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What is the deficit in phonological processing deficits: Auditory sensitivity, masking, or category formation?

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Abstract

Although children with language impairments, including those associated with reading, usually demonstrate deficits in phonological processing, there is minimal agreement as to the source of those deficits. This study examined two problems hypothesized to be possible sources: either poor auditory sensitivity to speech-relevant acoustic properties, mainly formant transitions, or enhanced masking of those properties. Adults and 8-year-olds with and without phonological processing deficits (PPD) participated. Children with PPD demonstrated weaker abilities than children with typical language development (TLD) in reading, sentence recall, and phonological awareness. Dependent measures were: 1) word recognition; 2) discrimination of spectral glides; and 3) phonetic judgments based on spectral and temporal cues. All tasks were conducted in quiet and in noise. Children with PPD showed neither poorer auditory sensitivity nor greater masking than adults and children with TLD, but did demonstrate an unanticipated deficit in category formation for non-speech sounds. These results suggest that these children may have an underlying deficit in perceptually organizing sensory information to form coherent categories.

Keywords

specific language impairment; reading disorder; language acquisition; developmental speech perception; phonological processing abilities

In spite of showing normal development in most areas, some children encounter difficulties in understanding and producing language (specific language impairment, or SLI) or in reading (reading disorder, or RD). Although these two problems are similar, children with SLI exhibit deficits primarily in grammar, phonology, and semantic skills (Tager-Flusberg & Cooper, 1999), whereas children with RD demonstrate primary deficits in printed word recognition (Lyon, Shaywitz, & Shaywitz, 2003).

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Statement of the problem

Although deficits for SLI are viewed as being in the "language" domain and RD is viewed as being within the domain of "reading", there is a strong reliance of the latter on the former (Pennington & Bishop, 2009). Reading is largely a phonetic task for languages such as English that use alphabetic orthographies: When written words are to be read and remembered, they are stored in a phonetic rather than a visual form (e.g., Baddeley, 1970; Conrad, 1964). The fundamental task of children learning to read is to construct a link between speech and the arbitrary symbols used in writing. To do so they need to have an awareness of the phonetic structure of speech because the alphabetic system is designed to represent phonetic units (Mann & Liberman, 1984). Investigators vary in the criteria used for including children in studies of language problems, with some specifying SLI and others RD. Nonetheless, at the heart of many of these disorders lies a deficit in the ability to recover and/or use phonetic structure in linguistic processing (e.g., Boada & Pennington, 2006; Crain, 1989; Fletcher et al., 1994; Larrivee & Catts, 1999; Liberman, Shankweiler, Liberman, Fowler, & Fischer, 1977; Mann & Liberman, 1984; Mody, Studdert-Kennedy, & Brady, 1997; Nittrouer, 1999; Rosen & Manganari, 2001; Stanovich, 1988). These deficits involve problems explicitly in recognizing ***phonetic*** segments in the speech signal and define a more focused form of the broader term "phonological deficits," which involve problems recognizing all levels of linguistic structure, including syllables and rimes. But whereas individuals with language or reading problems generally develop the ability to recognize these larger linguistic units with age, they continue to remain insensitive to syllable-internal phonetic structure (Pennington, Van Orden, Smith, Green, & Haith, 1990). Furthermore, deficits in speech perception as well as in phonological processing have been identified in children with both SLI and RD (Boada & Pennington, 2006; Chiappe, Chiappe, & Siegel, 2001; Mody et al., 1997; Nittrouer, 1999). An intricate relationship exists between phonological processing and speech perception, as described in this quote by Mann and Foy (2003, p. 151):

> To the extent that both phonological awareness and speech perception depend on a common, internal representation of phonological structure, the integrity of speech perception should be associated with the instantiation of phonological awareness. Perception requires that information provided by the speech signal be linked to some type of internal phonological representation; comparison or manipulation of individual parts of a syllable or word requires some means of internally representing phonological structures.

Identifying the underlying cause of the phonological processing and speech perception problems that mark childhood SLI and RD has proven to be a significant challenge for psycholinguists.

Hypothesizing a deficit in auditory sensitivity

Although it is generally agreed that children with SLI and RD perceive speech and/or other signals differently from typically developing children, the nature of that perceptual deficit has been a matter of considerable debate. One particularly influential account suggested that language and reading problems arise from an auditory deficit specifically in "temporal processing" (e.g., Tallal, 1980). According to this view, slowed processing affects recovery of phonetic structure at the level of speech perception, and children with SLI and/or RD lack sensitivity to speech components that are only a few tens of milliseconds long (e.g., Tallal et al., 1996; Tallal, Miller, & Fitch, 1993). To examine this phenomenon, temporal order judgments (TOJs) have typically been used. In this procedure, two non-speech, steady-state tones of varying length are presented in series of between two and five tones at different rates of presentation. These experiments showed that most, but not all, children with language impairments made more recall errors than children with typical language development (TLD) when the tones were brief and presented rapidly (Reed, 1989; Tallal, 1980; Tallal & Piercy, 1973). This observed difficulty on the part of children with SLI to recall strings of rapidly changing tones was interpreted as indicating that these children likely have poor sensitivity to the patterns of formant transitions, which are rapidly changing spectral components of the speech signal (e.g., Tallal, 1980; Tallal, Miller, & Fitch, 1993; Tallal, Stark, Kallman, & Mellits, 1981; Tallal & Piercy, 1973; 1974).

Considerable effort has been expended testing that claim that children with language problems are poor at recovering phonetic structure because of poor sensitivity to formant transitions. For example, Elliott, Hammer, and Scholl (1989) examined auditory sensitivity to formant transitions in consonant-vowel syllables for children with TLD or SLI. Results showed that the children with SLI required greater differences in the extent of those formant transitions in order to discriminate stimuli. Following up on that work, Sussman (1993) examined whether auditory sensitivity to formant transitions or abilities to use those transitions in phonetic labeling differed for children with SLI as compared to those of both age-matched and younger, language-matched children with TLD. Results contradicted those of Elliott et al. in that Sussman found that children with SLI had similar sensitivity to formant transitions as their age-matched peers. However, their labeling functions for speech stimuli resembled those of the younger children in that there was significantly greater variability in the placement of phoneme boundaries. These results do not provide support for a deficit based strictly on sensitivity to rapidly changing frequency cues in the acoustic signal. Rather, the results suggest that children with SLI might have difficulty creating phonological representations.

Over the years, research by many other investigators has contradicted the claims of Tallal and colleagues. For example, Mody, Studdert-Kennedy, and Brady (1997) examined the temporal processing hypothesis as a possible explanation for the perceptual deficits of poor readers. They examined TOJs, discrimination of speech and non-speech signals, and sensitivity to brief transitional cues among second-grade children classified as either good or poor readers. Participants were selected to differ significantly with respect to their abilities to perform TOJs using synthetic /ba/ and /da/ syllables as a way of insuring that only children with language problems who performed poorly on the TOJ task were included. Results of Mody et al. showed that the poor readers with poor TOJs had greater difficulty discriminating /ba/ and /da/ syllables than the good readers. On the other hand, these children had no difficulty with either TOJs or the discrimination of syllable pairs that were highly contrastive (e.g., /ba/-/sa/). This finding suggested that perhaps it is not the rate of presentation, but rather the phonetic similarity between the stimuli being used in TOJs that cause the problem for children with RD. Without precisely formed phonological representations it is difficult to discriminate among categories that are similar. Research by others has also contradicted the temporal processing hypothesis, but supported the suggestion that children with SLI have difficulty creating well-defined phonological representations (e.g., Bishop, Carlyon, Deeks, & Bishop, 1999; Nittrouer, 1999; Rosen & Manganari, 2001).

Evidence from studies addressing verbal memory span is consistent with the hypothesis that a deficit in creating phonological representations is responsible for the problems of children with SLI and/or RD. For example, Brady, Shankweiler, and Mann (1983) examined verbal recall by 8-year-olds with and without RD. Results confirmed earlier reports that children with RD recall fewer words than children with good reading abilities. In addition, the children with good reading abilities showed an effect of phonetic distinctiveness in the recall of word order such that recall was more accurate for non-rhyming than for rhyming words. Children with RD were less capable of taking advantage of the phonetic distinctiveness of non-rhyming words, and so showed more similar error rates for both kinds of words than did the good readers. Upon examining the error patterns, it was apparent the children with RD were extracting some amount of phonetic information and using a phonetic coding strategy to some extent. Nevertheless they experienced greater difficulty than the other children in retaining the correct combination of phonetic sequences, which is evidence of less effective strategies.

