t* test for the low nor the one for the high F1 onset showed significant differences in the placement of phoneme boundaries for the two groups. Therefore, it may be concluded that children in the PPP group did not require longer gaps to judge these stimuli as having a stop closure following the /s/ noise.

/sɑ/ versus /ʃɑ/

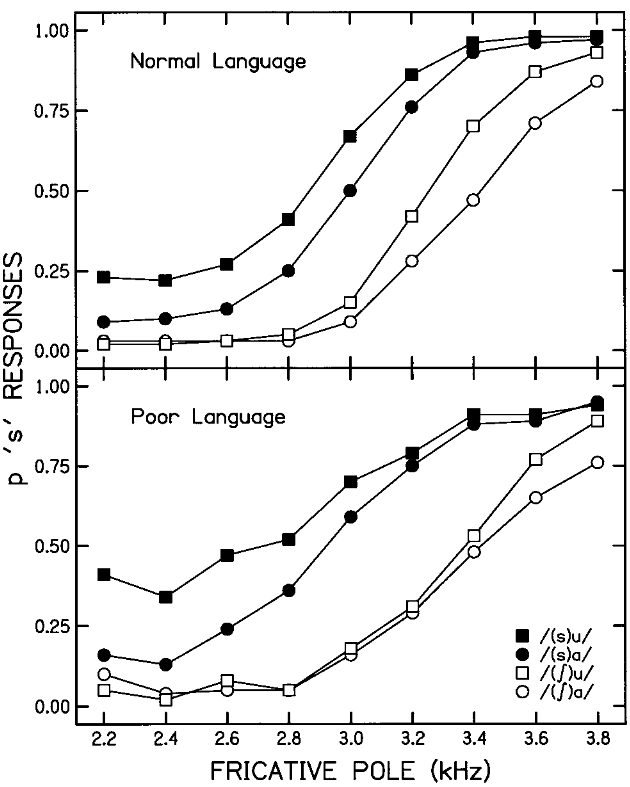
For these stimuli, the *t* test for mean slope revealed a significant difference between the two groups, $t(108) = 2.82$, $p = .006$. Thus we may conclude that children in the PPP group did not use the fricative-noise spectra as much as children in the NPP group in phonetic decisions about the syllable-initial fricative.

/su/ versus /ʃu/

For these stimuli, a statistically significant result was found for the *t* test on mean slope, $t(108) = 3.56$, $p < .001$, so it may again be concluded that children in the PPP group did not base their phonetic decisions about the syllable-initial fricative on the spectrum of the noise as much as children in the NPP group. For the *t* test on separation between functions, statistical significance was also found, $t(108) = -1.99$, $p = .049$. Mean separation in functions was 568 Hz for the NPP group and 789 Hz for the PPP group. Thus, children in PPP group actually based their phonetic decisions more on the formant transitions than did children in the NPP group.

Because statistically significant results were observed for the stimuli involving syllable-initial fricatives, mean labeling functions for the two groups were plotted and are shown in Figure 4. These functions are clearly shallower for the PPP group than for the NPP group, as would be expected from the slopes shown on Table 3. Figure 4 also shows that children in the PPP group used the formant transitions (i.e., whether they were appropriate for /s/ or /ʃ/) more than children in the NPP group. For example, when the vowel was /u/ and the formant transitions were appropriate for /s/ (the function with the filled squares), the probability of children in the PPP group responding that the syllable had an initial /s/ was always fairly high (at least above 0.25), regardless of what the noise spectrum was. When this pattern of result is compared to studies of normal development that have used these same or similar stimuli (Nittrouer, 1992, 1996a; Nittrouer & Miller, 1997; Nittrouer et al., in press; Nittrouer & Studdert-Kennedy, 1987), it is found that results for the children in the PPP group resemble those of younger children developing language normally.

Figure 4. Mean labeling functions for children in the NPP and in the PPP groups for /su/, /ʃu/, /sɑ/, and /ʃɑ/ stimuli. The continuous cue was the center frequency of the fricative noise, and the binary cue was whether formant transitions were appropriate for a syllable-initial /s/ or /ʃ/.