Hypothesizing enhanced masking effects

Brady et al. (1983) also examined recognition in noise of words and environmental sounds by the 8-year-olds with and without RD. In quiet, both groups were able to recognize the words and sounds with little error. With the addition of noise, recognition of the environmental sounds declined by a similar amount for both groups, but when it came to words, the children with RD were significantly worse than the good readers. Decrements were similar for both high- and low-frequency words. Brady et al. concluded that the ability to recover phonetic structure and use it to create a phonetic representation protects against masking, and children with RD are poor at doing so. Although some investigators have failed to find greater masking effects for listeners with reading disorders compared to normal readers (Hazan, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare, 2009), others have replicated the finding. For example, Ziegler, Pech-Georgel, George, Alario, and Lorenzi (2005) showed that consonant recognition was more degraded when noise was present for children with SLI than for children with TLD. Most recently, Ziegler, Pech-Georgel, George, and Lorenzi (2009) found that children with RD were poorer at recognizing words presented in noise than were children with TLD. Additionally they observed that the children with RD were poorer at recognizing steady-state sine waves modulated to replicate the amplitude envelopes of speech. Because of that combination of findings, these authors concluded that children with RD lack what they termed “speech robustness,” meaning that they did not have as stable phonological representations as other children. The notion of stable representations may be interpreted as meaning something slightly different from, though closely related to, the notion of precise representations. The latter suggests how well defined those representations are; the former suggests the idea of steadfastness, even in the face of perturbation. At present it is impossible to disentangle these notions. As with Brady et al., however, Ziegler et al. concluded that stable representations protect against the deleterious effects of noise masking. Of potential significance to the contradiction in findings across studies is the fact that Hazan et al. failed to find greater masking for adult dyslexics, not children. It could be that individuals with RD eventually develop adequate abilities to recognize words in noise by the time they reach adulthood, even though weak phonological representations persist.

Be that as it may, findings of both weak phonological representations and enhanced masking in children with SLI have been met with varying interpretations. On one hand there are those who would attribute the enhanced masking for speech precisely to those weak representations (e.g., Brady et al., 1983; Johnson, Pennington, Lee, & Boada, 2009; Rosen, Adlard, & van der Lely, 2009; Ziegler et al., 2009). In particular, Johnson et al. demonstrated clearly that poor phonological awareness predicted strong masking effects, not the other way around. On the other hand, there are investigators who view the enhanced masking as the primary deficit for children with SLI, explaining why phonological representations are so weakly established in the first place. In particular, Wright et al. (1997) examined several kinds of masking effects for 8-year-old children with and without SLI using non-speech signals. Results showed that the children with SLI required greater amplitude to detect tones in noise than did the children with TLD, primarily when the noise followed the tone; otherwise masking effects were similar for children with TLD and SLI. Based on that result the authors concluded that masking is the source of the phonological deficits seen in children with SLI: The acoustic properties needed for recovering phonetic structure are simply masked. Although others have subsequently replicated the finding of enhanced backwards masking for children with SLI, the same conclusion was not necessarily reached. Based on findings similar to those of Wright et al., Hartley, Hill, and Moore (2003) concluded that a more appropriate characterization of the problem is that children with SLI are less efficient at processing all acoustic signals, so require better signal-to-noise ratios to make the decision that a tone was heard.

Rosen and Manganari (2001) questioned what the implications of finding evidence of increased backward masking with non-speech stimuli might be for speech perception. If true, they reasoned, the deficits of children with language impairments in discriminating syllable pairs should be limited to syllable-initial distinctions where there is a following sound to serve as a masker. Results of their study, however, failed to support that prediction: Teenagers with SLI demonstrated no difference in their abilities to discriminate “ba” *vs*. “da” as compared to “ab” *vs*. “ad.” Consequently Rosen and Manganari dismissed masking as an explanation for the phonological deficits of children with SLI. That conclusion received resounding support when Rosen et al. (2009), using non-speech stimuli, found that roughly half of the teenagers with SLI whom they tested showed backward and simultaneous masking effects within normal limits for their age. In general, masking has remained as controversial of a potential explanation for the language problems faced by children with SLI and RD as explanations involving auditory sensitivity have been.

The current study

From the descriptions above we find that there have been two general classes of explanation for the deficits exhibited by children with SLI or RD: Those fitting the description of problems in auditory sensitivity to phonetically relevant acoustic properties in the speech signal (mostly formant transitions) and those in the class of enhanced masking explanations. One difficulty in trying to decide which of the two might account best for the problems of children with SLI or RD is that seldom have the two classes of explanation been tested with the same set of stimuli in the same children. The current study sought to correct that oversight by using the same stimuli to ask if children with SLI and/or RD demonstrate either of these sorts of problems, compared to their peers with TLD. Because phonological processing deficits are viewed as the common problem underlying both these disorders, children in this study were explicitly selected to have such deficits. Specifically then, this study was designed to ask two questions: 1) Do children with phonological processing deficits (PPD) demonstrate a deficit in auditory sensitivity to speech-relevant acoustic properties when compared to children with TLD? and/or 2) Do children with PPD experience greater masking effects for acoustic properties underlying speech perception? In this study, only the effects of masking on speech-relevant signal properties were examined. The stance was taken that if enhanced masking effects can explain any part of those weak phonological representations, evidence of masking for signal components relevant to phonetic categorization would need to be demonstrated.

Method

Participants

Fourteen adults (5 women, 9 men) and 28 children (7 girls, 21 boys) in the second half of second grade participated. The low proportion of girls reflects the fact that boys are more likely to be diagnosed with language problems (e.g., Choudhury & Benasich, 2003). All listeners reported being native speakers of American English and passed hearing screenings of the pure tones 0.5, 1.0, 2.0, 4.0, and 6.0 kHz presented at 25 dB HL to each ear separately. Adults were between the ages of 18 and 40 and all had at least an 11th grade reading level, determined by the reading subtest of the Wide Range Achievement Test-4 (WRAT-4; Wilkinson & Robertson, 2006).

Children were grouped by whether or not they had ever been diagnosed with a language impairment: 14 children had not been, and so were labeled as having typical language development, and 14 children had been diagnosed with a language impairment, which could mean a reading problem, by a speech-language pathologist. Testing conducted as part of the experimental protocol indicated that children in this group exhibited poorer phonological awareness than the children with TLD, and so this group was characterized by deficits in phonological processing. Mean age was 8 years, 5 months for the TLD group and 8 years, 3 months for the PPD group, with a standard deviation of 4 months for both. Groups were matched for gender composition as closely as possible, with four girls in the TLD group and three girls in the PPD group.

All children were recruited from the same suburban Columbus, Ohio school district. In the spring of the year, speech-language pathologists were asked to refer second graders with language problems who showed no signs of other deficits. In particular, all children were reported by referring speech-language pathologists to have non-verbal cognitive abilities within normal limits, no motor problems, no attention deficits, and no pragmatic problems, including those on the autism spectrum. These evaluations were gleaned from the records of the speech-language pathologists, who all followed similar evaluation protocols. Children in the TLD group came from the same schools as the children with language problems. Further testing to document abilities such as non-verbal, motor, or pragmatics were not done as part of the experimental protocol in this study both because these skills were already deemed to be within normal limits for the children with language problems by the referring speech-language pathologists and because the experimental protocol already involved three full sessions of testing.

The screening measures that were administered were given primarily to ensure that children in the TLD group did not have any speech or language problems that might have gone undiagnosed. One such measure involved speech articulation. The Goldman-Fristoe 2 Test of Articulation, Sounds-in-Words subtest (Goldman & Fristoe, 2000) was used, and all children in the TLD group were found to be error free. Eight children in the language-impaired group were similarly error free, but six children made one or more errors on this subtest. That was not considered to be reason for exclusion from participation precisely because speech sound disorder is known to co-occur with language impairment (Pennington & Bishop, 2009).

The reading subtest of the WRAT-4 was used to index reading abilities. Means in raw scores, standard scores and percentiles are given in Table 1. Although the mean score for children in the PPD group was not more than one standard deviation below the normative mean, a cutoff often used in clinical practice, it was more than two standard deviations below the mean of the TLD group. There was no overlap in scores for children in the two groups, and scores for the PPD children indicate that they were generally two years behind their peers in reading abilities.

For a screening of language abilities, one subtest from the Clinical Evaluation of Language Fundamentals, Fourth Edition (CELF-4; Semel, Wiig, & Secord, 2003) was administered: Recalling Sentences. This subtest was selected because it provides information about both expressive language and verbal working memory. Again, the mean score for children in the PPD group was not more than one standard deviation below the normative mean, but scores in this case were 1.5 standard deviations below the mean for the control group of children with TLD, with little overlap between groups. Taken together, scores from the reading subtest of the WRAT-4 and the sentence recall subtest of the CELF-4 suggest that children with PPD had weaker language abilities than typical children of the same age.

Equipment and materials

Testing took place in a sound booth with the computer that controlled the experiments in an adjacent room. Hearing was screened with a Welch Allyn TM262 audiometer and TDH-39 earphones. All stimuli were stored on the computer and presented through a Creative Labs Soundblaster card, a Samson headphone amplifier, and AKG-K141 headphones. The experimenter recorded responses onto the computer.

For the labeling tasks, two hand-drawn pictures (8 in. × 8 in.) were used to represent each response label: a picture of a brown boot was used for *boot* and a picture of a ghost was used for *booed*. For the discrimination tasks, a cardboard response card (4 in. × 14 in.) with a line dividing it into two 7-in. halves was used with all participants. On one half of the card were two black squares, and on the other half were one black square and one red circle. Ten other cardboard cards (4 in. × 14 in., not divided in half) were used for training with children. On six cards were two drawings of common objects (e.g., hat, flower). On three of these cards the same object was drawn twice, identical in size and color, and on the other three cards two different objects were drawn. On the remaining four cards were two drawings each of simple geometric shapes. Two cards showed the same shapes and the other two cards showed different shapes. Game boards with 10 steps were also used with children for all tasks. Cartoon pictures were used as reinforcement and were presented on a color monitor after completion of each block of stimuli, along with the sound of a bell.

Experimental tasks and stimuli

Experimental tasks fit four general categories: 1) phonological awareness; 2) word recognition in noise; 3) discrimination of non-speech spectral glides in quiet and noise; and 4) labeling of words with voiced and voiceless final stops in quiet and noise. All tasks used digitized stimuli with a 22.05 kHz sampling rate and 16 bit digitization; none was administered by live voice. All stimuli were presented at 68 dB SPL.

1) Phonological awareness—A central theme underlying this work is that many, if not all language impairments arise from specific difficulty on the part of affected individuals in recovering phonological structure, mainly phonetic structure, from the acoustic speech signal. For that reason, it was imperative that sensitive measurements be made of the abilities of participants in this study to recognize and manipulate that kind of structure.

Three phonological awareness tasks varying in difficulty were administered to each participant. The first task (and developmentally easiest) was one in which children must decide whether two words begin with the same or different initial consonants, termed the “initial consonant same-or-different” (ICSD) task. It was expected that both groups of children would demonstrate high levels of success with this task, indicating that all children had sensitivity to some level of phonetic structure, and the metalinguistic abilities to perform these sorts of tasks. This particular task was similar to one reported by Stanovich, Cunningham, and Cramer (1984), except that some words had consonant clusters in the target position, making it slightly more difficult. The 48 items on this task are shown in Appendix A.

The second task was one in which children had to decide which word, out of three, ends with the same final consonant as a target word. It was termed the “final consonant choice” (FCC) task. This task was more difficult than the first for two reasons. First, judgments regarding phonemes in the final position tend to be harder than judgments about initial phonemes (Hulme et al., 2002). Second, whereas the first task required the comparison of two items, the second required comparing a target to three items. This task was also similar to one reported by Stanovich et al. (1984), although consonant clusters were again included, making it more difficult than what they used. The 48 items used in this task are shown in Appendix B.

The third task examined a skill that is learned at older ages (e.g., Nittrouer, 1999). The “phoneme deletion” (PhonD) task had 32 items and required that the child provide the real word that would derive if a specified segment was removed from a nonsense syllable. This task is more difficult than the first two because the child not only has to access the phonological structure of an item, but also has to remove one segment from that structure, and blend the remaining parts. The items on this task are shown in Appendix C.

For each task, the number of items correct was the dependent measure. The software randomized the order of presentation of items within each task for each listener separately. In the FCC task with three items from which an answer could be selected, the order of presentation of those items was also randomized. The experimental trials for each task were preceded by six practice trials in which the listener received feedback about their responses. Once testing started, no feedback was provided.

2) Word recognition in noise—This task was included to quantify the magnitude of masking effects on speech for these children. Unlike most other experiments looking at word recognition in noise for children with PPD, a range of signal-to-noise ratios (SNRs) was used in this study. This made it possible to examine whether any potential disparities between children with TLD and those with PPD are influenced by the amount of noise. If children with PPD show greater masking effects than children with TLD, we might expect the magnitude of those group differences to increase with increasing noise levels.

Twenty word lists were used, each with ten phonetically balanced consonant-vowel-consonant (CVC) words. These word lists were taken from Mackersie, Boothroyd, and Minniear (2001). Noise with a flat spectrum was generated using a random-noise generator. The level of the noise relative to the speech stimuli varied in five equal steps between -6 and +6 dB, a range that has previously resulted in recognition scores between 25% and 75% correct for adults and children with TLD (Nittrouer, 2005). Four word lists were presented at each of the five SNRs. During presentation, the level of the words was held constant at 68 dB and the level of noise varied. Speech stimuli were mixed with the noise for each listener separately such that different lists were presented at each of the five SNRs across listeners. Furthermore, order of presentation of the lists varied across listeners so that the order of presentation of SNR was randomized. To ensure that recognition scores in noise reflected masking effects, rather than how well listeners can recognize the specific words, recognition scores in quiet were obtained after the speech in noise task was completed.

The dependent measure was the percentage of words recognized correctly. The experimenter recorded onto the computer whether the response was correct or not. The word had to be completely correct to be counted as such. Listeners had to correctly recognize at least 180 of the 200 words (90%) when presented in quiet to have their data included in this analysis.

3) Discrimination of non-speech spectral glides—Most hypotheses suggesting that problems in auditory sensitivity are the source of difficulty for children with SLI or RD focus on formant transitions as the locus of those problems. For that reason, children’s sensitivity to spectral glides, the non-speech equivalent of formant transitions, was examined.

Stimuli used for this task were composites of three sine waves, which can be designed so that listeners are predisposed to hear them as speech. However, that generally occurs with sentence-length stimuli. In this study the sine wave stimuli were brief, and instructions provided to listeners did not describe them in speech terms. Consequently listeners were not expected to recover a speech-like percept from these stimuli, and no listener reported hearing one.

Sine wave stimuli were created using TONE (Tice & Carrell, 1997). All were 150 ms long. The first 100 ms consisted of three steady-state sinusoids of the frequencies 650 Hz, 1130 Hz, and 2600 Hz. Thirteen stimuli were created by having the sinusoids fall over the last 50 ms by varying amounts. In this way they replicated the falling formants of words with mid-central vowels followed by bilabial stops. One stimulus (the “standard”) had flat tones throughout. The other twelve stimuli formed a continuum with all three sinusoids falling to ending frequencies that varied in 20-Hz steps. Offset frequencies varied between 650 Hz and 410 Hz for the lowest tone, between 1130 Hz and 890 Hz for the middle tone, and between 2600 Hz and 2360 Hz for the highest tone. For the noise condition, noise was generated in the same way as for the speech recognition task. Stimuli were presented in noise at 0 dB SNR.

An AX procedure was used, and the standard (A) was the stimulus without glides. Each of the 13 stimuli, including the standard, was presented as a comparison stimulus (X). The inter-stimulus interval was 450 ms. In the noise condition, stimuli were embedded in the middle of 550 ms of noise, with 50-ms on and off ramps, leaving 50-ms gaps in the noise between the A and the X interval.

Participants responded by pointing to the picture of the two black squares and saying *same* if the stimuli were judged as being the same, and by pointing to the picture of the black square and red circle and saying *different* if the stimuli were judged as different.

Several kinds of training were provided. Before any testing with the acoustic stimuli was done with children, they were shown the drawings of the six same and different objects and asked to report if the two objects on each card were the same or different. Feedback was given at this point, if needed. Then they were shown the four cards with drawings of same and different geometric shapes and asked to report if the two shapes were the same or different, without feedback. Participants had to be able to respond correctly to all cards to move on to training with auditory stimuli. Finally, children were shown the card with the two squares on one half and a circle and a square on the other half and asked to point to “same” and to “different.” Adults’ training started with this step. These preliminary steps with visual stimuli ensured that all participants understood the concepts of same and different.

Next, all participants were presented with two pairs of acoustic stimuli: one pair consisting of the steady-state tone (the A stimulus) presented twice, and one pair consisting of that stimulus and the maximally different stimulus, each presented once. These pairs were presented five times in random order. Participants were asked to report whether the stimuli were the same or different and were given feedback. Then these same training stimuli were presented, and participants had to report if they were the same or different, but without feedback. Participants needed to respond correctly to nine of ten trials without feedback in order to proceed to testing in the quiet condition. For the noise condition one additional preliminary task was inserted: The stimuli were presented in noise at a +6 dB SNR. The listener again needed to respond correctly to at least nine of ten presentations to proceed to testing. During testing, the 13 stimulus pairs were presented in random order ten times each, in blocks of 13. Listeners needed to respond correctly to 80% of the physically identical and maximally different pairs during testing in order for their data to be included in the analyses. Children moved a marker to the next number on the game board after each block.

The discrimination functions of each participant formed cumulative normal distributions, and probit functions were fit to these distributions (Finney, 1971). From these fitted functions, distribution means were calculated and termed “difference thresholds.” These thresholds were the 50% points on the fitted discrimination functions and were used in statistical analyses to examine potential differences in sensitivity between groups, and differences between the quiet and noise conditions within each group. The slopes of those functions were also computed, and are the change in probit units per stimulus step. Here these values were multiplied by 1 kHz to create whole numbers that are more interpretable.

4) Labeling of words with voiced and voiceless final stops—Again, the most influential hypothesis suggesting that poor auditory sensitivity to speech-relevant acoustic properties explains the problems that children with language deficits experience in recovering phonological structure from the speech signal focuses on formant transitions (e.g., Tallal, 1980; Tallal & Piercy, 1974; Tallal et al., 1996). For that reason, a labeling task was used that involved a manipulation in the extent of formant transitions. At the same time, if a deficit in making phonetic decisions based on formant transitions were to be observed for children with PPD it would be important to demonstrate that these children do not simply lack sensitivity to speech-relevant acoustic properties of any kind. Therefore, stimuli in this labeling task also involved another property: stimulus duration.

Stimuli were natural tokens of an adult, male speaker saying *boot* and *booed*. Most experiments examining phonetic labeling by children with SLI or RD have used syllable-initial contrasts. By using a syllable-final contrast, the source of masking (in the noise condition) would be attributable solely to the noise, rather than to any syllable components that might follow the phonetic segment being labeled. Three tokens of each were used so there was variation in properties such as fundamental frequency and intonation.