Discussion

The purpose of this study was to examine whether children with poor phonological processing abilities show evidence of a temporal processing deficit. To this end, 110 children participated. Ninety-three of these children had normal reading abilities, and 17 had reading abilities well below average. In the current study, all children met appropriate criteria for participation. These 110 children were administered tests to determine if the two groups differed in language abilities, particularly those abilities that depend on phonological processing, and to test explicitly the hypothesis that temporal processing deficits account for poor phonological processing abilities. The children in the PPP group demonstrated poor phonological awareness, difficulty coding linguistic materials in working memory, and difficulty comprehending sentences with complex syntax. In summary, the two groups of children in this study demonstrated differences in every language ability measured.

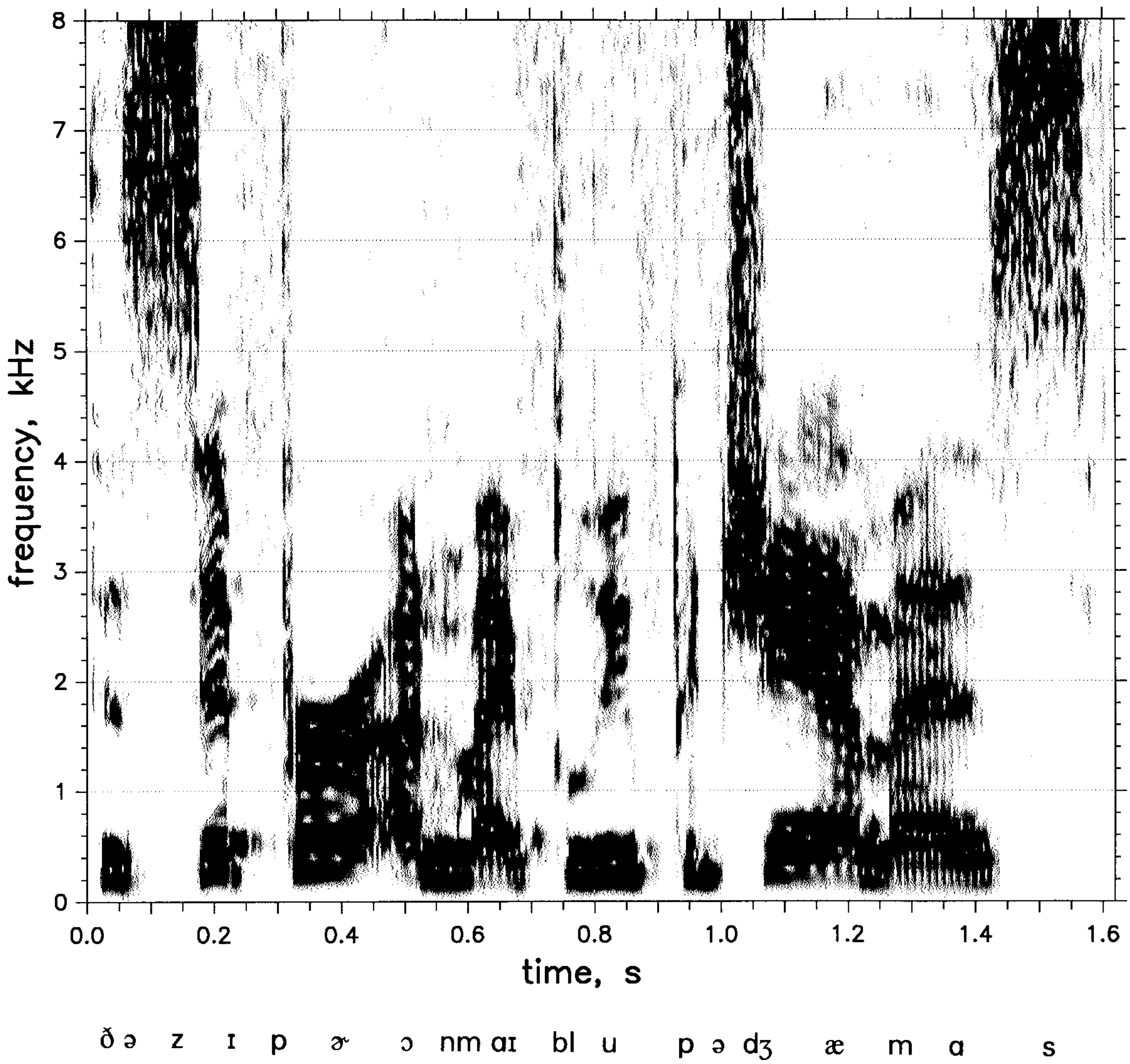
In spite of their demonstrated language differences, children in the two groups showed no differences in abilities to process rapidly presented information. In the temporal processing task, children in the PPP group were not disproportionately affected, compared to children in the NPP group, by rapid rates of stimulus presentation. In labeling tasks with speech stimuli, children in the PPP group were able to use both brief and transitional cues to the same extent as children in the NPP group in making phonetic judgments. Contrary to predictions of the temporal processing hypothesis then, children with demonstrated phonological processing problems depended on brief and transitional signal portions for speech perception. In fact, for decisions regarding syllable-initial fricatives, children in the PPP group based their phonetic judgments more on formant transitions than the other children. At the same time, children in the PPP group failed to make as much use of the long, steady-state information provided by the fricative noises. In summary, no evidence was found that the children with poor phonological processing abilities had temporal processing deficits. Consequently, we must answer the question posed in the title of this paper (Do temporal processing deficits cause phonological processing problems?) with a clear *no*.