For each word, the release burst of the final stop and any voicing during closure was deleted. Vocalic length was manipulated either by reiterating a single pitch period from the most stable region of the vocalic portion or by deleting pitch periods from that stable region. Thus, formant offset transitions were left intact. Seven stimuli were created for each token in this way, varying in length from the mean length of the three tokens of the word ending in a voiceless stop to the mean length of the three tokens ending in a voiced stop (97 to 258 ms). Steps were kept as equal in size as possible across the continua, averaging 27 Hz, or two pitch periods. Mean F1 frequency at voicing offset was 300 Hz across the three tokens of *boot* and 268 Hz across the three tokens of *booed*. For the noise condition, noise was generated in the same way as for the speech recognition task, and the stimuli were presented at 0 dB SNR. Noise files were 1 sec long, with 100-ms on and off ramps. Words were embedded in the middle.

During the labeling tasks, listeners responded by saying the label and pointing to the picture that represented their selection. Several kinds of training were provided. First, unedited versions of the words (i.e., with the release bursts and voicing during closures intact) were presented. Each of the six words (e.g., three tokens each of *boot* and *booed*) was presented twice. The listener had to respond correctly to at least 11 of the 12 without feedback to proceed to the next preliminary task. This requirement ensured that all listeners could perform the task and that they recognized the voicing distinction for completely intact words presented in quiet. Next the best exemplars of the six stimuli were presented twice each in quiet. The term “best exemplar” is used here to refer to the stimulus in which formant transitions and vocalic duration most clearly signaled a specific voicing decision. These stimuli had the final release bursts and any voicing during closure removed. The listener needed to respond correctly to at least 11 of the 12 best exemplars without feedback to proceed to testing in the quiet condition. This requirement ensured that all listeners were able to make voicing judgments based on one or the other of the available cues (vocalic duration and formant transitions), or a combination of those cues. For the noise condition, an additional preliminary task was administered: Stimuli were also presented in noise at a +6 dB SNR. The listener again needed to respond correctly to at least 11 of the 12 presentations to proceed to testing. During testing, ten blocks of the 14 stimuli were presented. To have their data included in the final analyses, listeners needed to respond correctly to 80% of the endpoint stimuli during testing. Because there were three tokens with each kind of offset transition (voiced or voiceless), the program was designed to select randomly one of the three to present during the first block, and then repeat this random selection during the next block without replacement. After three blocks the process was repeated until ten blocks had been presented. Children moved a marker to the next number on the game board after each block.

Each listener’s labeling responses were used to construct cumulative distributions of the proportion of *booed* responses across levels of the acoustic property manipulated in a continuous fashion (vocalic duration in this study) for each level of the acoustic property manipulated in a dichotomous fashion (formant offsets in this study). Best-fit lines were then obtained using probit analysis (Finney, 1971). From these probit functions, distribution means (i.e., phoneme boundaries) and slopes were computed. Typically phoneme boundaries are given in physical units for the property manipulated in a continuous fashion, such as Hz or ms. However, here pitch periods were deleted or reiterated to form the continuum, so step size varied slightly. Consequently, phoneme boundaries are given in steps as the units of description. Similarly, slope is given as the change in probit units per step. Probit analysis can extrapolate so that phoneme boundaries outside of the range tested can be obtained. For this work, the values that extrapolated phoneme boundaries could take were limited to 3.5 steps beyond the lowest and highest values tested.

Table 2 indicates which of the two possible effects originally hypothesized to possibly underlie phonological processing deficits (auditory sensitivity or enhanced masking) each dependent measure most clearly examined.

General test procedures

Testing took place over three sessions on different days distributed across no more than two weeks. For all children, this testing occurred in the spring or early summer of their second grade year. In the first session the screening measures were administered, followed by the 20 word lists in noise. All participants heard the 20 word lists in noise on the first day and in quiet on the third day in order to diminish the possibility that there would be learning effects. After the word lists on the first day, listeners were presented with one of the three phonological awareness tasks. One phonological awareness task was presented in each session with the order varied across listeners. The last task presented in the first session was one of the discrimination or labeling tasks, in either noise or quiet. Order of presentation of the four discrimination and labeling tasks (one of each in noise and quiet) was randomized across listeners and spread out over the three sessions. On the second day, listeners were presented with one discrimination and one labeling task (one in quiet and one in noise), with a phonological awareness task between them. On the final day, participants heard the 20 word lists in quiet, followed by the last phonological awareness and discrimination or labeling tasks.

Results

1) Phonological Awareness

Table 3 displays group means (and standard deviations) for the number of items correct on the three phonological awareness tasks. One-way analyses of variance (ANOVAs) with group as the between-subjects factor were performed on data from each task. Because outcomes were significant for all three, *post hoc t* tests were done. Results are shown in Table 4. Here, as with other analyses, exact p values are given when $p < .10$. Results are described simply as not significant (NS) when $p > .10$.

For the ICSD task, the main effect of group was significant, but only the *post hoc* comparison of adults *vs*. children with PPD was significant. Children in the TLD and PPD groups did not perform differently from each other on the ICSD task, indicating that the children with PPD had sensitivity to phonetic structure at this level. The main effect of group was significant for both the FCC and PhonD tasks, with children in the PPD group performing significantly more poorly than adults and children in the TLD group on both tasks. Children in the TLD group performed similarly to adults on the FCC task, but more poorly on the PhonD task.

Finally, a two-way ANOVA was performed using data only from the two children's groups, with group as the between-subjects factor and task as the within-subjects factor. Both main effects were statistically significant: group, $F(1,26) = 11.49$, $p = .002$, and task, $F(2,52) = 42.96$, $p < .001$. In addition, the Group × Task interaction was significant, $F(2,52) = 6.56$, $p = .003$. Thus, performance by the children with PPD did indeed diminish across tasks from the developmentally simplest to the harder tasks relative to that of the children with TLD.

2) Word recognition in noise

Figure 1 shows mean percent-correct recognition scores for each group in quiet and at each SNR. All participants were able to recognize more than 90% of the words correctly in quiet. Specifically, mean scores in quiet (and standard deviations) were 98.1% (0.9%) for adults, 95.5% (1.6%) for the TLD group, and 94.1% (2.2%) for the PPD group. A one-way ANOVA done with group as the between-subjects factor showed a significant group effect, $F(2,39) = 21.36$, $p < .001$. The pairwise t tests showed that adults performed differently from both children with TLD, $t(39) = 4.16$, $p < .001$, and children with PPD, $t(39) = 6.45$, $p < .001$. When Bonferroni corrections for multiple comparisons were applied, both of these p values were significant at the .001 level. The comparison of children with TLD and PPD was also significant, $t(39) = 2.28$, $p = .028$, but is significant at only the .10 level when a Bonferroni correction is applied.

Turning to recognition in noise, scores were similar for the two children's groups while adults had scores roughly 5-15 percentage points better than those of the children's groups at all SNRs. Across SNRs, mean recognition scores (and standard deviations) were 41.3% (5.1%) for adults, 31.5% (3.5%) for the TLD group, and 29.9% (3.0%) for the PPD group. A two-way ANOVA was performed on these recognition scores in noise, with group as the between-subjects factor and SNR as the within-subjects factor. The main effect of group was significant, $F(2,39) = 33.24$, $p < .001$, as was the main effect of SNR, $F(4,156) = 286.96$, $p < .001$. The Group × SNR interaction was not significant, so the decrease in scores with decreasing SNR was consistent across groups. The significant group effect was due to the better overall recognition scores demonstrated by adults. Using pairwise t tests to compare mean recognition scores across SNRs, significant differences were found for adults *vs*. TLD, $t(39) = 6.48$, $p < .001$, and adults *vs.* PPD, $t(39) = 7.52$, $p < .001$. Both are significant at the .001 level with Bonferroni corrections. No difference was found for the two groups of children, so it may be concluded that they demonstrated equivalent abilities to recognize these words in noise.

3) Discrimination of non-speech spectral glides

One child with PPD failed to recognize 80% of the endpoints correctly (i.e., presentation of the physically identical and maximally different tones) during testing of both conditions and another child with PPD failed to recognize at least 80% in the noise condition, so their data were excluded from the standard analysis. Both children demonstrated the greatest difficulty correctly recognizing the physically identical tones as the same, with each child only recognizing one of the maximally different pairs incorrectly. One child reported hearing 60% of the pairs with physically identical stimuli as different in quiet and 70% as different in noise. The other child reported hearing 50% of the identical pairs as different in the noise condition. The fact that incorrectly judging identical tones as different yields a smaller difference threshold means that including data from these two children would have artificially decreased the mean difference threshold for the PPD group. That is, by demonstrating the tendency to label all presentations, including the identical tones, as different, the participants' difference thresholds, and so the group mean, would indicate that a smaller frequency change is needed for these children to notice a difference between two stimuli. In fact, the more accurate account of their performance is that they failed to form salient and consistent representations of the standard stimulus.

Quiet condition—Figure 2 shows discrimination functions for the quiet and noise conditions separately for each group. The F1 offset frequency of the comparison stimulus is shown on the x axis. From left to right, comparison stimuli change from being identical to the standard to being maximally different. Table 5 lists mean difference thresholds and slopes for each group for the quiet and noise conditions. From the table it appears that the children with PPD required more extensive glides (i.e., lower F1 offset frequencies) than both the adults and TLD group to judge non-speech stimuli as different in the quiet condition: Difference thresholds were roughly 10 Hz greater for the PPD group than for the other two groups. However, a one-way ANOVA computed on difference thresholds in the quiet condition with group as the between-subject variable indicated no significant group effect. Therefore, it should be concluded that the children with PPD were no less sensitive to the glides than were listeners in the other two groups.

Whereas the difference thresholds indicate sensitivity to glides, slope in this case indicates consistency of responses, which is a metric of how firmly categories were established. From both Figure 2 and Table 5 it appears that children were less consistent than adults in their discrimination. A one-way ANOVA with group as the between-subjects factor was performed on slopes in the quiet condition. A significant group effect was found for the quiet condition, so pairwise *post hoc* comparisons were done. Results are presented in Table 6, and support impressions from Figure 2 and Table 5. Of the three groups, adults showed the steepest slopes, indicating that the adults were significantly more consistent in their responses. Children with PPD did not differ from those with TLD.

In spite of finding no significant difference in slopes for the two children's groups, it appears that children in the PPD group were less consistent in discriminating stimuli near the endpoints, particularly the "same" endpoint. In an AX task, the ability to correctly judge physically identical stimuli as the same is an indication of how well the listener has formed a category for the standard (A) and is able to recognize stimuli as members of that category. Whereas the adults and TLD group demonstrated no or little difficulty correctly judging physically identical stimuli as the same, the children with PPD had greater difficulty. Mean "different" responses (and standard deviations) were 0.0% (0%), 2.8% (6.1%), and 9.2%

(11.2%) for adults, TLD and PPD groups, respectively. When data from the two children with PPD whose data were excluded are added back in, mean "different" responses for their group jumps to 12.9% (17.3%). These scores showed a significant group effect, $F(2,39) = 8.87$, $p < .001$, and *post hoc t* tests between the PPD group and each of the other groups were significant: PPD *vs*. adults, $t(39) = 4.08$, $p < .001$, and PPD *vs*. TLD, $t(39) = 2.95$, $p = .005$. With Bonferroni corrections, the first of these is significant at the .001 level and the second is significant at the .05 level. From these results, it appears that the children with PPD had difficulty forming a precise "standard" category. And it should be added that this trend was not for a minority of the children with PPD: All of the adults recognized all of the physically identical pairs as the same, as did 11 of the 14 children with TLD. Only five of the 14 children with PPD had perfect recognition scores for these physically identical stimuli.

Next, discrimination of maximally different stimuli is considered. In an AX task, the discrimination of different stimuli is generally taken as an indication of how sensitive a listener is to a physical difference between the standard and other stimuli. Once the proportion of "different" responses reaches asymptote, however, stimuli beyond that point might be considered as exemplars of a "different" category. Therefore, the consistency of responses to those stimuli can also index listeners' abilities to form categories. In this study the decision was made to examine discrimination for the five stimuli closest to the 410-Hz end of the continuum because functions were relatively flat across those five (i.e., reached asymptote), for all three groups. Mean "different" responses (and standard deviations) were 99.1% (2.8%) for adults, 96.0% (6.5%) for the TLD group, and 93.1% (13.0%) for the PPD group. When data from the two children with PPD whose data had been excluded are added back in, this last value does not really change: It is 92.9% (12.5%). The main effect of group was significant, $F(2,39) = 4.48$, $p = .012$, but only the *post hoc t* test of adults *vs*. children with PPD was significant, $t(39) = 2.99$, $p = .005$. With a Bonferroni correction, this is significant at the .05 level. Taken together, results from this discrimination task indicate that the children with PPD had similar sensitivities to glides as listeners in the other groups, but had more difficulty creating stable categories near the continuum endpoints. This specific finding was not predicted as a possible outcome before testing, but could nonetheless help explain some inconsistencies in previously reported data from experiments designed to examine the sensitivity of children with PPD to changes in acoustic properties. If children with PPD actually have difficulty forming categories it means that they may be biased towards responding that stimuli are different, whether they really recognize that difference or not. That situation would blur results across studies on auditory sensitivity because results could vary depending on how much the dependent measure required categorization of some kind. In this study, it helps to explain why there was a difference between the two children's groups for the physically identical stimuli, but not for stimuli close to the maximally different end of the continuum.

Noise condition—Results of discrimination in noise provide information regarding the effects of masking on the perception of auditory cues. If enhanced masking can explain the language deficits of children with PPD we would expect performance by these children to be more greatly and negatively affected by having to make discrimination judgments in noise. To test that prediction, within-groups *t* tests were computed comparing difference thresholds and slopes in quiet and in noise. A significant noise effect was found only for difference thresholds and only for the TLD group, $t(13) = 3.00$, $p = .010$, indicating that these children were slightly less sensitive to glides when they were presented in noise. No difference was found for the PPD group, indicating that these children did not experience enhanced masking of this particular cue. The concern might be raised that the failure to find stronger masking effects, and to find them for more listeners, could indicate that the level of masking selected simply was not great enough. However, it will be recalled that at 0 dB SNR listeners generally had only 15 to 45 percent correct word recognition.

4) Labeling of voiced and voiceless final stops

All listeners responded with better than 80% accuracy to endpoint stimuli in this task, and so data from all participants were included.

Quiet condition—Figure 3 shows the labeling functions for these speech stimuli. Vocalic duration is shown on the x axis, and changes, left to right, from shortest (most *boot*-like) to longest (most *booed*-like). Separate functions are shown for stimuli with *boot* and *booed* offset transitions. Functions appear similarly placed for all three groups, and indicate that listeners responded *booed* at relatively short vocalic durations when offset transitions were appropriate for this voiced final stop. Vocalic duration had to be substantially longer for listeners to respond *booed* when formant transitions were appropriate for *boot*. In fact, labeling functions barely crossed the 50% line for adults, and did not for children.

Table 7 shows phoneme boundaries, differences in phoneme boundaries, and slopes for each group separately when stimuli were presented in quiet and at 0 dB SNR. None of the one-way ANOVAs performed on phoneme boundaries revealed any group differences in placement of these boundaries, even though it appears as if children, particularly those in the PPD group, placed phoneme boundaries at longer vocalic durations than adults when offset transitions were appropriate for *boot*. The separation between labeling functions (measured as the difference between phoneme boundaries of the *boot* and *booed* continua) indexes the weight assigned to offset transitions (Nittrouer, 2004). Here it appears as if children with PPD weighted those offset transitions more than listeners in the other two groups. To investigate possible group differences in weighting of formant transitions, a one-way ANOVA with group as the between-subjects factor was performed on these difference scores (i.e., *boot* boundary - *booed* boundary). Again, no statistically significant group effect was found. Therefore, these results indicate only that the children with PPD did not have any particular difficulty attending to formant transitions and that these children assigned similar perceptual weight to these dynamic cues as did both the adults and children with TLD.

For labeling tasks that vary two cues, the slope of the functions indexes the amount of perceptual weight assigned to the acoustic property represented on the x axis, which is vocalic duration in this case (Nittrouer, 2004). One-way ANOVAs revealed significant group effects for the slopes of both *boot* and *booed* stimuli, and so *post hoc t* tests were done comparing each group to the others. Results are shown in Table 8. Significant *post hoc* comparisons were observed between adults and both groups of children for stimuli with *boot* offset transitions, and between the adults and children with TLD for stimuli with *booed* offset transitions. No significant differences between the two groups of children were found. This leads to the conclusion that, in general, adults assigned more weight to vocalic duration than children, but children with PPD assigned similar weights as did children with TLD.

Noise condition—Listeners were asked to label these stimuli in noise to examine whether the PPD group experienced increased masking of phonetically relevant acoustic cues, specifically of offset formant transitions. Increased masking of these cues would yield less separation between labeling functions, or less weight assigned to the transitions in the noise condition as compared to quiet. Figure 3 shows that the labeling functions for all three groups appear similar for stimuli presented in quiet and at 0 dB SNR (i.e., when comparing the quiet and noise conditions within each group), suggesting that none of the groups experienced masking of the formant transitions. Additionally, the steepness of the labeling functions for each group look similar across the quiet and noise conditions, suggesting little to no change in weight assigned to vocalic duration. Paired *t* tests were computed to examine potential effects of noise on differences in phoneme boundaries or slopes for each group separately. No significant effects were found for changes in the separation of labeling functions, indicating that the weight assigned to offset transitions did not change with the introduction of noise for any group.

When it comes to slope, however, some significant differences across conditions were found. For slope of the *boot* labeling function, a significant difference in steepness was found for the TLD group, $t(13) = 2.24$, $p = .043$, reflecting an increase in steepness for the noise over the quiet condition. Results approached significance for both the adults, $t(13) = 2.10$, $p = .056$, and the PPD group, $t(13) = 2.14$, $p = .052$, similarly reflecting an increase in steepness for the noise condition. Significant results were also found for changes in slope for the *booed* stimuli between the two conditions, but only for adults, $t(13) = 2.35$, $p = .035$. Again, slope increased in the noise condition, compared to the quiet condition. These increases in slope (obtained from children with TLD for the *boot* condition and from adults for the *booed* condition) when stimuli were embedded in noise indicate that more perceptual weight was assigned to vocalic duration. That shift presumably would occur if formant transitions were masked, but vocalic duration was still readily available. The small, but statistically non-significant, decrease in separation between *boot* and *booed* functions for the noise condition, compared to the quiet condition, supports that suggestion. The fact that children with PPD were the only group to demonstrate no shift for either formant condition provides weak evidence that they may not be as facile at changing perceptual strategies as are listeners in the other two groups. However, the finding provides no evidence of enhanced masking for the children with PPD, and so it seems fair to conclude that these children did not experience greater masking.