The results reported here match results from other studies explicitly testing the hypothesis that temporal processing deficits underlie language problems. For example, Mody et al. (1997) found that children with poor reading abilities had difficulty reporting the order of rapidly presented syllable pairs *only* when those syllables were phonetically similar. Consequently, the authors concluded that the poor readers did not have a temporal processing deficit, but instead had difficulty classifying perceptually similar stimuli. That conclusion for speech stimuli complements the conclusion reached by Nicolson and Fawcett (1994) for nonspeech stimuli. Those authors looked at reaction times for children with dyslexia. They found that reaction times were no different between children with dyslexia and several control groups, as long as the task was simply to push a button as quickly as possible after hearing a tone. However, when the children were instructed to push the button after hearing a specific tone (i.e., the "low" or the "high" tone), the children with dyslexia were significantly slower in their response times. The authors concluded that children with dyslexia had more trouble classifying stimuli. Finally, Reed (1989) found that children with reading problems had difficulty recalling the order of rapidly presented stimulus pairs. However, because of a procedural difference between her study and others (the children in Reed's study could begin responding to the first stimulus as soon as it was presented), Reed concluded that these children actually had a "...deficit in perception of the stimuli rather than in processing their temporal order per se" (p. 287). Because of these earlier studies, it was not a complete surprise when the current results failed to reveal an underlying temporal processing deficit for children with phonological processing problems.

Neither was it a complete surprise to find that children with phonological processing problems were able to use formant transitions at least as well as other children in making phonetic decisions. Even before we undertook this experiment, objections could have been raised to attempts by Tallal and colleagues to attribute the language learning problems of some children to specific constraints on processing the formant transitions of acoustic speech signals. Again, the view of the speech signal held by this group is that of relatively long, spectrally stable signal regions corresponding to vowels interspersed with brief, spectrally changing signal regions corresponding to consonants. In fact, this depiction is not typical of real speech signals at all. Figure 5 displays a spectrogram we created by performing an FFT analysis on a portion of a sentence downloaded in audio form from the Web site of the two papers published in *Science* by Merzenich et al., 1996 and Tallal et al., 1996 (http://www.ld.ucsf.edu). The complete sentence ("The zipper on my blue pajamas is easier to reach than the buttons on my dress.") was used in those studies. In Figure 5, the portion "The zipper on my blue pajamas…" is shown. As can be seen, there are no steady-state spectral regions of 250 ms corresponding to vowels. The longest region of steady-state information is associated with the /s/ on the end of "pajamas" and is approximately 150 ms long. In fact, the acoustic signal of speech is best described as a continuously changing spectral array, in which any one temporal slice provides information about more than one phonetic segment. The terms "vowels" and "consonants" refer to abstract psychological entities, rather than to physical entities that can be isolated in the speech waveform.