Discussion

The purpose of the current experiment was to examine possible differences in auditory sensitivities and masking effects between children with PPD and those with TLD. Prominent hypotheses have suggested that either diminished sensitivity to acoustic properties, particularly formant transitions, or enhanced masking of speech-relevant properties may account for the poor abilities at recovering phonological structure from the speech stream exhibited by many children with language impairments. Accordingly this study focused on two main questions: 1) Do children with PPD demonstrate a difference in auditory sensitivity to speech-relevant acoustic properties? and/or 2) Do children with PPD show greater masking of those properties?

To address these questions, three groups of listeners participated: adults and two groups of children. On the basis of their word reading and sentence recall abilities, the children with PPD were found to form a group distinct from the TLD group on language skills other than those specifically affiliated with phonological processing, even though the performance of children with PPD on those skills would not be categorized as clinically significant in many cases. Of greater importance to the hypothesis being examined was the finding that children in the PPD group performed significantly more poorly on two phonological awareness tasks than the children in the TLD group. The fact that children in both groups performed similarly on one phonological awareness task, the simplest, indicates that children in the PPD group had some awareness of phonological structure and were able to perform the sorts of meta-cognitive operations required by these tasks. Thus their poor performance on the other two tasks was taken as evidence that they did indeed have a weaker grasp of phonological structure.

Results from the non-speech discrimination task showed that children in the two groups had similar sensitivities to spectral glides, the non-speech equivalent of formant transitions. Furthermore, the phonetic labeling task showed that children with PPD weighted formant transitions at least as strongly as adults and children with TLD: Differences in phoneme boundaries as a function of offset transitions were slightly greater for the children with PPD, although the difference was not statistically significant. So to answer the first question posed by this study, the children with PPD did not have impaired sensitivity to the acoustic properties underlying phonetic categorization. In spite of similar sensitivities for the spectral glides, however, children with PPD were found to be less consistent in deciding whether stimuli near the endpoints of the non-speech continuum were the same or different. Because AX discrimination can be viewed as a categorization task in which the perceiver forms a category for the standard (A) and must decide if the comparison stimulus (X) is a member of that category or not, it appears that children with PPD were less capable of making this judgment, a possibility not originally predicted. The finding that children with PPD weighted formant transitions at least as much as other listeners in their phonetic judgments means that the finding in the discrimination task can not be dismissed as poorer selective attention to the relevant acoustic property.

The problems that children with PPD demonstrated in discriminating the non-speech pairs near the endpoints are similar to those observed in previous studies for phonetic judgments (e.g., Godfrey, Syrdal-Lasky, Millay, and Knox, 1981; Sussman, 1993). Similarly to the result reported here for non-speech stimuli, Sussman was able to show that the problem children with SLI in that study had in forming phonetic categories was not based on diminished sensitivities to formant transitions. Thus it appears that children with SLI (and so presumably with problems in phonological processing) exhibit a general deficit in their abilities to form both speech and non-speech acoustic categories. The only possible challenge to that conclusion is the fact that unlike earlier studies, children with PPD in this study demonstrated no special problems categorizing endpoints in the phonetic labeling task. However, differences in outcomes across studies might be explained by stimulus design. In earlier studies, single continua varying in the extent to which the formant transitions signaled one phonetic category or the other were created (Godfrey et al., 1981; Sussman, 1993). In order for those traditional categorical perception studies to work, all other acoustic properties are necessarily set to values ambiguous for the two category labels. Such ambiguity might disproportionately affect children with PPD: If they have more difficulty with category formation than other listeners, they may require more complete acoustic information to make judgments than such stimuli can provide. In the current study, two stimulus continua, one with *boot* offset transitions and one with *booed* offset transitions, were created. Vocalic duration varied continuously. This means that listeners in the current study had two properties that they could use in making phonetic decisions: offset formant transitions and vocalic duration. Having two salient properties likely helped children with PPD to categorize these speech stimuli. The non-speech stimuli, on the other hand, varied on only one property.

The second question addressed by this study involved the possibility that children with PPD would demonstrate enhanced masking. In separate earlier studies this effect has been reported either only for non-speech stimuli (e.g., Rosen et al., 2009; Wright et al., 1997) or only for speech stimuli (e.g., Brady et al., 1983; Ziegler et al., 2009). In this study, three tasks failed to find evidence of greater masking on the part of children with PPD compared to children with TLD, for both speech and non-speech stimuli alike. However, results did show that children in general had raised thresholds for speech recognition in background noise compared to adults. At the same time, performance on neither the discrimination with non-speech stimuli task nor the labeling task with speech stimuli was affected by the introduction of noise at 0 dB SNR for children with PPD. Listeners in all groups showed the same weighting of formant transitions for the quiet and noise conditions; adults and children with TLD showed increases in the weighting of vocalic duration in the noise over the quiet condition, but the effect was small. These findings leave open the question of what accounted for masking in the word recognition task because noise did not seem to interfere specifically with listeners' sensitivities to the acoustic properties that were relevant to the decision they needed to make. We suggest that here the notion of "speech robustness" offered by Ziegler et al. (2009) may be especially relevant. Perhaps all children, those with TLD and PPD alike, have less stable phonological representations than adults, and so noise is more readily able to perturb recognition. In other studies where a constant SNR has been used, it may be that children with TLD were able to cope better than children with PPD. In this study, the roving SNR may have introduced enough additional uncertainty to negatively affect children with TLD.

No large differences in speech perception were found for the PPD children compared to the TLD children when examining results from the labeling task. Children with PPD appear to have weighted the dynamic cue, formant transitions, to a slightly greater extent than children with TLD (and adults), judging by the larger separation for children with PPD in labeling functions depending on whether formant transitions were appropriate for one or the other phonetic label. Although this difference in weighting of formant transitions was not statistically significant, its presence does allow us to dismiss the possibility that children in the PPD group were somehow less selectively attentive to spectral glides than listeners in the other two groups. Rather, these children seem to attend quite well to these sorts of properties.

When it comes to the temporal cue, vocalic duration, it was clearly weighted to a similar extent by children in both groups. However, differences were found between the adults and both groups of children in terms of weighting of this cue, judging from slopes of the labeling functions. The adults assigned more weight to vocalic duration than either group of children, a finding that is similar to previous outcomes (e.g., Greenlee, 1980; Nittrouer, 2004). These results provide further contradiction to the predictions of the temporal processing hypothesis: The children with PPD in this study had no greater difficulty harnessing a temporal property for use in linguistic decisions than other children.

In summary, this study was designed to determine whether impaired auditory sensitivity and/or enhanced masking were present in children with PPD. No evidence was found to support either of these suggestions. Children with PPD were equally sensitive to glides in the non-speech discrimination task and assigned equal weight to formant transitions as both adults and age-matched peers. Additionally, these children did not experience greater effects of masking for components of either non-speech or speech signals. In fact, these children did not experience any masking in these tasks at all. However, the children with PPD demonstrated one difference from the other groups: They were less consistent in their judgments of physically identical stimuli as belonging to the same category. Although children with PPD in this experiment demonstrated this deficit strictly for non-speech stimuli, it is consistent with evidence that children with SLI have only weakly formed phonetic categories, as demonstrated by poor performance on tasks requiring them to manipulate phonetic structure in some way (e.g., Crain, 1989; Fletcher et al., 1994; Liberman et al., 1977; Mann & Liberman, 1984; Mody et al., 1997; Nittrouer, 1999; Stanovich, 1988). Combined these results suggest that we may be looking for clues concerning the underlying deficit of SLI in all the wrong places. Perhaps the problems experienced by these children may be attributed to difficulty in using various kinds of sensory input to create well-defined and robust categories. When it comes to speech signals, this idea has been termed "phonetic coherence," and refers to the way that various components of the speech signal are combined to form a linguistically meaningful percept (Best, Studdert-Kennedy, Manuel, & Rubin-Spitz, 1989). This idea differs from traditional notions of categorical perception, which denotes a much more passive process in which stimuli are parsed into one of two categories as a function of settings on a single acoustic property. On the other hand, the notion that children with PPD are poor at creating well-defined, stable categories is complementary to the idea that these children have "phonological coding" problems. Phonological coding connotes the idea that language users need to be able to create welldefined categories from sensory information in the signal. The suggestion that those categories also need to be stable, or robust as Ziegler et al. (2009) phrase it, refers to the idea that the categories should not be easily perturbed by interfering factors such as noise. Results of this study suggest that children who are poor at forming well-defined and stable phonological categories may actually be poor at constructing categories from sensory input in general. The suggestion that the problem underlying phonological processing deficits, and so underlying many language impairments, is a deficit in creating categories may help explain why results of studies using other language measures may be variable where children with language impairments are concerned: The precise behavioral consequences of this underlying deficit likely depend on factors such as the nature of the stimuli used, the ages of the children, and task demands.

There is however, one caveat to offering the deficit in category formation observed here for children with PPD as explanation for the problems underling developmental language impairments, and that is that the children in this study with PPD did not show especially poor performance on the other language measures. Of course, these children were recruited explicitly to have diagnosed language problems, but no other apparent deficits. The reason for this selection criterion was that often children with severe language impairments are diagnosed with other deficits, as well. Consequently, it can be difficult to identify a single source for poor performance on dependent measures. We tried to avoid this situation by recruiting children diagnosed solely with language deficits. At least in this instance, implementing that exclusionary criterion produced a group of children from whom those language deficits were not necessarily severe. It is reasonable to suggest that children with significantly poorer performance on the sentence recall or word reading tasks would have demonstrated only poorer category formation skills than what was observed for the children with PPD in this study. In turn, that deficit in creating well-defined and stable categories may have negatively impacted their abilities to perform other tasks, as well, such as phonetic labeling and word recognition in noise.

The findings reported here emphasize the important role that the ability to perceptually organize sensory information plays in how an individual functions in the world. Future studies need to explicitly examine the hypothesis that, although perfectly sensitive to relevant acoustic structure, children with language impairments related to weak phonological processing abilities are poor at creating phonetic categories from that structure. If such a problem indeed exists, it is likely to be multifaceted in nature, with no immediately predictable relation between signal structure and deficit. It is equally imaginable that children who have difficulty forming perceptual categories would encounter difficulty with impoverished signals, such as ones often used in categorical perception experiments, and with complex stimuli that require the integration of several sensory inputs. Research efforts need to explore thoroughly these relations between signal structure and category formation. Finally, future efforts should also focus on examining how other factors influence the ways that these hypothesized underlying deficits are realized overall in the child's functioning.

Appendix

Appendix A

Items from the initial consonant same-or-different (ICSD) task. Items with the same initial consonant for the target and comparison are italicized.

Practice Items

1. Bark	*Barn*	2. Jump	Shirt	3. Mat	Cap
4. Pet	*Pack*	5. Blue	*Bag*	6. Star	Clown
Test Items					
1. Leap	*Lip*	2. Key	*Kite*	3. Crumb	Drip
4. Date	Bag	5. Gate	*Gum*	6. King	Dime
7. Dark	Pet	8. Toes	*Tip*	9. Class	Swing
10. Web	Man	11. Tree	Star	12. Milk	*Moon*
13. Pin	Boat	14. Claw	*Crib*	15. Lock	Pail
16. Bit	Girl	17. Foot	Pan	18. Drum	Flag
19. Bone	*Bud*	20. Fun	*Fan*	21. Rug	*Rag*
22. Can	Pit	23. Peel	*Pat*	24. Tile	Mask
25. Note	Wheel	26. Meat	Lace	27. Soap	*Salt*
28. Day	Box	29. Wash	Vine	30. Zip	*Zoo*
31. Stick	*Slide*	32. Plum	*Price*	33. Win	*Well*
34. Pear	*Pen*	35. Soup	Light	36. Frog	Brush
37. Fist	Sap	38. Met	*Map*	39. Heel	*House*
40. Leg	*Lock*	41. Prize	Stair	42. Rain	Kid
43. Sled	*Stick*	44. Sun	Bin	45. Sky	*Sleep*
46. Glue	*Grape*	47. Jeep	*Jug*	48. Duck	*Door*

Appendix B

Items from the final consonant choice (FCC) task. The target word is given in the left column, with the three choices in the right columns. The correct response is shown first here and is italicized.

Practice Items							
1. Rib	*Mob*	Phone	Heat	2. Stove	*Cave*	Hose	Stamp
3. Hoof	*Tough*	Shed	Cop	4. Lamp	*Tip*	Rock	Juice
5. Fist	*Hat*	Knob	Stem	6. Head	*Rod*	Hem	Fork
Test Items							
1. Nail	*Bill*	Voice	Chef	2. Car	*Stair*	Foot	Can
3. Hill	*Bowl*	Moon	Hip	4. Pole	*Mail*	Land	Poke
5. Chair	*Deer*	Slide	Chain	6. Door	*Pear*	Food	Dorm
7. Gum	*Lamb*	Shoe	Gust	8. Doll	*Wheel*	Pig	Beef
9. Dime	*Broom*	Note	Cube	10. Train	*Van*	Grade	Cape
11. Home	*Drum*	Mouth	Prince	12. Comb	*Room*	Cob	Drip
13. Pan	*Skin*	Grass	Beach	14. Spoon	*Fin*	Cheese	Back
15. Thumb	*Cream*	Tub	Jug	16. Bear	*Shore*	Rat	Clown
17. Ball	*Pool*	Clip	Steak	18. Rain	*Yawn*	Sled	Thief
19. Hook	*Neck*	Mop	Weed	20. Truck	*Bike*	Trust	Wave
21. Boat	*Skate*	Bone	Frog	22. Mud	*Crowd*	Mug	Dot
23. Hive	*Glove*	Hike	Light	24. Leaf	*Roof*	Leak	Suit
25. Bug	*Leg*	Bus	Rope	26. Cup	*Lip*	Plate	Trash

27. House	*Kiss*	Mall	Dream	28. Fish	*Brush*	Shop	Gym
29. Meat	*Date*	Camp	Sock	30. Duck	*Rake*	Song	Bath
31. Kite	*Bat*	Mouse	Grape	32. Nose	*Maze*	Goose	Zoo
33. Cough	*Knife*	Log	Dough	34. Dress	*Rice*	Noise	Tape
35. Crib	*Job*	Hair	Wish	36. Flag	*Rug*	Step	Cook
37. Worm	*Team*	Soup	Price	38. Wrist	*Throat*	Risk	Store
39. Sand	*Kid*	Sash	Flute	40. Hand	*Lid*	Hail	Run
41. Milk	*Block*	Mitt	Tail	42. Vest	*Cat*	Star	Mess
43. Ant	*Gate*	Fan	School	44. Desk	*Lock*	Tube	Path
45. Barn	*Pin*	Night	Tag	46. Box	*Face*	Mask	Book
47. Park	*Lake*	Bed	Crown	48. Horse	*Ice*	Lunch	Bag

Appendix C

Items from the phoneme deletion (PhonD) task. The segment to be deleted is in parentheses. The correct response is found by removing the segment to be deleted.

Practice Items	
1. pin(t)	2. p(r)ot
3. (t)ink	4. no(s)te
5. bar(p)	6. s(k)elf
Test Items	
1. (b)ice	2. toe(b)
3. (p)ate	4. ace(p)
5. (b)arch	6. tea(p)
7. (k)elm	8. blue(t)
9. jar(l)	10. s(k)ad
11. hil(p)	12. c(r)oal
13. (g)lamp	14. ma(k)t
15. s(p)alt	16. (p)ran
17. s(t)ip	18. fli(m)p
19. c(l)art	20. (b)rock
21. cream(p)	22. hi(f)t
23. dril(k)	24. mee(s)t
25. (s)want	26. p(l)ost
27. her(m)	28. (f)rip
29. tri(s)ck	30. star(p)
31. fla(k)t	32. (s)part

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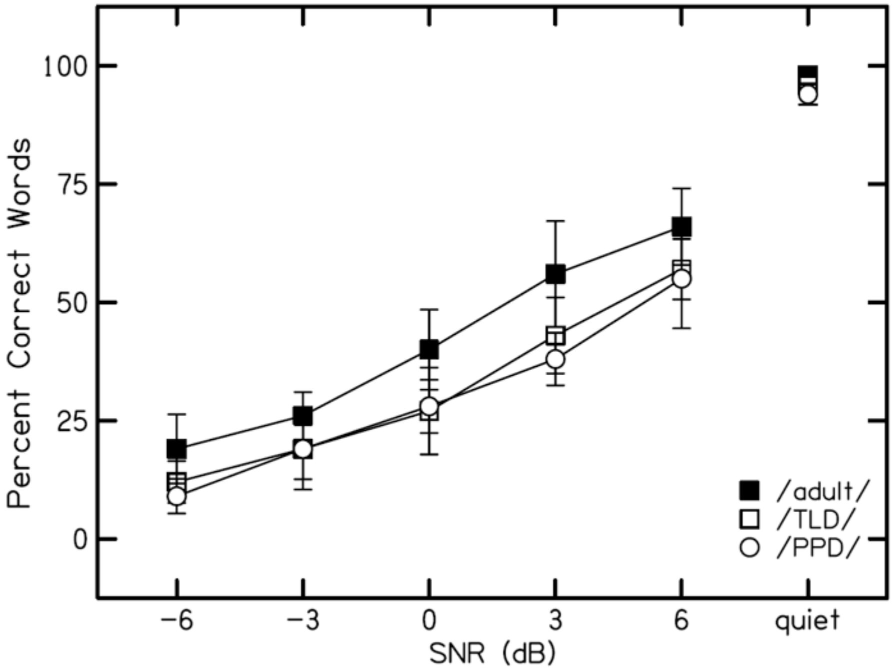

Figure 1.
Percent-correct word recognition for CVC words heard at five SNRs and in quiet.