In conclusion, subtle perceptual deficits were found in this study for children who had difficulty with phonological processing. However, the observed deficits were not found to have anything to do specifically with the processing of rapidly presented signals. Especially, this study failed to find any suggestion that children with poor phonological processing abilities had difficulty with formant transitions, the purported "trouble spot" in the speech signal for these children. Consequently, we may question the theoretical basis of Fast ForWord, the intervention program derived from the temporal processing deficit account of language problems (e.g., *Curriculum/Technology Quarterly*, 1998). There is no reason to believe that experience with the artificially slowed speech (that specifically extends formant transitions beyond natural rates) used in Fast ForWord would improve the language abilities of children with language learning problems, particularly phonological processing problems, because no evidence was found that these children have difficulty processing rapidly presented information. In fact, one study replicated the speech processing procedures used in Fast ForWord,

Figure 5. A spectrogram of "The zipper on my blue pajamas…"



and found no improvement in the abilities of children with language learning impairments to recognize stop-vowel sequences (McAnally, Hansen, Cornelissen, & Stein, 1997). Of course, we must then ask why so many children with such a variety of language problems have reportedly demonstrated dramatic improvements with Fast ForWord (see the special issue of *Curriculum / Technology Quarterly*, 1998, devoted to this topic for a complete review of these results). Regarding that question, this study is silent, but three other studies suggested that children with language learning impairments have more difficulty than other children classifying stimuli (Nicolson & Fawcett, 1994; Mody et al., 1997; Reed, 1989). It may be that simply presenting stimuli more slowly affords these children the extra time needed to classify a stimulus before the next is presented. In other words, the speech processing technique of extending formant transitions probably provides no special benefit, but having extra time may.

Difficulty learning language can be one of the most devastating problems a child can face because it impacts all other areas of learning. However, in our zeal to find ways to ameliorate this problem, we should not rush to implement new programs before they are fully understood and found to be effective by independent investigators. It simply does not do for clinicians to "…let the grown-ups argue theory all they want, but if the computer game works, play it," as suggested by the editorial piece accompanying the publication of the Merzenich et al. and Tallal et al. 1996 *Science* articles (Barinaga, 1996, p. 28). Every clinician must be a theorist; otherwise we will never know if we are doing the best we can for our clients.

Acknowledgments

This work was supported by Grant P60 DC-00982 from the National Institute on Deafness and Other Communication Disorders to Boys Town National Research Hospital. Court S. Crowther, Nancy Luke, Mary Jane Manhart, Marnie E. Miller, and John Schneider helped with data collection and analysis. Walt Jesteadt, Donna L. Neff, and Carol J. Strong provided comments on an earlier draft of this manuscript.

References

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

Bar-Shalom, E. G., Crain, S., & Shankweiler, D. P. (1993). A comparison of comprehension and production abilities of good and poor readers. *Applied Psycholinguistics, 14*, 197–227.

Barinaga, M. (1996). Giving language skills a boost. *Science, 271*, 27–28.

Best, C. T., Morrongiello, B. A., & Robson, R. C. (1981). Perceptual equivalence of acoustic cues in speech and nonspeech perception. *Perception & Psychophysics, 29*, 191–211.

Bradley, L., & Bryant, P. E. (1983). Categorizing sounds and learning to read—A causal connection. *Nature, 310*, 419–421.

Brady, S., Poggie, E., & Rapala, M. M. (1989). Speech repetition abilities in children who differ in reading skill. *Language and Speech, 32*, 109–122.

Brady, S., Shankweiler, D., & Mann, V. (1983). Speech perception and memory coding in relation to reading ability. *Journal of Experimental Child Psychology, 35*, 345–367.

Byrne, B. (1981). Deficient syntactic control in poor readers: Is a weak phonetic memory code responsible? *Applied Psycholinguistics, 2*, 201–212.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic Bulletin & Review, 2*, 460–493.

Fox, B., & Routh, D. K. (1980). Phonemic analysis and severe reading disability in children. *Journal of Psycholinguistic Research, 9*, 115–119.

Gathercole, S. E., & Baddeley, A. D. (1990). Phonological memory deficits in language disordered children: Is there a causal connection? *Journal of Memory and Language, 29*, 336–360.

Goldman, R., & Fristoe, M. (1986). *Goldman, Fristoe Test of Articulation*. Circle Pines, MN: American Guidance Service.

Hall, J. W., Wilson, K. P., Humphreys, M. S., Tinzmann, M. B., & Bowyer, P. M. (1983). Phonemic-similarity effects in good vs. poor readers. *Memory & Cognition, 11*, 520–527.

James, D., Van Steenbrugge, W., & Chiveralls, K. (1994). Underlying deficits in language-disordered children with central auditory processing difficulties. *Applied Psycholinguistics, 15*, 311–328.

Jastak, S., & Wilkinson, G. S. (1984). *The Wide Range Achievement Test–Revised*. Wilmington, DE: Jastak Associates.

Mann, L. (Ed.). (1998). *Curriculum / Technology Quarterly, 7*(2).

Mann, V. A. (1980). Influence of preceding liquid on stop-consonant perception. *Perception & Psychophysics, 28*, 407–412.

Mann, V. A., & Liberman, I. Y. (1984). Phonological awareness and verbal short-term memory. *Journal of Learning Disabilities, 17*, 592–599.

McAnally, K. I., Hansen, P. C., Cornelissen, P. L., & Stein, J. F. (1997). Effect of time and frequency manipulation on syllable perception in developmental dyslexics. *Journal of Speech, Language, and Hearing Research, 40*, 912–924.

Merzenich, M. M., Jenkins, W. M., Johnston, P., Schreiner, C., Miller, S. L., & Tallal, P. (1996). Temporal processing deficits of language-learning impaired children ameliorated by training. *Science, 271*, 77–81.

Mody, M., Studdert-Kennedy, M., & Brady, S. (1997). Speech perception deficits in poor readers: Auditory processing or phonological coding? *Journal of Experimental Child Psychology, 64*, 199–231.

Morrongiello, B. A., Robson, R. C., Best, C. T., & Clifton, R. K. (1984). Trading relations in the perception of speech by five-year-old children. *Journal of Experimental Child Psychology, 37*, 231–250.

Nicolson, R. I., & Fawcett, A. J. (1994). Reaction times and dyslexia. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 47A*, 29–48.

Nittrouer, S. (1992). Age-related differences in perceptual effects of formant transitions within syllables and across syllable boundaries. *Journal of Phonetics, 20*, 1–32.

Nittrouer, S. (1996a). Discriminability and perceptual weighting of some acoustic cues to speech perception by 3-year-olds. *Journal of Speech and Hearing Research, 39*, 278–297.

Nittrouer, S. (1996b). The relation between speech perception and phonemic awareness: Evidence from low-SES children and children with chronic OM. *Journal of Speech and Hearing Research, 39*, 1059–1070.

Nittrouer, S., Miller, M. E., Crowther, C. S., & Manhart, M. J. (in press). The effect of segmental order on fricative labeling by children and adults. *Perception & Psychophysics*.

Nittrouer, S., & Miller, M. E. (1997). Predicting developmental shifts in perceptual weighting schemes. *Journal of the Acoustical Society of America, 101*, 2253–2266.

Nittrouer, S., & Studdert-Kennedy, M. (1987). The role of coarticulatory effects in the perception of fricatives by children and adults. *Journal of Speech and Hearing Research, 30*, 319–329.

Pennington, B. F., Van Orden, G. C., Smith, S. D., Green, P. A., & Haith, M. M. (1990). Phonological processing skills and deficits in adult dyslexics. *Child Development, 61*, 1753–1778.

Pratt, A. C., & Brady, S. (1988). Relation of phonological awareness to reading disability in children and adults. *Journal of Educational Psychology, 80*, 319–323.

Reed, M. A. (1989). Speech perception and the discrimination of brief auditory cues in reading disabled children. *Journal of Experimental Child Psychology*, *48*, 270–292.

Smith, S. T., Macaruso, P., Shankweiler, D., & Crain, S. (1989). Syntactic comprehension in young poor readers. *Applied Psycholinguistics*, *10*, 429–454.

Smith, S. T., Mann, V. A., & Shankweiler, D. (1986). Spoken language comprehension by good and poor readers: A study with the Token Test. *Cortex*, *22*, 627–632.

Spring, C., & Perry, L. (1983). Naming speed and serial recall in poor and adequate readers. *Contemporary Educational Psychology*, *8*, 141–145.

Stanovich, K. E., Cunningham, A. E., & Cramer, B. B. (1984). Assessing phonological awareness in kindergarten children: Issues of task comparability. *Journal of Experimental Child Psychology*, *38*, 175–190.

Stein, C. L., Cairns, H. S., & Zurif, E. B. (1984). Sentence comprehension limitations related to syntactic deficits in reading-disabled children. *Applied Psycholinguistics*, *5*, 305–322.

Studdert-Kennedy, M., & Mody, M. (1995). Auditory temporal perception deficits in the reading-impaired: A critical review of the evidence. *Psychonomic Bulletin & Review*, *2*, 508–514.

Tallal, P. (1980a). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language*, *9*, 182–198.