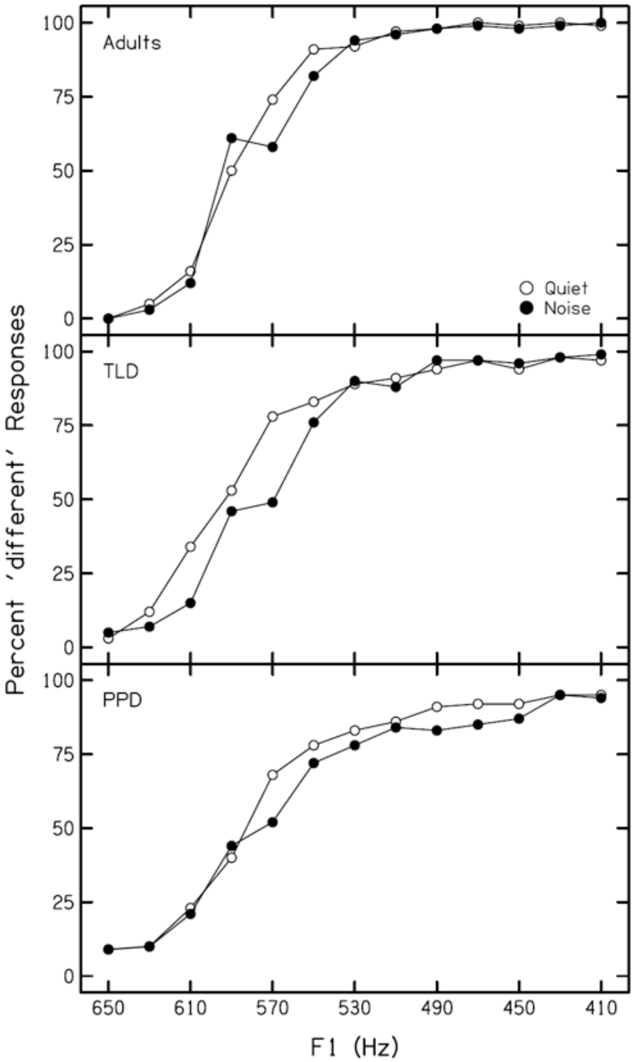

Figure 2.
Discrimination functions for non-speech spectral stimuli in quiet and at 0 dB SNR, plotted by listener group.

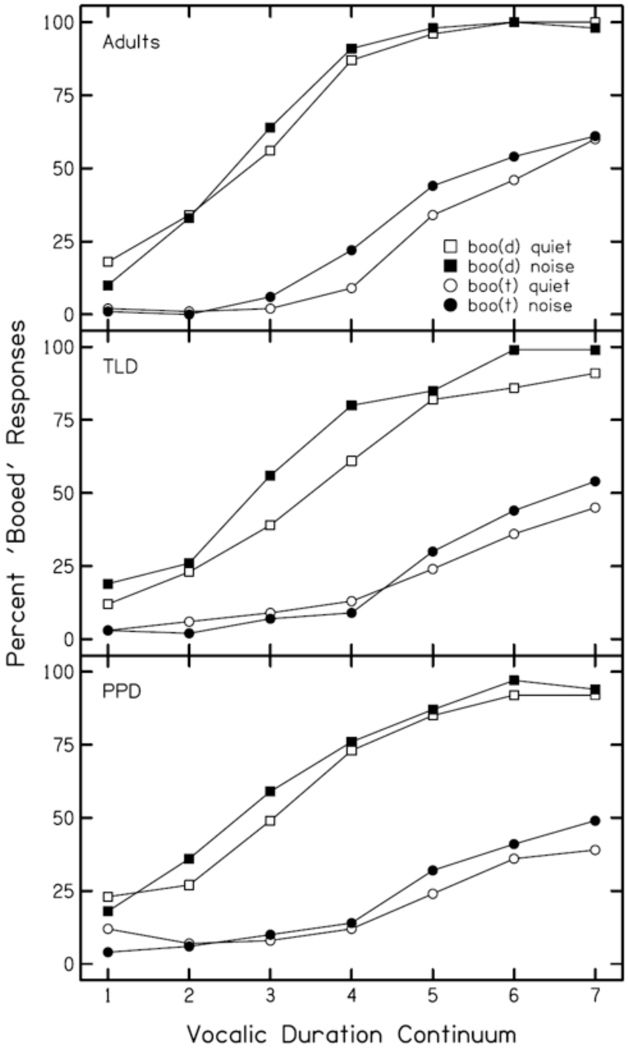

Figure 3.

Labeling functions for *boot/booed* stimuli presented in quiet and at 0 dB SNR, plotted by listener group.

Table 1

Scores from the Word Reading subtest of the Wide Range Achievement Test (WRAT) and the Recalling Sentences subtest of the Clinical Evaluation of Language Function-4 for the two groups of children, with standard deviations in parentheses.

	TLD	PPD
Word Reading (Raw)	41.0 (5.4)	28.4 (3.9)
Word Reading (Standard)	124.3 (9.6)	96.3 (10.4)
Word Reading (Percentile)	91.8 (6.8)	42.2 (24.6)
Recalling Sentences (Raw)	63.7 (12.8)	47.0 (8.5)
Recalling Sentences (Scaled)	11.7 (2.8)	8.2 (1.8)
Recalling Sentences (Percentile)	66.0 (27.8)	31.1 (18.5)

TLD = Typical Language Development; PPD = Phonological Processing Deficits. Shown are mean raw scores and percentile ranks for both subtests. Mean standard scores are shown for the Word Reading subtest and mean scaled scores are shown for Recalling Sentences.

Table 2

Designation of which phenomenon, auditory sensitivity or enhanced masking, is most clearly examined by each dependent measure.

	Auditory Sensitivity	Enhanced Masking
Word recognition in noise		√
Discrimination of spectral glides (quiet)	√	
Discrimination of spectral glides (noise)		√
Labeling of final stops (quiet)	√	
Labeling of finals stops (noise)		√

Table 3

Mean number of items correct (and standard deviations) on the three tests of phonological awareness for the three groups of participants.

	Adults	**TLD**	**PPD**
ICSD	47.4 (1.6)	45.5 (2.5)	43.4 (6.4)
FCC	44.6 (2.6)	39.0 (7.3)	24.7 (12.7)
PhonD	30.9 (1.2)	24.8 (6.2)	16.4 (8.3)

ICSD = Initial Consonant Same or Different; FCC = Final Consonant Choice; and PhonD = Phoneme Deletion. Total number of items on each task was 48 for ICSD and FCC, and 32 for PhonD.

Table 4

Results of ANOVAs and *post hoc t* tests done on scores for the three tests of phonological awareness.

	df	F or t	p	Bonferroni significance
ICSD				
Group effect	2,39	3.29	.048	
Adults *vs*. TLD	39	1.21	*ns*	
Adults *vs*. PPD	39	2.57	.014	.05
TLD *vs*. PPD	39	1.35	*ns*	
FCC				
Group effect	2,39	19.96	<.001	
Adults *vs*. TLD	39	1.72	.094	
Adults *vs*. PPD	39	6.12	<.001	.001
TLD *vs*. PPD	39	4.41	<.001	.001
PhonD				
Group effect	2,39	20.10	<.001	
Adults *vs*. TLD	39	2.66	.011	.05
Adults *vs*. PPD	39	6.31	<.001	.001
TLD *vs*. PPD	39	3.66	<.001	.01

ICSD = Initial Consonant Same or Different; FCC = Final Consonant Choice; and PhonD = Phoneme Deletion.

Table 5

Mean difference thresholds and slopes for the discrimination task for each group in quiet and noise, with standard deviations in parentheses.

	Adults	TLD	PPD
Difference Threshold			
Quiet	582.9 (18.4)	585.8 (27.9)	573.2 (34.6)
Noise	578.9 (24.3)	573.6 (24.8)	563.4 (35.3)
Slope			
Quiet	37.6 (10.9)	26.2 (11.7)	20.1 (8.6)
Noise	37.6 (11.0)	26.8 (9.0)	22.1 (12.2)

Table 6

Results of ANOVAs and *post hoc t* tests done on slopes for the discrimination task in quiet.

	df	**F or t**	**p**	**Bonferroni significance**
Group effect	2,38	9.67	<.001	
Adults *vs*. TLD	38	2.87	.007	.05
Adults *vs*. PPD	38	4.31	<.001	.001
TLD *vs*. PPD	38	1.50	*ns*	

Table 7

Mean phoneme boundaries, differences in phoneme boundaries and slopes for the labeling task for each group in quiet and noise, with standard deviations in parentheses.

	Adults	**TLD**	**PPD**
Phoneme Boundary			
boot quiet	6.7 (2.0)	7.7 (2.0)	8.2 (2.3)
booed quiet	2.5 (0.8)	3.5 (1.1)	2.9 (1.1)
boot noise	6.6 (2.6)	6.7 (1.8)	7.6 (2.4)
booed noise	2.5 (0.6)	2.7 (0.8)	2.6 (0.7)
boot-booed Difference			
quiet	4.2 (2.3)	4.2 (2.7)	5.3 (3.0)
noise	4.1 (3.1)	4.0 (2.2)	5.0 (2.4)
Slope			
boot quiet	0.6 (0.4)	0.3 (0.3)	0.3 (0.2)
booed quiet	0.8 (0.2)	0.6 (0.2)	0.6 (0.4)
boot noise	0.8 (0.6)	0.6 (0.4)	0.5 (0.4)
booed noise	1.2 (0.5)	0.7 (0.2)	0.6 (0.3)

Table 8

Results of ANOVAs and post hoc *t* tests done on slopes for the labeling task in quiet.

	df	F or t	p	Bonferroni significance
boot				
Group effect	2,39	5.49	.008	
Adults *vs*. TLD	39	2.52	.016	.05
Adults *vs*. PPD	39	3.12	.003	.01
TLD *vs*. PPD	39	0.60	*ns*	
booed				
Group effect	2,39	3.50	.040	
Adults *vs*. TLD	39	2.54	.015	.05
Adults *vs*. PPD	39	1.92	.062	
TLD *vs*. PPD	39	0.62	*ns*	