Tallal, P. (1980b). Perceptual requisites for language. In R. L. Schiefelbusch (Ed.), *Nonspeech language and communication: Analysis and intervention* (pp. 450–467). Baltimore: University Park Press.

Tallal, P. (1984). Temporal or phonetic processing deficit in dyslexia? That is the question. *Applied Psycholinguistics*, *5*, 167–169.

Tallal, P. (1994). In the perception of speech time is of the essence. In G. Buzsaki, R. Llinas, W. Singer, A. Berthoz, & Y. Christen (Eds.), *Temporal coding in the brain* (pp. 291–299). Berlin: Springer-Verlag.

Tallal, P., Miller, S., & Fitch, R. H. (1993). Neurobiological basis of speech: A case for the preeminence of temporal processing. *Annals of the New York Academy of Sciences*, *682*, 27–47.

Tallal, P., & Piercy, M. (1973a). Defects of non-verbal auditory perception in children with developmental aphasia. *Nature*, *241*, 468–469.

Tallal, P., & Piercy, M. (1973b). Developmental aphasia: Impaired rate of non-verbal processing as a function of sensory modality. *Neuropsychologia*, *11*, 389–398.

Tallal, P., & Piercy, M. (1974). Developmental aphasia: Rate of auditory processing and selective impairment of consonant perception. *Neuropsychologia*, *12*, 83–93.

Tallal, P., & Piercy, M. (1975). Developmental aphasia: The perception of brief vowels and extended stop consonants. *Neuropsychologia*, *13*, 69–74.

Tallal, P., & Piercy, M. (1978). Defects of auditory perception in children with developmental dysphasia. In M. A. Wyke (Ed.), *Developmental dysphasia* (pp. 63–84). London: Academic Press.

Tallal, P., & Stark, R. E. (1981). Speech acoustic-cue discrimination abilities of normally developing and language-impaired children. *Journal of the Acoustical Society of America*, *69*, 568–574.

Tallal, P., & Stark, R. E. (1982). Perceptual/Motor profiles of reading impaired children with or without concomitant oral language deficits. *Annals of Dyslexia*, *32*, 163–176.

Tallal, P., Stark, R., Kallman, C., & Mellits, D. (1981). A reexamination of some nonverbal perceptual abilities of language-impaired and normal children as a function of age and sensory modality. *Journal of Speech and Hearing Research*, *24*, 351–357.

Tallal, P., Miller, S. L., Bedi, G., Byma, G., Wang, X., Nagarajan, S. S., Schreiner, C., Jenkins, W. M., & Merzenich, M. M. (1996). Language comprehension in language-learning impaired children improved with acoustically modified speech. *Science*, *271*, 81–84.

Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin*, *101*, 192–212.

Wechsler, D. (1991). *Wechsler Intelligence Scale for Children–Third Edition*. San Antonio, TX: Harcourt Brace Janovich.

Werner, L. A. (1992). Interpreting developmental psychoacoustics. In L. A. Werner & E. W. Rubel (Eds.), *Developmental Psychoacoustics* (pp. 47–88). Washington, DC: American Psychological Association.

Received August 12, 1998

Accepted January 28, 1999

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Appendix A. Items from the initial-consonant-the-same task. The target word is given in the left column, with the three choices in the right columns. The correct response is italicized.

Practice

	ball	*book*	seed	mouth
	face	pig	*fur*	top
	seal	can	dog	*sun*

Test

1.	milk	date	*moon*	bag
2.	pear	*pen*	tile	mask
3.	stick	*slide*	drum	flag
4.	bone	meat	lace	*bud*
5.	soap	king	dime	*salt*
6.	claw	prize	*crib*	stair
7.	leg	pin	*lock*	boat
8.	duck	*door*	soup	light
9.	plum	tree	star	*price*
10.	key	fist	*kite*	sap
11.	zip	*zoo*	web	man
12.	gate	sun	bin	*gum*
13.	rug	can	*rag*	pit
14.	sky	*sleep*	crumb	drip
15.	fun	dark	pet	*fan*
16.	peel	wash	*pat*	vine
17.	grape	class	*glue*	swing
18.	leap	*lip*	note	wheel
19.	house	rain	*heel*	kid
20.	toes	bit	girl	*tip*
21.	win	*well*	foot	pan
22.	met	*map*	day	box
23.	sled	frog	brush	*stick*
24.	jeep	lock	pail	*jug*

Appendix B. Items from the phoneme deletion task. The segment to be deleted is in parentheses. The correct response is apparent by simply removing the segment to be deleted.

Practice

pin(t)	p(r)ot
(t)ink	no(s)te
bar(p)	s(k)elf

Test

1.	(b)ice	17.	s(t)ip
2.	toe(b)	18.	fli(m)p
3.	(p)ate	19.	c(l)art
4.	as(p)	20.	(b)rock
5.	(b)arch	21.	cream(p)
6.	tea(p)	22.	hi(f)t
7.	(k)elm	23.	dril(k)
8.	blue(t)	24.	mee(s)t
9.	jar(l)	25.	(s)want
10.	s(k)ad	26.	p(l)ost
11.	hil(p)	27.	her(m)
12.	c(r)oal	28.	(f)rip
13.	(g)lamp	29.	tri(s)ck
14.	ma(k)t	30.	star(p)
15.	s(p)alt	31.	fla(k)t
16.	(p)ran	32.	(s)part

Appendix C. Items from the pig-latin task. The correct response is given in parentheses.

Practice

go	(ogay)	stick	(ticksay)
pat	(atpay)	drip	(ripday)
happy	(appyhay)	strap	(trapsay)
candy	(andycay)	scram	(cramsay)
thick	(ickthay)	snapshot	(napshotsay)
where	(erewhay)	shop	(opshay)

Test

1. day	(ayday)	25. dragon	(ragonday)
2. box	(oxbay)	26. sprint	(printsay)
3. lady	(adylay)	27. screamer	(creamersay)
4. funny	(unnyfay)	28. game	(amegay)
5. chatter	(atterchay)	29. rabbit	(abbitray)
6. strike	(trikesay)	30. dresser	(resserday)
7. strangle	(tranglesay)	31. mitten	(ittenmay)
8. gray	(raygay)	32. splitting	(plittingsay)
9. third	(irdthay)	33. man	(anmay)
10. happen	(appenhay)	34. choppy	(oppychay)
11. screw	(crewsay)	35. braver	(raverbay)
12. flatter	(latterfay)	36. what	(atwhay)
13. shelter	(eltershay)	37. wind	(indway)
14. steak	(teaksay)	38. fault	(aultfay)
15. shone	(oneshay)	39. green	(reengay)
16. shudder	(uddershay)	40. chicken	(ickenchay)
17. blow	(lowbay)	41. splatter	(plattersay)
18. shiny	(inyshay)	42. thirst	(irstthay)
19. that	(atthay)	43. scratch	(cratchsay)
20. shelf	(elfshay)	44. stronger	(trongersay)
21. strict	(trictsay)	45. blanket	(lanketbay)
22. brief	(riefbay)	46. straw	(trawsay)
23. closet	(losetcay)	47. weather	(eatherway)
24. blend	(lendbay)	48. strainer	(trainersay)

Appendix D. Four of the five sets of sentences presented in the task of comprehension of complex syntax. The fifth set is provided in the text. "S" means subject; "O" means object. These letters in the sentence description (on left) describe the roles of the italicized noun phrase (which is the noun in the empty position of the relative clause) in the main clause (first position) and in the relative clause (second position) of the sentence.

SS:	*The man* who held a basket lifted the girl.
SO:	*The girl* who the man lifted held a basket.
OS:	The man lifted *the girl* who held a basket.
OO:	The girl lifted *the man* that a basket was beside.
CC:	The girl lifted the man and held a basket.
SS:	*The man* who held an umbrella touched the lady.
SO:	*The man* who the lady touched held an umbrella.
OS:	The man touched *the lady* who held an umbrella.
OO:	The man touched *the lady* that an umbrella covered.
CC:	The lady touched the man and held an umbrella.
SS:	*The girl* who hugged a teddy bear pushed the boy.
SO:	*The boy* who the girl pushed hugged a teddy bear.
OS:	The girl pushed *the boy* who hugged a teddy bear.
OO:	The boy pushed *the girl* who the hat was on.
CC:	The boy pushed the girl and hugged a teddy bear.
SS:	*The lion* that ate the food followed the bear.
SO:	*The lion* that the bear followed ate the food.
OS:	The lion followed *the bear* that ate the food.
OO:	The bear followed *the lion* that a rope hung from.
CC:	The bear followed the lion and ate the food.